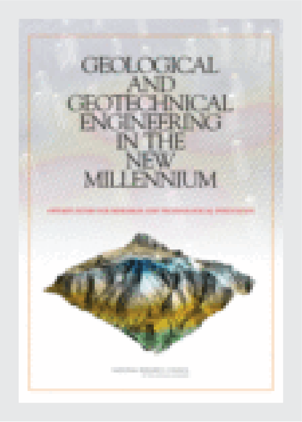


Geological and Geotechnical Engineering in the New Millennium: Opportunities for Research and Technological Innovation

DETAILS

222 pages | 7 x 10 | null
ISBN null | DOI 10.17226/11558

AUTHORS

Committee on Geological and Geotechnical Engineering in the New Millennium; Opportunities for Research and Technological Innovation, Committee on Geological and Geotechnical Engineering, National Research Council

GEOLOGICAL AND GEOTECHNICAL ENGINEERING IN THE NEW MILLENNIUM

OPPORTUNITIES FOR RESEARCH AND TECHNOLOGICAL INNOVATION

Committee on Geological and Geotechnical Engineering
in the New Millennium:
Opportunities for Research and Technological Innovation

Committee on Geological and Geotechnical Engineering

Board on Earth Sciences and Resources
Division on Earth and Life Studies

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
WASHINGTON, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, N.W. Washington, DC 20001

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This study was supported by Grant No. CMS-0229020 between the National Academy of Sciences and the National Science Foundation. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the organizations or agencies that provided support for the project.

International Standard Book Number 0-309-10009-7

Additional copies of this report are available from the National Academies Press, 500 Fifth Street, N.W., Lockbox 285, Washington, DC 20055; (800) 624-6242 or (202) 334-3313 (in the Washington metropolitan area); Internet, http://www.nap.edu.

Printed in the United States of America

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Wm. A. Wulf is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. Wm. A. Wulf are chair and vice chair, respectively, of the National Research Council.

www.national-academies.org

COMMITTEE ON GEOLOGICAL AND GEOTECHNICAL ENGINEERING IN THE NEW MILLENNIUM: OPPORTUNITIES FOR RESEARCH AND TECHNOLOGICAL INNOVATION

Members

JANE C. S. LONG, *Chair*, Lawrence Livermore National Laboratory, Livermore, California
BERNARD AMADEI, University of Colorado, Boulder
JEAN-PIERRE BARDET, University of Southern California, Los Angeles
JOHN T. CHRISTIAN, Waban, Massachusetts
STEVEN D. GLASER, University of California, Berkeley
DEBORAH J. GOODINGS, University of Maryland, College Park
EDWARD KAVAZANJIAN JR., Arizona State University, Tempe
DAVID W. MAJOR, GeoSyntec Consultants Inc., Ontario, Canada
JAMES K. MITCHELL, Virginia Polytechnic Institute and State University, Blacksburg
MARY M. POULTON, The University of Arizona, Tucson
J. CARLOS SANTAMARINA, Georgia Institute of Technology, Atlanta

Staff

ANTHONY R. DE SOUZA, Director
JENNIFER T. ESTEP, Financial Associate
CAETLIN M. OFIESH, Research Assistant
RADHIKA CHARI, Senior Project Assistant (until March 2004)
AMANDA M. ROBERTS, Program Assistant (from July 2004)

COMMITTEE ON GEOLOGICAL AND GEOTECHNICAL ENGINEERING

Members

NICHOLAS SITAR, *Chair*, University of California, Berkeley
SUSAN E. BURNS, University of Virginia, Charlottesville
JOHN T. CHRISTIAN, Waban, Massachusetts
KIM DE RUBERTIS, Cashmere, Washington
THOMAS W. DOE, Golder Associates, Redmond, Washington
JOANNE T. FREDRICH, Sandia National Laboratories, Albuquerque, New Mexico
LARRY W. LAKE, The University of Texas, Austin
RAY E. MARTIN, Ray E. Martin, LLC, Ashland, Virginia
MARY M. POULTON, The University of Arizona, Tucson
DONALD W. STEEPLES, University of Kansas, Lawrence

Staff

SAMMANTHA L. MAGSINO, Program Officer
AMANDA M. ROBERTS, Program Assistant

BOARD ON EARTH SCIENCES AND RESOURCES

Members

GEORGE M. HORNBERGER, *Chair*, University of Virginia, Charlottesville
M. LEE ALLISON, Office of the Governor, Topeka, Kansas
STEVEN R. BOHLEN, Joint Oceanographic Institutions, Washington, D.C.
ADAM M. DZIEWONSKI, Harvard University, Cambridge, Massachusetts
KATHERINE H. FREEMAN, The Pennsylvania State University, University Park
RHEA L. GRAHAM, New Mexico Interstate Stream Commission, Albuquerque
ROBYN HANNIGAN, Arkansas State University, State University
V. RAMA MURTHY, University of Minnesota, Minneapolis
RAYMOND A. PRICE, Queen's University, Kingston, Ontario
MARK SCHAEFER, NatureServe, Arlington, Virginia
BILLIE L. TURNER II, Clark University, Worcester, Massachusetts
STEPHEN G. WELLS, Desert Research Institute, Reno, Nevada
THOMAS J. WILBANKS, Oak Ridge National Laboratory, Oak Ridge, Tennessee

Staff

ANTHONY R. DE SOUZA, Director
ELIZABETH A. EIDE, Senior Program Officer
DAVID A. FEARY, Senior Program Officer
ANNE M. LINN, Senior Program Officer
ANN G. FRAZIER, Program Officer
SAMMANTHA L. MAGSINO, Program Officer
RONALD F. ABLER, Senior Scholar
HEDY J. ROSSMEISSL, Senior Scholar
VERNA J. BOWEN, Administrative and Financial Associate
JENNIFER T. ESTEP, Financial Associate
TANJA E. PILZAK, Research Associate
CAETLIN M. OFIESH, Research Assistant
JAMES B. DAVIS, Program Assistant
JARED P. ENO, Program Assistant
AMANDA M. ROBERTS, Program Assistant

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Braden Allenby, Arizona State University, Tempe
Chris Breeds, Sub Terra, North Bend, Washington
Corale Brierley, Brierley Consultancy LLC, Highlands Ranch, Colorado
John Dunicliff, Geotechnical Instrumentation Consultant, Devon, England
Henry Hatch, Former Chief of Engineers, U.S. Army, Oakton, Virginia
Elvin R. Heiberg, III, Heiberg Associates, Arlington, Virginia
Norbert Morgenstern, University of Alberta, Edmonton, Canada

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by William Fisher, The University of Texas at Austin. Appointed by the NRC, he was responsible for making certain that an independent examination of the report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Preface

The charge to this committee—to envision the future of geotechnology—is at once a grand challenge and a problem. In many ways, geotechnology is a mature field having come to its majority in the last 50 years. Many serious problems have been solved. We know how to build strong foundations, safe dams, and stable roads and tunnels. We have a good understanding about the behavior and protection of groundwater, how to extract the petroleum resources, and develop a geothermal field. We understand quite a bit about the soil conditions that lead to liquefaction during an earthquake or make landslides likely. If there is a major problem, it is that the state of the practice worldwide does not match the state of the art. Even when the knowledge exists, economics or ignorance lead to harmful, suboptimal, and dangerous practice. People still build trailer parks on flood plains.

Those of us who have been trained to this state of the art are trained to keep digging deeper (in the intellectual sense) and to refine and improve our understanding and methods. We are more tuned to what we still do not know and cannot yet do versus reflecting on how far we have come and how much we are now capable of compared to the past. Given the approaches and lexicons we are used to, we have a kind of Zeno's paradox in moving forward. Each step forward is smaller than the last in comparison to the totality of progress in the field. Quantum leaps are farther and fewer using the same paradigms, technology, and approaches.

The problems have also changed. We can no longer expect to do an engineering project that has no reference to the impacts of the design on social structures, economics, and the environment. Sustainability has become an imperative recognized by the engineering profession (see, for example, the World Federation of Engineering Organizations website, http://www.unesco.org/wfeo/) in general and the professional societies involving geoengineering (e.g., the American Society Civil Engineers, Society of Manufacturing Engineers, Society of Petroleum Engineers). Earth-type problems are now recognized on regional and global scales. Engineers need to embrace social science aspects of their problems if they are to develop acceptable designs.

Geoengineering as a discipline and practice can and should change. Geoengineers should look to entirely new technologies and approaches to solve problems faster, better, cheaper. The problems geoengineers solve are important to society, and the current technological constraints are in many cases less likely to be solved by beating them with old approaches than they are to be cracked by new technological and more interdisciplinary approaches. Geoengineers, with their focus on Earth are poised to expand their roles and lead in the solution of modern Earth systems problems, such as global change, emission free energy supply, global water supply, and urban systems.

Changing established fields of engineering is not easy. It is a truism that practitioners and researchers are most comfortable in the realm of their known approaches and problem spaces. It is perhaps more important to realize that geoengineers know that the problems they have been solving still need to be solved and the techniques and technology they currently use are still *a propos*. Part of moving ahead involves being able to feel the confidence that the significant progress made to date will not be lost through a love affair with the new and exciting. At the same time that this report promotes and encourages change, the committee also felt the stress of this change. As much as we found enthusiasm and genuine excitement about the possibilities of the future, we were not immune to concerns about the future of support for, and education in, traditional geoengineering.

As chair, it is my hope that the readers of this report will be captured by the imaginative and creative possibilities of embracing whole new technological approaches to research and the migration to problems that have become dominant issues for our world today. If we do not find better ways to solve our traditional problems, economic and environmental concerns will push these solutions further and further out of reach. For example, we certainly know how to build underground infrastructure in cities, but we had to spend over $14.6 billion to construct Boston's Central Artery and the disruption to the city was lengthy and extensive. Many such projects will be required in our cities but will we have the ability to do them if we cannot significantly decrease the cost, reliability and time of construction, not to mention our ability to manage them? The ability to build such structures as safe dams, extensive highways, and safe water supply systems was an imperative of the last century. Perhaps the most important imperative of this century is sustainability and the most salient feature of sustainability is the scale of the problem. Geoengineering is a great starting point for addressing many Earth system issues, and I see tremendous importance in this endeavor. It has been the committee's privilege to learn, think, and write about this. We hope you become as interested in the possibilities as we are.

Finally, I would like to thank the committee members who worked so hard to complete this report.

Jane C. S. Long
Chair

Contents

APPENDIXES

Summary

The field of geoengineering is at a crossroads where the path to high-tech solutions meets the path to expanding applications of geotechnology. In this report, the term "geoengineering" includes all types of engineering that deal with Earth materials, such as geotechnical engineering, geological engineering, hydrological engineering, and Earth-related parts of petroleum engineering and mining engineering. The rapid expansion of nanotechnology, biotechnology, and information technology begs the question of how these new approaches might come to play in developing better solutions for geotechnological problems.

This report presents a vision for the future of geotechnology aimed at National Science Foundation (NSF) program managers, the geological and geotechnical engineering community as a whole, and other interested parties, including Congress, federal and state agencies, industry, academia, and other stakeholders in geoengineering research. Some of the ideas may be close to reality whereas others may turn out to be elusive, but they all present possibilities to strive for and potential goals for the future. Geoengineers are poised to expand their roles and lead in finding solutions for modern Earth systems problems, such as global change,[1] emissions-free energy supply, global water supply, and urban systems.

---

[1] By global change we refer to all of the anthropogenically induced changes in Earth's environment, including notably climate change induced by energy use

The type and scope of geotechnical problems are changing, and yet geotechnologists are for the most part not prepared for these changes. The world now faces challenges in Earth systems where engineering problems meet societal and environmental issues. For example, sustainable development of the built environment and natural resources is a new societal imperative for the twenty-first century (NRC, 1999). Sustainable development will require a new understanding and management of the behavior of Earth materials from the nanoscale to the macro- and even global scale and link the engineering management of Earth processes with economic and environmental goals. An expansion of the traditional role for geoengineers will be geoengineering for Earth systems, which will include efforts to integrate social, environmental, and scientific issues into engineering solutions for Earth systems problems. This expanded scope will require new types and quantities of data, benchmarking, and new efforts in modeling. Some of the critical problems to be addressed by geoengineering for Earth systems will include dealing with the legacy and future of energy use, developing geotechnology that is environmentally responsible and economically beneficial—especially for the developing world—holistic infrastructure solutions for urban environments, and managing the emerging critical issues of global change.

Many different types of problems and projects, ranging from the microscale to the global scale, draw on the geosciences and geotechnology for solutions and effective implementation. This report focuses on the necessary technology and science to enable problem identification and solving, robust and cost-effective designs, efficient and safe construction, assurance of long-term serviceability, protection from natural hazards, and continuing respect for the environment. These tasks are the essence of modern geoengineering.

The Geotechnical and Geohazards Systems Program of the National Science Foundation asked the National Research Council's Committee

---

patterns and the associated changes in water supplies, the occurrence of and our susceptibility to natural disasters, sea level rise, weather patterns, as well as the changes induced by urbanization, agriculture, lumbering, industrial contamination, and mining.

on Geological and Geotechnical Engineering in the New Millennium: Opportunities for Research and Technological Innovation to conduct a study to provide advice on future research directions and opportunities in geological and geotechnical engineering, concentrating on techniques for characterizing, stabilizing, and monitoring the subsurface. The committee addressed the following in its statement of task:

1. Updated the report *Geotechnology: Its Impact on Economic Growth, the Environment, and National Security* (NRC, 1989) by assessing major gaps in the current states of knowledge and practice in the field of geoengineering. Areas included, but were not limited to, research capabilities and needs, practice and fundamental problems facing it, culture, and workforce.

2. Provided a vision for the field of geoengineering.

    - What societal needs can geoengineering help meet? Examples include infrastructure, homeland security, urban sprawl, traffic congestion, and environmental degradation.
    - What new directions would improve geoengineering in ways that will better help meet these needs?

3. Explored ways for achieving this vision and recommended implementation strategies.

    - What new and emerging technologies are needed, including biotechnology, microelectromechanical systems (MEMS), nanotechnology, cyber infrastructure, and others?
    - What workforce changes are needed?
    - What opportunities are there for interdisciplinary collaboration?
    - What barriers and constraints are there to achieving this vision?

This report provides a vision for the field of geotechnology. It looks at opportunities that should be seized now to address future needs. It explores ways to make geoengineering more expansive in both scope and approach. The problems of today and tomorrow will need to be solved with a wider variety of tools and scientific information than is currently employed, including Earth sciences, biological sciences, nanotechnology, information technology, and MEMS. The problems geoengineers solve are part of complex human, geological, and biological systems. We need to recognize and address the systems context for geoengineering in order to construct appropriate solutions to problems that are affected by society, economics, geology, and biology. We especially see a need for geoengineering in the emerging field of geoengineering for Earth systems in an attempt to manage and sustain a habitable and beneficial environment on Earth.

The goal of geoengineering research and technology innovation in both the short and long term should be to provide the knowledge and understanding that will enable problem solving and projects to be done with more certainty, faster, cheaper, better, and with proper respect for sustainability and environmental protection. To address these issues, the committee developed three categories of findings and recommendations. The first category covers knowledge gaps identified in the 1989 report *Geotechnology: Its Impact on Economic Growth, the Environment, and National Security* (NRC, 1989), gaps not yet satisfactorily resolved by the geoengineering community. This section addresses how new tools and technologies can be used to fill in these knowledge gaps and tackle new applications in geoengineering. The second category is a compelling new imperative for geoengineering for Earth systems, a systems engineering approach for increasingly complex social, environmental, and economic factors that lead to sustainable development of our infrastructure and resources. The third category relates to changes in interdisciplinary research and education necessary to ensure that a diverse workforce is able to apply new tools and technologies to new applications of geoengineering. Primarily, the committee's findings and recommendations are directed to the National Science Foundation, but suggestions for other agencies, education, and practice are made as well.

KNOWLEDGE GAPS AND NEW TOOLS

In 1989, the role of geoengineering in addressing societal needs was documented by the Geotechnical Board of the National Research Council in *Geotechnology: Its Impact on Economic Growth, the Environment, and National Security* (NRC, 1989). Societal needs addressed by geotechnology were grouped into seven broad national issues:

1. waste management,
2. infrastructure development and rehabilitation,
3. construction efficiency and innovation,
4. national security,
5. resource discovery and recovery,
6. mitigation of natural hazards, and
7. frontier exploration and development.

For each of these seven issues, the 1989 report identified critical needs and recommended actions for advancing the role of geoengineering. Table 2.1 summarizes these critical needs and recommended actions.

Finding

The committee finds that significant knowledge gaps continue to challenge the practice of geoengineering, especially the ability to characterize the subsurface; account for time effects; understand biogeochemical processes in soils and rocks; stabilize soils and rocks; use enhanced computing, information, and communication technologies; and understand geomaterials in extreme environments. (See Chapter 2 for the full list of knowledge gaps.) The committee is concerned that resources for investigator-initiated research at the National Science Foundation are diminishing and believes that the balance between investigator-initiated research and directed research is unbalanced toward directed research.

Geoengineering is burdened by a lack of adequate characterization of the geomedia and paucity of necessary information, which contributes to some extent to the unavoidable uncertainty in design. We are still unable to translate our fundamental understanding of the physics and chemistry of soils and rocks and the microscale behavior of particulate systems in ways that enable us to quantify the engineering properties and behavior needed for engineering analysis of materials at the macroscale. Given these problems, paradigms for dealing with the resulting uncertainty are poorly understood and even more poorly practiced. There is a need for (1) improved characterization technology; (2) improved quantification of the uncertainties associated with characterization; and (3) improved methods for assessing the potential impacts of these uncertainties on engineering decisions requiring engineering judgment (i.e., on risk analysis for engineering decision making).

Recommendation

The National Science Foundation should

- continue to direct funding into the fundamental knowledge gaps and needs in geoengineering.
- restore the balance between investigator-initiated research and directed research, and should allocate resources to increase the success rate for unsolicited proposals in geoengineering (and civil and mechanical systems) to a level commensurate with other programs in the engineering directorate.

Finding

The committee sees tremendous opportunities for advancing geoengineering through interaction with other disciplines, especially in the areas of biotechnology, nanotechnology, MEMS and microsensors, geosensing, information technology, cyberinfrastructure, and multispatial and multitemporal geographical data modeling, analysis, and visualization.

Pilot projects in vertical integration of research between multiple disciplines—perhaps including industry, multiple government agencies, and multiple universities—should be explored as alternatives to more traditional interdisciplinary proposals.

New technology—already available or under development—promises exciting new possibilities for geoengineering. Some applications of these new technologies that the committee found of particular interest use

1. microbes to stabilize or remediate soils,
2. nanotechnology to modify the behavior of clay,
3. nanosensors and MEMS to characterize and monitor the behavior of geomaterials and geosystems,
4. remote sensing and noninvasive ground-based sensing techniques, and
5. next-generation geologic data models to bridge sensing, computation, and real-time simulation of behavior for adaptive management purposes and geophysics for urban infrastructure detection.

Some of these new technologies likely will have major impacts on geoengineering, such as revolutionizing the way geosystems are characterized, modified, and monitored. However, many of the applications of these new technologies have yet to be identified. In taking advantage of these new technologies, most geoengineering researchers would benefit from additional background in such areas as electronics, biology, chemistry, material science, information technology, and the geosciences. Rapid progress in applying these new technologies will require revised educational programs and novel research schemes, as well as updated and re-equipped laboratory facilities.

Recommendation

The National Science Foundation should create opportunities to explore emerging technologies and associated opportunities in three different types of activities. The first is designed to train researchers in new technologies through directed seed funds for interdisciplinary initiatives, such as continuing education of faculty (off-campus intensive courses), theme-specific sabbaticals, exploratory research initiatives, and focused workshops. The second is to provide funding for new equipment for the adaptation and development of emerging technologies for geoengineering applications.

The National Science Foundation Geomechanics and Geohazards Program should emphasize the application of biotechnology, nanotechnology, MEMS, and information technology to geoengineering in its annual Small Business Innovation Research Program solicitation.

GEOENGINEERING FOR EARTH SYSTEMS

Finding

There are no isolated activities in this rapidly changing world. A decision in one place has repercussions in other places, sometimes with dramatic and unanticipated consequences. The influence of countless decisions at all scales is having a marked impact on the environment. In order to respond effectively to issues caused by human interactions with Earth systems, the committee sees a need for a broadened geoengineering discipline. Sustainable development provides a new paradigm for geoengineering practice, in which the tools, techniques, and scientific advances of multiple disciplines are brought to bear on ever more complex problems.

Geoengineering has made significant progress since 1989 in addressing societal needs. However, there has been a change in perspective from national to global and a realization that social, economic, and environmental dimensions must be included to develop robust solutions to fulfill these needs. Increased attention to anthropogenic effects on our environment and to sustainable development are important manifestations of this change in perspective.

Recommendation

The National Science Foundation should create an interdisciplinary initiative on Earth systems engineering, including Geoengineering for Earth Systems (GES). The problems of GES occur on all scales, from the nano- and microscale behavior of geomaterials, to the place-specific mesoscale investigations and the scale of the globe that responds to climate change.

A GES initiative should include any research problem that (1) involves geotechnology and (2) has Earth systems implications or exists in an Earth systems context. In this regard, Earth systems have components that depend on each other (i.e., the outcome of one part of the problem affects the process in another part of the problem), with feedback loops and perhaps dynamical interactions. The parts of the system come from the biosphere (all life on Earth), geosphere (the rocks, soil, water, and atmosphere of Earth), and anthrosphere (political, economic, and social systems), as well as individual components in these spheres. This initiative should include the development of geosystems models and support for adaptive management, data collection, management, interpretation, analysis, and visualization.

Finding

Multiple government agencies, such as the Department of the Interior, Department of Energy, National Aeronautics and Space Administration, Department of Agriculture, Department of Transportation, Department of Defense, and Department of Homeland Security, have interests in Earth system problems. These agencies would be well served by advances in geoengineering that could help to address the complex problems, knowledge gaps, and needs they face.

Recommendation

National Science Foundation program directors should participate in GES research and development efforts with other agencies by developing a GES roundtable, sharing and jointly archiving information, and leveraging through cofunded projects.

The committee recommends that a workshop be organized to wrestle with the issue of engaging geoengineers in public policy initiatives on Geoengineering for Earth Systems and sustainable development. The National Science Foundation is the ideal sponsor of such a workshop, and the United States Universities Council on Geotechnical Education and Research must be urged to be an active participant along with the American Society of Civil Engineers, American Rock Mechanics Association, and other professional societies. The societies must be represented by their leading practicing-engineer members, rather than by executive administrators of the societies. Unconventional thinking related directly to issues of research and practice and engagement in public policy will be required before the details of how the workshop should be administered are developed.

INTERDISCIPLINARY RESEARCH AND EDUCATION

Finding

Research and educational institutions are normally organized by discipline. The above findings and recommendations can be realized only if the institutions involved recognize the challenge and find new ways to accommodate research, education, and practice. For truly interdisciplinary solutions, cooperation must be invited, encouraged, and rewarded. Structures must exist in universities as well as funding agencies to facilitate collaboration.

Recommendations

The committee recommends that the National Science Foundation

- Encourage cross-disciplinary collaboration and collaboration between researchers and industry practitioners and among tool developers and potential tool users in its proposal preparation guidelines; include such collaboration as an explicit proposal evaluation criterion in its proposal preparation guidelines; and include cross-disciplinary collaboration as an explicit proposal evaluation criterion. Geoengineering proposal review panels should include researchers from related (cross-disciplinary) fields and from other federal research entities to the extent possible.

- Encourage communication among researchers through principal investigator workshops where principal investigators describe their current NSF-funded work. The National Science Foundation should also require timely dissemination and sharing of experimental data and analytical models using the protocols and data dictionaries being developed for the Network for Earthquake Engineering Simulation project. Proposals should provide specific information on dissemination of this information, and "Results of Prior Research" should document dissemination of data from previous NSF-funded work.
- Conduct a critical evaluation of existing collaboratories and develop criteria for evaluation of collaboratory proposals, including consideration of the relative merit of funding a collaboratory versus funding individual and small-group research.

Finding

A more diverse workforce in terms of educational background, technical expertise, and application domains, as well as more traditional measures of diversity, is required to bring a broad range of cultural understanding, skills, knowledge, and practice to bear on complex geoengineering problems. In parallel with a new perspective on interdisciplinary research and the transfer and adaptation of knowledge between disciplines, a new perspective on science and engineering education is required so that the new workforce is truly ready to do the research and practice.

The diversity of the geoengineering workforce has improved in the last 30 years but more improvement is still needed. The long-term vitality of the geoengineering field depends on the entry of diverse, creative talent to the field.

Recommendation

The National Science Foundation should make use of the data it has collected during its efforts to improve the educational foundation for a diverse student population and study new measures that could be taken to improve diversity in geoengineering. This effort should also include exploring, evaluating, and expanding programs that cultivate interaction between principally undergraduate institutions and research institutions.

Finding

The structure of universities can facilitate interdisciplinary research but is still lacking in its support of interdisciplinary engineering education.

Recommendation

The National Science Foundation should create an interdisciplinary undergraduate education program to support education appropriate to Geoengineering for Earth Systems and adaptation and transfer of knowledge to geoengineering from such disciplines as nanotechnology, biotechnology, and infotechnology.

The National Science Foundation should leverage research funding to engage design and consulting engineers in geoengineering research and development activities. Proposal evaluation criteria could include credit for matching funds and in-kind services from industry, or some portion of available research funds could be dedicated to projects with matching industry support.

In concluding its work, the committee was pleased to learn of the recently completed National Academy of Engineering report *Engineering Research and America's Future: Meeting the Challenges of a Global Economy*. The main recommendations in that report are for increased investments at the federal and state levels, especially for fundamental research; upgrading and expanding laboratories, equipment, information technologies, and other infrastructure needs of universities; cultivating greater U.S. student interest in, and aptitude for, careers in engineering and in engineering research in particular; development and implementation of innovative curricula; and revision of current immigration procedures to make it easier to attract top scientific and engineering talent from around the world. Each of these recommendations should be adapted specifically to help meet the challenges of geoengineering in the twenty-first century.

This report provides a vision for geological and geotechnical engineering in the new millennium and suggests societal needs that the discipline can help to address. It explores ways that geoengineering should change to achieve this vision. If implemented, the recommendations presented should lead to a revitalization of geotechnology. The excitement of using new and powerful technology will modernize and energize the field, resulting in better and less expensive solutions to long-term applications of geotechnology. New initiatives in GES will allow for geotechnology to address critical issues that affect the sustainability of life on Earth. By looking to new technologies and approaches, geo-engineers can help to solve pressing Earth systems problems at all scales.

CHAPTER ONE

Introduction

1.1 PAST, PRESENT, AND FUTURE SCENARIOS

Can you imagine a world where none of its billions of people lack potable water? Imagine a world where the energy needs of its ever-growing population are met without releasing huge amounts of carbon dioxide into the atmosphere and without other deleterious impacts on the environment. Imagine a world where infrastructure development keeps pace with population growth and urbanization, providing secure, affordable, and reliable shelter, transportation systems, waste management, water supply, and energy distribution for all its inhabitants. Imagine a world where foundations and tunnel linings are built using microorganisms to strengthen and stiffen the foundation soil. Imagine a world where advanced warning of impending natural hazards allows for sufficient time to prevent loss of life and to mitigate direct and indirect economic and social impacts. Imagine a world where toxic and other harmful discharges to the environment have ceased and where all past environmental impacts have been remediated. It may be hard to imagine such a world because it is so different from the world we live in, but with adequate investment in geoengineering research and development at least some, if not most, of this may be within our grasp. The purpose of this report is to examine strategies for such investment. The context for these strategies can be examined by looking at selected vignettes that illustrate where we have come from, where we are, and where we must go as geoengineers.

1.1.1 The Past: Lessons We Learned

On the evening of October 9, 1963, after a period of heavy rain, a block of rock of some 270 million m^3 detached from the mountainside above the reservoir impounded by the Vajont Dam in the Italian Alps (see Figure 1.1). The rock mass reached an estimated velocity of 110 km/hr by the time it reached the reservoir. The wave of water displaced by the landslide destroyed the town of Casso, 260 m above the reservoir on the opposite side of the valley, and then sent a wave of water 250 m high over the top of one of the world's tallest dams and crested at 262 m. In Longarone and other hamlets downstream 2,500 unsuspecting villagers lost their lives that evening. The dam remained intact.

The geology of the reservoir area was incompletely understood and mapped. The analysis conducted after the disaster found that the massive slide occurred along an unrecognized clay layer in the limestone bedrock. The lack of knowledge of the geology and a misunderstanding of the

FIGURE 1.1 The Vajont landslide looking from upstream (image courtesy of Professor E. Bromhead, Kingston University; used with permission).

geomechanical behavior of the rock mass led to a reservoir management policy that ultimately resulted in disaster. Pore pressures built up along the clay seam and reduced the normal strength and shear modulus of the rock mass, resulting in a catastrophic brittle failure (Petley, 1996).

Forty years ago large dams were among the most complex structures that geoengineers dealt with, but our understanding of the interaction between such large structures, the reservoirs they impound, and the rock masses on which they were built was limited. There were sizeable gaps in our understanding of geomechanics, our ability to map the subsurface, and our ability to provide adequately for human safety. The studies that followed the Vajont Dam failure improved our understanding of the geomechanical behavior of rock masses.

1.1.2 The Present—Lessons We Are Learning

The Central Artery/Tunnel Project in Boston, Massachusetts, (the "Big Dig") is one of the most complex and costly public infrastructure projects undertaken in the United States (NRC, 2003a). More than one third of the project is underground, a condition that may foretell an important trend in urban infrastructure development in this century. The project had many noteworthy technological accomplishments in geotechnical engineering. The deep slurry walls constructed in soft clay were the largest use of such a construction technique in North America. These walls facilitated successful completion of deep excavations adjacent to fragile historic structures with few adverse effects. The soil freezing and tunnel jacking at Fort Point Channel allowed a tunnel to be constructed under active railroad tracks with no disruption in service. An underpinning technique allowed a tunnel to be constructed under the Red Line subway without settlement or disruption in service of the public transportation network.

Perhaps the most important aspect of this project was that it managed the relocation of complex urban infrastructure from surface to underground while minimizing the impact on the population living in the vicinity and the disruption in service to those using the existing infrastructure. One major reason for the successful mitigation effort was the improved ability to predict, measure, and control ground movement during construction projects. One informal estimate put the savings due to the effective instrumentation at many million dollars (Personal communication from W. Allen Marr to John Christian, March 2003). The improved understanding of the geotechnical behavior of soil and rock masses, new tools and technologies that aid characterization of the subsurface, and improved ability to match construction technology to geotechnical behavior has given city planners new options for relocation of urban infrastructure. The Central Artery/Tunnel Project team worked closely with the affected populations to mitigate the noise, dust, utility, and transportation disruptions associated with construction. The incorporation of the social aspects of the construction design and execution begins to follow some principles of sustainable development (see for example http://www.nae.edu/nae/naehome.nsf/weblinks/NAEW-4NHMAT?opendocument/).

While the project was successfully completed by most measures of success, the record was not perfect. The project was originally estimated to cost $2.6 billion in 1982 dollars; it is now projected to cost $14.6 billion (2002 dollars) (NRC, 2003a) after completion in 2005. In addition to an increase in the scope of the project, a significant portion of the overrun was caused by three factors: (1) inadequate mitigation and community involvement in plans for crossing the Charles River, leading to litigation and delay; (2) unforeseen geotechnical complications in crossing the Fort Point Channel; and (3) inflation. In addition to the initial cost overrun, breaches in the panels and leaks in the overhead connections have developed and are currently subjects of intense study and ongoing repair efforts. Thus, although the project dealt effectively with many complex issues, community mitigation and geoengineering issues combined to create major delays and cost overruns. One of the lessons of the Big Dig is that the cost of underground relocation of infrastructure is still high and must be reduced. Reducing the cost of critical infrastructure improvements in the inner city environment will require research and innovation.

1.1.3 The Future—Lessons We Must Learn

New technologies and tools will change the way geoengineering is done in the future (see Chapter 3). The coupled interaction between the biological and mineralogical components of Earth materials must be explored to understand fully the behavior of a rock or soil mass and the consequences for large- and small-scale phenomena. New engineering approaches will be accommodated by "smart" materials that sense and communicate the status of their structural or chemical integrity, the use of biogeomembranes that are composed of microorganisms, and the use of biological organisms to stabilize and improve the ground and remediate the soil and groundwater. New structures can be engineered in and on Earth that minimize pollution and disruption to the environment or self-heal because they incorporate biological processes as part of the structure.

There are many situations where geoengineers can benefit from real-time, ubiquitous data in order to understand and manage Earth processes. This need will be addressed by new monitoring network schemes under, on, and above the Earth's surface that provide feedback on the response of the rock or soil mass to human and natural forces. The ability to see into Earth with high resolution, at low cost, with minimum disruption, and with results in real time requires new types of sensors at the microscale, new deployment strategies of sensors to monitor pore spaces and rock fractures from within the soil or rock mass rather than from surface or boreholes, and the ability for small, distributed sensors to communicate with each other and to a central computer.

The large data streams made possible by improved sensing capabilities will require new approaches to management of data, database structures, computer models for understanding and prediction of geomechanical behavior, and multispatial, temporal modeling, and visualization of the geosystem.

Sustainable development of the built environment and natural resources is a new societal imperative for the twenty-first century (NRC, 1999; Sidebar 1.1). Sustainable development will require a new understanding and management of the behavior of Earth materials from the

SIDEBAR 1.1
Excerpts from "The Role of the Civil Engineer in Sustainable Development"

Sustainable Development is the challenge of meeting human needs for natural resources, industrial products, energy, food, transportation, shelter and effective waste management while conserving and protecting environmental quality and the natural resource base essential for future development.

The American Society of Civil Engineers (ASCE) recognizes the leadership role of engineers in sustainable development, and their responsibility to provide quality and innovation in addressing the challenges of sustainability. The ASCE Code of Ethics requires civil engineers to strive to comply with the principles of sustainable development in the performance of their professional duties. ASCE will work on a global scale to promote public recognition and understanding of the needs and opportunities for sustainable development.

Issue

The demand on natural resources is fast outstripping supply in the developed and developing world. Environmental, economic, social and technological development must be seen as interdependent and complementary concepts, where economic competitiveness and ecological sustainability are complementary aspects of the common goal of improving the quality of life.

Sustainable development requires strengthening and broadening the education of engineers and finding innovative ways to achieve needed development while conserving and preserving natural resources.

To achieve these objectives, ASCE supports the following implementation strategies:

- Promote broad understanding of political, economic, social, and technical issues and processes as related to sustainable development.
- Advance the skills, knowledge, and information to facilitate a sustainable future; including habitats, natural systems, system flows, and the effects of all phases of the life cycle of projects on the ecosystem.
- Advocate economic approaches that recognize natural resources and our environment as capital assets.
- Promote multidisciplinary, whole system, integrated, and multi-objective goals in all phases of project planning, design, construction, operations, and decommissioning.
- Consider reduction of vulnerability to natural, accidental, and willful hazards to be part of sustainable development.
- Promote performance-based standards and guidelines as bases for voluntary actions and for regulations, in sustainable development for new and existing infrastructure.

Rationale

Engineers have a leading role in planning, designing, building, and ensuring a sustainable future. Engineers provide the bridge between science and society. In this role, engineers must actively promote and participate in multidisciplinary teams with other professionals, such as ecologists, economists, and sociologists, to effectively address the issues and challenges of sustainable development.

SOURCE: ASCE (2004a).

nanoscale to the macro- and even global scale and the linking of engineering management of Earth processes with economic and environmental goals. An expansion of the traditional role for geoengineers will be Geoengineering for Earth Systems (GES) (see Chapter 4), which will include efforts to integrate social, environmental, and scientific issues into engineering solutions for Earth systems problems. This expanded scope will require new types and quantities of data, benchmarking, and new efforts in modeling. Some of the critical problems addressed by GES will include dealing with the legacy and future of energy use; developing geotechnology that is environmentally responsible and economically beneficial, especially for the developing world; holistic infrastructure solutions for urban environments; and perhaps most importantly, managing the emerging critical issues of global change.

No amount of smart new devices will replace engineering geological characterization and synthesis, in the broadest sense, which comes largely with experience. As well, a major challenge for the future is that engineers will need to be able to understand and implement highly technical solutions in concert with meeting the needs of economical constraints and societal concerns.

This future for geoengineering can be realized by a workforce that is broadly educated, able to adapt to emerging problems and technologies, and representative of all segments of society. This workforce should be educated in a university system that facilitates and rewards interdisciplinary education and research (see Chapter 5).

1.2 RESEARCH ISSUES FOR GEOENGINEERING

This committee uses the term "geoengineering" to be inclusive of all types of engineering that deal with Earth materials such as geotechnical engineering, geological engineering, hydrological engineering, as well as Earth-related parts of petroleum engineering and mining engineering.

Many different types of problems and projects, ranging from the microscale to the global scale, draw on the geosciences and geotechnology for their solution and effective implementation. This report focuses on the technology and science that must be known to enable problem identification and solving, robust and cost-effective designs, efficient and safe construction, assurance of long-term serviceability, protection from natural hazards, and continuing respect for the environment and concern for societal interests. These tasks are the essence of modern geoengineering. Geoengineers try to answer questions such as the following:

- What are the soils and rocks, and where are the boundaries?
- Where is the groundwater and how is it moving?
- How do the soils and rocks respond to different stimuli (e.g., loading, unloading, exposure, flows of fluids, changes in temperature, disturbance)?
- Why do these materials respond this way?
- How can we beneficially control or modify the response of these materials?
- How do we relate the answers to the problem at hand?

In virtually every case of building on, in, or with Earth materials, geoengineers need to know about the following:

- Volume change properties;
- Stress deformation and strength properties;
- Fluid and gas conductivity through the soils and rocks;
- How will what we do change what we have; and
- Interactions that modify material properties. (Such interactions are particularly important for some problems, such as waste containment and storage, resource development and recovery, and environmental protection, restoration, and enhancement.)

The goal of geoengineering research and technology innovation in both the short and long term should be to provide the knowledge and understanding that will enable problem solving and projects to be done with more certainty, faster, cheaper, better, and with proper respect for sustainability and environmental protection.

This report explores ways to make geoengineering more expansive in both scope and approach. The problems of today and tomorrow will need to be solved with a wider variety of tools and scientific information than is currently employed, including Earth sciences, biological sciences, nanotechnology, information technology, and microelectromechanical systems (MEMS). The problems geoengineers solve are part of complex human, geologic, and biological systems. We need to recognize and address the systems context for geoengineering in order to construct appropriate solutions to problems that are affected by society, economics, geology, and biology. Perhaps most dramatically, we see a need for geoengineering in the emerging field of GES in our attempt to manage and sustain a habitable and beneficial environment on our Earth.

In order to motivate the changes we recommend in this report, the committee imagines a new future for geoengineering. Some of the ideas may be close to reality whereas others may turn out to be elusory, but they all present possibilities to strive for and potential goals for the future.

1.3 STUDY AND REPORT

The Geotechnical and Geohazards Systems Program of the National Science Foundation (NSF) asked the National Research Council (NRC) to conduct a study to provide advice on future research directions and opportunities in geological and geotechnical engineering, concentrating on techniques for characterizing, stabilizing, and monitoring the subsurface. Initially the committee was asked to identify research priorities, potential interdisciplinary collaborations, and applications of technological advances to geological and geotechnical engineering. After the first meeting, the original statement of task was expanded, and the committee was asked to address the following:

1. Update the report *Geotechnology: Its Impact on Economic Growth, the Environment, and National Security* (NRC, 1989) by assessing major gaps in the current states of knowledge and practice in the field of geoengineering. Areas to be addressed should include,

but are not be limited to, research capabilities and needs, practice and fundamental problems facing it, culture, and workforce.

2. Provide a vision for the field of geoengineering.

   - What societal needs can geoengineering help meet? Examples include infrastructure, homeland security, urban sprawl, traffic congestion, and environmental degradation.
   - What new directions would improve geoengineering in ways that will better help meet these needs?

3. Explore ways for achieving this vision and recommend implementation strategies.

   - What new and emerging technologies are needed, including biotechnology, MEMS, nanotechnology, cyberinfrastructure, and others?
   - What workforce changes are needed?
   - What opportunities are there for interdisciplinary collaboration?
   - What barriers and constraints are there to achieving this vision?

The committee consisted of 12 members drawn from industry and academia (see Appendix A). Two members of the committee were also members of the NRC Geotechnical Board that authored *Geotechnology: Its Impact on Economic Growth, the Environment, and National Security* (NRC, 1989). The committee met five times to gather and evaluate information and to prepare its consensus report. The first two meetings were open meetings and were held in September 2003 in Washington, D.C., and in November 2003 in Irvine, California. The third meeting was a workshop held in February 2004 in Irvine, California. The committee met twice in closed session (March and April 2004 in Irvine, California) for discussion and development of the consensus report. The committee was briefed by and received written information from NSF representatives and experts from industry, nonprofit organizations, academia, and state and federal government agencies (see Appendix B). Committee members also relied on information from published literature, technical reports (including previous NRC reports), and their own expertise.

In keeping with its charge, the committee did not review NSF program elements or other geotechnology research programs in the federal government. This report provides advice for NSF program managers, but it also contains advice for the geological and geotechnical engineering community as a whole, and for other interested parties, including Congress, federal and state agencies, industry, academia, and the general public. The report recommends research directions, but as it is not a program review, it does not include specific budgetary recommendations.

The report is organized as follows. Chapter 2 provides an update of the 1989 report on *Geotechnology: Its Impacts on Economic Growth, the Environment, and National Security* (NRC, 1989). The committee identifies the changes in societal issues that create new imperatives for geotechnology and discusses what has been done to address the research agenda outline in NRC (1989), what is new, what is different, and what still needs to be done. Chapter 3 develops the committee's vision for geoengineering in more detail by examining the new tools, technologies, and scientific advances in other disciplines and what they mean for geoengineering research. Chapter 4 introduces a new direction for GES and provides some guidance on a possible new GES initiative. Chapter 5 presents institutional issues and suggests some implementation strategies for NSF, as well as educational and research institutions and industry. Chapter 6 summarizes the committee's findings and recommendations.

CHAPTER TWO

Updating the 1989 Geotechnology Report: Where Do We Stand?

In 1989, the role of geoengineering in addressing societal needs was documented by the Geotechnical Board of the National Research Council in *Geotechnology: Its Impacts on Economic Growth, the Environment, and National Security* (NRC, 1989), referred to hereinafter as "the 1989 report." Societal needs addressed by geotechnology were grouped into seven broad national issues:

1. waste management;
2. infrastructure development and rehabilitation;
3. construction efficiency and innovation;
4. national security;
5. resource discovery and recovery;
6. mitigation of natural hazards; and
7. frontier exploration and development.

For each of these seven issues, the 1989 report identified national needs and critical issues and recommended actions for advancing the role of geoengineering (see Table 2.1).

Table 2.2 summarizes the committee's perspective on the current status and critical issues in geoengineering with respect to the seven broad areas where geoengineering contributes to societal needs, as identified in the 1989 report. Included in this table is a list of unresolved issues and opportunities to advance the contributions of geoengineering in

TABLE 2.1 Societal Needs Addressed by Geotechnology

NATIONAL NEED AND CRITICAL ISSUE (NRC, 1989)	RECOMMENDED ACTIONS (NRC, 1989)	MAJOR ACCOMPLISHMENTS THROUGH 2004
Waste Management		
Current processes used to initiate remediation of toxic and hazardous waste problems and permit new disposal facilities are slow, complex, costly, and adversarial. There is an urgent need for rapid, effective, and economical cleanup of waste-contaminated sites.	Develop more technically attainable regulatory standards.	New standards and regulations are more realistic: EPA's EMS concept developed.
	Introduce new waste containment and treatment technologies.	Significant advances have been made in waste containment and in situ remediation technologies.
	Allow technical considerations higher priority than enforcement considerations.	Risk-based corrective action has allowed for more realistic site-specific requirements.
	Change the Remedial Investigation/Feasibility Study process to the observational approach.	Monitored natural attenuation represents an application of the observational approach to remediation.
	Improve instrumentation needed for performance assessment.	Automated and remote measuring and monitoring systems have been developed.
	Improve site characterization.	Some advances, but better site characterization is still a critical need.

TABLE 2.1 Continued

NATIONAL NEED AND CRITICAL ISSUE (NRC, 1989)	RECOMMENDED ACTIONS (NRC, 1989)	MAJOR ACCOMPLISHMENTS THROUGH 2004
Infrastructure Development and Rehabilitation		
Meeting the backlogged rehabilitation needs of existing facilities and development of new infrastructure systems requires a coordinated interdisciplinary approach, with geotechnology playing a prominent role.	Develop new materials.	Geosynthetic materials have been developed for many applications.
	Develop remote sensing techniques to both locate and characterize existing facilities.	Significant advances in GPR, LIDAR, InSAR, and airborne methods.
	Develop nondisruptive designs for repair and replacement of infrastructure.	Trenchless technologies, minimally invasive ground improvement, directional drilling, advanced ground reinforcement technologies now available.
	Develop geotechnical instrumentation for site characterization and performance assessment.	Some advances in instrumentation, but continuing research and development is needed. Better means of communicating the value of instrumentation to project owners are also needed.
	Develop new and better soil and rock modification techniques.	Remains one of the most studied areas, especially grouting methods, deep densification, reinforcement. Renewed interest in admixture stabilization.
	Provide a technical basis for life-cycle analysis and design.	Advances have been made on materials flows and a better understanding of inventory analysis for construction materials. Technologies are well established for life-cycle analysis for metals and other building materials, many completed by groups interested in understanding their own materials as well as for comparative reasons.

continued

TABLE 2.1 Continued

NATIONAL NEED AND CRITICAL ISSUE (NRC, 1989)	RECOMMENDED ACTIONS (NRC, 1989)	MAJOR ACCOMPLISHMENTS THROUGH 2004
Construction Efficiency and Innovation		
There is a continuing need for development of innovative construction equipment and techniques to efficiently attack the geotechnical aspects of construction.	Improve our capabilities in site characterization.	Little change in practice. Remains a critical need.
	Develop new contractual procedures for quantification and distribution of project subsurface risks.	Probabilistic methods for developing cost estimates and presenting them to public authorities have been adopted by some jurisdictions.
	Support research on equipment and technology to assist construction managers.	New equipment and methods continually introduced, but improvements tend to be incremental.
	Initiate a system of accountability and rewards to drive investment in research and innovation for new equipment and methods.	New project delivery methods, including design-build and build-operate-transfer, provide rewards for innovation, but geoengineers not fully engaged.
National Security		
We must help meet the national security needs of the United States.	Develop a more systematic approach to ground shock predictions.	Significant progress has been achieved since 2001 in the estimates of nuclear ground shock and of effects on underground structure, through several new efforts involving joint teams of DOD and DOE experts.
	Provide a pool of trained professionals for the weapons effect community.	DOD and DOE teams include both senior and junior investigators and results are being thoroughly documented.

TABLE 2.1 Continued

NATIONAL NEED AND CRITICAL ISSUE (NRC, 1989)	RECOMMENDED ACTIONS (NRC, 1989)	MAJOR ACCOMPLISHMENTS THROUGH 2004
Resource Discovery and Recovery		
Cost-effective approaches to the discovery and recovery of U.S. natural resources are needed.	Improve our ability to "see through" Earth.	Research continues; incremental advances have been made.
	Improve our ability to drill through rock.	Substantial advances in directional drilling, measuring while drilling, and measurement of drilling parameters have been made in the petroleum industry.
	Develop rock excavation methods that are faster and less damaging.	Adaptation of drilling technology from the petroleum industry to the geotechnical and construction communities is needed.
Mitigation of Natural Hazards		
Technology must be used to more effectively reduce losses, both in lives and in monetary costs, resulting from natural hazards.	Promote better land use planning.	National and regional hazard maps (liquefaction, flood, landslide) developed; enhancements to zoning laws in some areas.
	Encourage the use of state-of-the-art technology for design and construction for hazard mitigation.	State-of-the-art technologies are being applied, but continuing effort and emphasis is warranted.
	Incorporate risk assessment in design and mitigation strategies.	Reliability analysis becoming an integral part of many projects. Formal risk assessment still rare.
	Participate in large-scale field research.	Seven National Geotechnical Experimentation Sites, NEES initiative are breaking new ground.
	Promote international exchange of technology and cooperation in research.	Numerous international technology exchanges, scanning tours, conferences.

continued

TABLE 2.1 Continued

NATIONAL NEED AND CRITICAL ISSUE (NRC, 1989)	RECOMMENDED ACTIONS (NRC, 1989)	MAJOR ACCOMPLISHMENTS THROUGH 2004
Frontier Exploration and Development		
We must continue to explore and expand polar, deep undersea, lunar, and planetary frontiers.	Conduct basic research on seafloor sediments, arctic regions, and extraterrestrial materials.	NSF, NASA, USGS, and oil companies are pursuing research in these areas; geoengineers most active in seafloor and arctic regions.
	Educate the public on technical capabilities and possibilities in these areas.	Little progress.
	Develop courses that address the unique needs of frontier research.	Occasional special courses and conferences.

NOTE: DOD = Department of Defense; DOE = Department of Energy; EMS = Environmental Management Systems; EPA = Environmental Protection Agency; GPR = ground penetrating radar; InSAR = Interferometric Synthetic Aperture Radar; LIDAR = light detection and ranging; NASA = National Aeronautics and Space Administration; NEES = Network for Earthquake Engineering Simulation; NSF = National Science Foundation; USGS = U.S. Geological Survey.

TABLE 2.2 Unresolved Issues and New Opportunities for Geoengineering

NATIONAL NEED[a]	2004 STATUS AND CRITICAL ISSUES	UNRESOLVED ISSUES AND NEW OPPORTUNITIES
Waste Management and Environmental Protection	**Status:** Many new technologies have been implemented and more are under development. Risk-based corrective action and monitored natural attenuation have provided significant savings in many cases. **Critical Issues:** Many challenging sites still need to be remediated. Additional technological development is still needed, including development of appropriate waste containment and remediation technology for developing countries and technology for reduction, reuse, and recycling of waste materials. Cleanup, restoration, and protection of wetlands, rivers, harbors, and other waterways has become an important consideration.	• Significant global environmental problems • Formal adoption of the observational method (adaptive management) for site remediation projects • Bioengineering methods for in situ remediation and containment barriers • Long-term stewardship of waste landfills and contaminated sites • Consideration of wastes as "resources out of place" • "Cradle to cradle" management of wastes • Strategies and technologies for alternatives to landfilling • Carbon sequestration • Remediation of contaminated sediments • Regional databases and data models for environmental data • Advanced sensors and remote sensing • Urban surface water management; erosion and sediment control

continued

TABLE 2.2 Continued

NATIONAL NEED[a]	2004 STATUS AND CRITICAL ISSUES	UNRESOLVED ISSUES AND NEW OPPORTUNITIES
Infrastructure Development and Rehabilitation	**Status:** New materials and technologies have made significant inroads in practice. However, little progress has been made in clearing the backlog of infrastructure needs. Life-cycle cost analyses are more refined and sophisticated, but still not widely embraced for selection of preferred alternatives. Sustainability considerations are becoming more important. **Critical Issues:** Wider use of life-cycle cost analyses, including incorporation of sustainable development and other social values, improved modeling of environmental impacts of infrastructure development, rehabilitation of existing geofacilities, and enhanced durability of geoconstruction.	• More discriminating, penetrating, and cost-effective methods for seeing through the ground • Better coordination between planners, designers, constructors, and users • Passive methods for ground improvement, including biostabilization • Regional databases and data models • Smart geosystems and adaptive management methods (using the observational method) • Biofilms for corrosion protection • Long-term durability of geosynthetic materials • Use of formal reliability and life-cycle cost analysis • Quantification and reduction of uncertainties

TABLE 2.2 Continued

NATIONAL NEED[a]	2004 STATUS AND CRITICAL ISSUES	UNRESOLVED ISSUES AND NEW OPPORTUNITIES
Construction Efficiency and Innovation	**Status:** New project delivery methods (e.g., design, build) have had an impact on innovation and efficiency. Significant advances have been made with respect to new equipment and techniques for geotechnical construction, particularly with respect to ground improvement. More efficient means of underground construction remains a critical need and improved methods for site characterization remains one of the greatest needs in geoengineering. **Critical Issues:** More efficient and economical and less disruptive underground construction and ground improvement, minimizing environmental impacts of construction activities.	• Improved site characterization • Remotely controlled, automated earthwork construction • Better matching of soil and rock conditions with equipment and methods • Use of adaptive management systems for application of the observational method • Many aspects of tunneling and underground construction methods, including materials handling, directional control, excavation, safety, ground support • Trenchless technologies • More energy- and cost-efficient ground improvement, including biotechnologies • Easier handling and better improvement of wet and weak soils
National Security	**Status:** Homeland security has become a critical national need, and focus has shifted from national to global. **Critical Issues:** Providing adequate, appropriate, and reliable civil infrastructure; securing civil infrastructure against internal and external threats; reducing dependence on foreign oil; providing secure sources for strategic natural resources.	• New and better methods for hardening sensitive and critical structures and infrastructure • Improved methods for threat detection, including detecting and locating underground intrusion and surface traffic • Appropriate energy, sanitation, and water technologies for developing countries • Development of secure reserves of strategic resources

continued

TABLE 2.2 Continued

NATIONAL NEED[a]	2004 STATUS AND CRITICAL ISSUES	UNRESOLVED ISSUES AND NEW OPPORTUNITIES
Resource Discovery and Recovery	**Status:** Sustainability concerns have moved to the forefront for energy and water resources development. **Critical Issues:** Providing necessary resources for sustainable development and national security and minimizing environmental impacts of resource recovery and use.	• More reliable, discriminating, and penetrating methods for seeing into Earth • Optimization of energy resources • More sustainable resource recovery methods • Improved waste and tailings handling and disposal methods • Carbon sequestration • Groundwater recovery, protection, and recharge
Mitigation of Natural Hazards	**Status:** National and regional hazard maps (earthquake, flood, and landslide) have been incorporated into zoning laws and land use planning in some areas. Formal geohazards risk assessment is becoming an integral part of some projects. However, many communities are still at risk and continued research is needed. **Critical Issues:** Improved regional hazard monitoring, forecasting, communication, and land use planning; appropriate hazard mitigation technology for developing countries.	• Less complicated and more easily understood risk and reliability assessment methods • Remote sensing for hazard forecasting and monitoring • Nonintrusive and passive methods for mitigation of geohazard risks to existing structures and facilities, including biotechnologies • Land use planning and zoning to account for geohazards and their potential consequences • Appropriate technology to mitigate major losses of life and property in the developing world

TABLE 2.2 Continued

NATIONAL NEED[a]	2004 STATUS AND CRITICAL ISSUES	UNRESOLVED ISSUES AND NEW OPPORTUNITIES
Frontier Exploration and Development	**Status:** NSF, NASA, USGS, and oil companies are pursuing research in these areas. However, geoengineers are often not involved in these ventures. **Critical Issues:** Exploration at the frontiers of the natural universe ultimately leading to new frontiers for natural resource recovery and human habitation.	• Fundamental knowledge and understanding • New sources of natural resources (long term) • New habitats (very long term)

[a] As defined by the Geotechnical Board (NRC, 1989).

these areas. The unresolved issues and the opportunities to address them are discussed in more detail in subsequent sections of this chapter. The chapter concludes with the committee's perspective on the major knowledge gaps that need to be closed for geoengineering to realize its potential in addressing these issues and opportunities.

2.1 WASTE MANAGEMENT

As one of the least mature areas of geotechnical practice in 1989, it is not surprising that waste management is one of the areas in which substantial progress has been made since that time. The 1989 report identified an urgent need for rapid, effective, and economical cleanup of waste-contaminated sites. While progress has been made, many sites remain to be remediated, particularly large complex sites such as Pit 9 at

Idaho National Laboratory and the radioactive tank leakage sites at Hanford. There are also numerous military bases abandoned under base realignment initiatives and large industrial sites that involve multiple contaminants and large volumes of waste that await final action (NACEPT, 2004). The pace of remediation has slowed somewhat because of funding constraints and technology gaps. However, the cost and time required to remediate less complicated sites has decreased significantly. New regulations and interpretations of existing regulations have become more realistic with respect to what is technically achievable and what is necessary to protect human health and the environment without being overly burdensome. The transition from waste treatment and stabilization to waste containment and monitoring as the presumptive remedy for many contaminated sites is but one manifestation of this trend toward less burdensome remedies. Another manifestation of this trend is the increasing use of risk-based corrective action, as it not only provides relief from burdensome zero-discharge standards but also facilitates beneficial reuse of impacted brownfield sites. Significant advancements have also been made in instrumentation and monitoring systems for environmental management with the implementation of automated and remote systems for groundwater and vadose zone monitoring.

Monitored natural attenuation is a prime example of the evolution toward less burdensome, more economical approaches to environmental remediation. Monitored natural attenuation applies the traditional geotechnical philosophy of the observational method (Peck, 1969) (see Sidebar 4.4) to achieve an economical but protective remedy for soil or groundwater pollution.

There has also been considerable progress in development of new and improved technologies for waste containment. Geosynthetic composite caps and liners, wherein a geomembrane liner is combined with either a compacted low permeability soil layer or a geosynthetic clay liner (see Figure 2.1), are widely used for waste containment and have become the prescriptive remedy for many waste containment applications. Performance-based standards may allow for even more economical

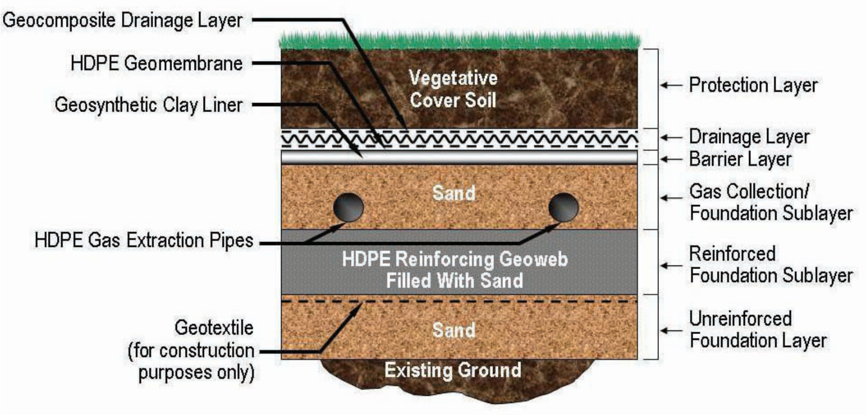


FIGURE 2.1 McColl Superfund site geosynthetic composite final cover. SOURCE: P. Collins et al. (1998).

containment systems when warranted by site-specific considerations (e.g., the use of evapotranspirative soil covers in arid and semiarid climates) (Kavazanjian, 2001).

Geoengineering has made substantial progress in waste management since 1989, but significant challenges remain. As the simpler sites move toward remediation, the more recalcitrant sites remain unabated. In addition to these persistent problems, there is a continuous stream of emerging environmental remediation issues (e.g., methyl tertiary butyl ether, perchlorate, and pharmaceutical contamination of groundwater). Fortunately, treatment technologies for remediation of impacted soil and groundwater have continued to be developed at a rapid pace. Conventional pump-and-treat and excavate-and-dispose remedies are being replaced with increasing frequency by a variety of in situ technologies, including permeable reactive barriers, vapor extraction, and air sparging. Ex situ treatment technologies, such as thermal desorption, are also being developed and applied. A host of other innovative technologies are under development, including various biotechnologies (bioaugmentation, biostimulation), aerobic remediation, and electrokinetic remediation. While the development of bioengineering methods to address soil and groundwater contamination shows great promise in reducing the cost of remediation for many of these issues, development of delivery methods for nutrients and organisms for bioengineering remediation strategies remains a significant challenge for the geoengineer.

The payoff from advances in waste management technology has been significant. Between 1980 and 2000, cleanup and construction was completed at 757 Superfund sites. More than three times as many Superfund sites were cleaned up between 1993 and 2000 than in all the prior years of the program combined (see http://www.epa.gov/oerrpage/superfund/action/20years/index.htm). Tools such as presumptive remedies and response strategies are being used to speed up the response process at Superfund sites. These tools and other technologies have also helped drive down costs associated with remediation of many Superfund sites. Although the cleanup pace has slowed somewhat because Congress has not reached a compromise on reauthorization of Superfund legislation, it is clear that even fewer sites would have been closed or in corrective action today without the technical advances of the past 20 years. Ultimately, site remediation and waste containment technology may no longer be required and may become artifacts of an earlier, less environmentally aware age. However, this time is far in the future, and numerous sites remain to be remediated and large volumes of waste still must be disposed in landfills every year.

Development of new and enhanced methods for geoenvironmental site characterization has lagged behind the rapid rate of advance in waste containment and remediation technologies. There have been some incremental advances in site characterization (e.g., fiber optic cone sensors for cone penetrometers to assess the presence of organic constituents in soil and groundwater and geophysical tracking of contaminant plumes); however, these advances have been slow to be adopted in practice. In most cases, site investigation for environmental remediation and protection is conducted today using the same techniques that were used in 1989 (i.e., a limited number of intrusive probes and testing of recovered samples are employed, with both the probe and testing programs developed by engineers based upon their professional judgment). This situation is not unique to waste management, but rather reflects the general state of geotechnical practice with respect to site characterization.

Besides soil and groundwater remediation, critical issues in waste management and environmental protection include mitigation of other environmental "insults" from human activities on local, regional, and global scales, appropriate waste containment and remediation technology for developing countries, and reduction, reuse, and recycling of waste materials. For instance, remediation of contaminated sediments is an emerging issue in waste management and remediation. Geotechnical considerations play an important role in selecting the appropriate remedy for contaminated sediments from available options, including dredging, capping in situ, and monitored natural attenuation. With respect to environmental impact mitigation activities, advanced sensing technologies, including remote sensing systems, will be required to collect the required data for regional and global impact modeling. Model development and monitoring data collection and interpretation will also require the development of large regional databases and data models for environmental (and geoenvironmental) data. Emerging environmental and waste management issues in which geoengineering should play a significant role include carbon sequestration (NRC, 2003e) for mitigating the potential for global climate impacts from fossil energy use and other industrial activities, advanced technologies for beneficial reuse of solid wastes, remediation of contaminated sediments, and redevelopment of brownfield sites. Waste issues associated with the resource extraction industries are discussed in section 2.5, Resource Discovery and Recovery.

In addition to development of new remediation technologies, development of advanced techniques for source control (e.g., waste containment, erosion control, and surface water and groundwater protection) are important geoenvironmental geoengineering considerations. The development of safe and economical waste containment systems, including the development of appropriate technologies for developing countries, remains an important task for geoengineers, as do surface water and groundwater management. Geosynthetic erosion control materials have not only significantly reduced the amount of sediment transported from newly graded sites, they have also provided for more aesthetic and sustainable surface water management systems. Replacing concrete drainage swales with vegetated channels stabilized by rolled erosion control products (see Figure 2.2) not only improves the aesthetics of the system but also reduces the time of concentration and peak flow for surface water runoff, enhances infiltration of surface water

FIGURE 2.2 Geosynthetically stabilized vegetated drainage channel. Sunshine Canyon Landfill, Sylmar, California (photo courtesy of SI Geosolutions).

and replenishment of groundwater resources, and can provide treatment of surface water impacted by organic constituents (see Figure 2.2).

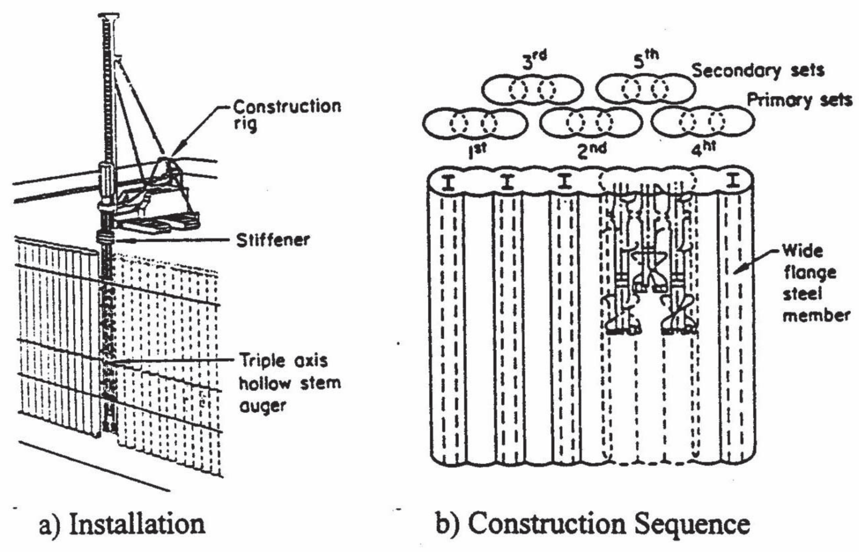
Biotechnology should also play an increasingly important role in geoengineering for waste management in the coming decades. Biotechnology for remediation and for source control offers the promise of effective, energy-efficient technologies. Furthermore, application of biotechnology may be relatively low cost, facilitating its use in developing countries.

2.2 INFRASTRUCTURE DEVELOPMENT AND REHABILITATION

Recognizing the existing backlog of infrastructure development and rehabilitation needs, the 1989 report called for a coordinated interdisciplinary approach to address this issue. Specific recommendations in the 1989 report included development of new materials for geoconstruction, improved noninvasive (e.g., geophysical) subsurface exploration techniques, nondisruptive construction and rehabilitation techniques, new and improved ground modification techniques, and life-cycle analysis and design. Geotechnology has made significant progress since 1989 in developing less disruptive, cheaper, faster, and less intrusive methods for infrastructure construction and rehabilitation. Geosynthetic materials and ground improvement techniques are routinely applied on major infrastructure development projects. In many states mechanically stabilized earth walls have become the de facto standard for bridge abutments and retaining walls for earthfill, and soil nailing and ground anchors are used with increasing frequency to retain cut slopes. Prefabricated geosynthetic drainage systems have reduced both the cost and installation time for drainage systems behind walls and beneath and adjacent to pavements.

Significant advances in other ground improvement technologies have occurred in parallel with developments in geosynthetic materials. Grouting technologies, including jet grouting and compaction grouting, continue to be developed and refined as a means of stabilizing problem soils while minimizing disruption to adjacent facilities. Deep soil mixing, wherein cementitious material is mixed in situ to strengthen and stiffen soil, has made great inroads in infrastructure development over the past 15 years, progressing from an innovative new technology offered in the United States by only one vendor to a standard technology, including both wet mix and dry mix methods (see Figure 2.3). This mixing has played an important role in numerous major projects, including Boston's Central Artery/Tunnel Project.

Advances in trenchless technologies since 1989 have provided new, cost-effective methods for rehabilitating aging sewer systems, river crossings for pipelines, and utility installations in dense urban corridors. Slip lining, both with resin-impregnated socks and high-density polyethylene pipe, and pipe bursting, wherein an "inflatable" tool is inserted into an existing buried pipe and expanded to increase the diameter of the



a) Installation

b) Construction Sequence

FIGURE 2.3 Installation of deep soil mixed walls. SOURCE: O'Rourke and McGinn (2003).

hole (and capacity of the pipe) prior to slip lining, have become standard techniques for sewer system rehabilitation. Horizontal directional drilling technology has seen significant improvements in accuracy (guidance) and reach (distance). Significant advancements have also been made in pipe jacking (i.e., jacking of large-diameter pipes and conduits from excavated pits and conduits through the ground without open excavation) (see Sidebar 2.1) and the use of micromole tunneling technology or small-diameter "robotic" tunneling machines (see Sidebar 2.1). Improvements in larger-diameter driven tunneling systems (e.g., transit tunnels) have been less dramatic. Nonetheless, there have been improvements in earth pressure balance tunneling machine technology, in ground reinforcement and stabilization techniques. Moreover, improved, automated monitoring systems have facilitated adaptive management approaches (the use of the observational method) to tunneling adjacent to sensitive structures and utilities.

Improvements in site characterization technologies have been slow and mostly incremental. However, significant improvements have been made in the application of ground penetrating radar for identifying subsurface utilities and shallow obstructions above the water table, and in the use of airborne survey methods for evaluating site conditions (e.g., near-surface soil type, geomorphology, shallow groundwater bodies). Despite these advances, our ability to see into the Earth, both invasively and noninvasively, is still limited and represents one of the areas of geoengineering with the greatest need for advancements (NRC, 2000).

Despite advances in methods for infrastructure development and rehabilitation, a large backlog of necessary infrastructure projects still exists (ASCE, 2005). In part, this backlog is due to insufficient financial resources to address all infrastructure needs, including maintenance and rehabilitation of existing infrastructure. Maintenance and rehabilitation costs are exacerbated by the failure to predict the need for, and to perform, timely maintenance as well as the failure to include life-cycle costs during initial project development. The American Society of Civil Engineers' 2005 update of its 2003 Report Card for America's Infrastructure (ASCE, 2005; Table 2.3) showed no improvement and some

SIDEBAR 2.1
Tunnel Jacking and Ground Freezing on the Central Artery/Tunnel Project in Boston, Massachusetts

The Central Artery/Tunnel (CA/T) Project, now nearing completion and the largest infrastructure project in the United States, has replaced the aging and under-capacity elevated Central Artery (I-93) in the center of Boston, Massachusetts, with a modern underground expressway to improve traffic flow through the center of the city. The CA/T Project includes a new South Bay Interchange between I-93 and the Massachusetts Turnpike (I-90), and the extension of I-90 from its previous terminus at the edge of downtown Boston to the city's Logan International Airport. The I-90 extension passes under the network of rail tracks leading into South Station, one of two major rail stations in Boston. Maintaining normal train operations at this regional transportation hub was the critical requirement to be addressed in developing construction methods for the new sections of highway. Staged cut-and-cover construction could not be used because the depth of the excavations (up to 60 feet)

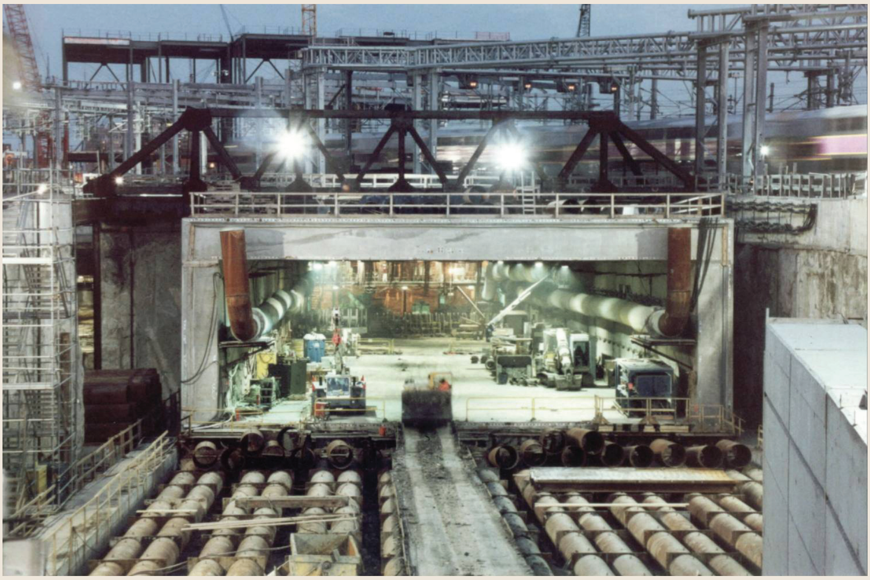


FIGURE: A view of the rear end of the tunnel box being jacked into place for the eastbound lanes of I-90 below the railroad tracks in Boston. A train is visible, passing over top of the tunnel. This jacked tunnel box was 36 feet high, 79 feet wide, and 379 feet long, and weighed approximately 32,000 tons. Used with the permission of the Massachusetts Turnpike Authority.

FIGURE: An aerial shot of the worksite in Boston where the tunnel jacking was done, showing the two large pits from which the I-90 westbound tunnel box (left side, with a series of steel struts across the top of the pit to brace it) and the I-90 eastbound tunnel box (pit to right) were jacked. At the time this photo was taken, the westbound tunnel box had been completely jacked into place, while the eastbound tunnel box jacking operation was still in progress. Used with the permission of the Massachusetts Turnpike Authority.

would require taking tracks out or service for weeks or months at a time, causing unacceptable disruption of train schedules. Conventional tunneling techniques would also have been difficult at this site because of the width of the underground openings needed to accommodate the required roadway width and side plenums for ventilation, the shallow depth of cover (7 to 20 feet) dictated by the roadway profile, and the soft ground conditions below the water table.

continued

SIDEBAR 2.1 Continued

The technique used for constructing the three underground crossings below the South Station track network was tunnel jacking. The method is generally applied in soft ground where the underground crossing is relatively short and the ground is weak enough to allow the tunnel to be pushed through the ground without excavation. The technique has evolved from pipe jacking (i.e., jacking of relatively small diameter pipes through embankments and from pits beneath roadways, rail lines, and utility corridors). The technological development of the tunnel jacking method has involved scaling up pipe jacking methods to place progressively larger concrete sections, reaching the size required to carry a multilane highway. The use of tunnel jacking on the CA/T Project was the first such application in the United States and one of the largest applications of the method to date. Tunnel jacking for the CA/T Project also involved the innovative use of ground freezing to stabilize the soft ground around the portal (entrance point) for the jacked tunnel.

Three tunnel box sections were built in large thrust pits constructed adjacent to each alignment for the new interchange. The typical cross-section of the jacked tunnel was 38–78 feet, with respective lengths of 167, 258, and 379 feet and approximate weights ranging from 17,000 to 31,000 tons. The jacking systems consisted of rear and intermediate jacking stations, employing in the case of the longest tunnel a total of 87 individual jacks that delivered a combined maximum thrust capacity of 46,500 tons.

The tunnels were excavated through a geologic profile consisting of historic fill containing the remnants of waterfront, industrial, and railroad structures built in the area in the past 150 years, underlain by organic sediments and marine clay. Groundwater was 5 to 10 feet below surface grade. Stabilization of these weak, saturated soils to control the loss of ground into the face during installation of each jacked tunnel was critical to the success of the project, both to limit ground movements in the track area above and to assist directional control of tunnel boxes as they were advanced into the ground. To address these concerns, an innovative ground-freezing approach that provided a stable, essentially dry excavation face over the full height and width of the tunnel was implemented by the contractor. Freezing of the ground was accomplished through the installation of a series of vertical freeze pipes through which brine chilled in an on-site refrigeration plant was circulated. More than 1,700 freeze pipes were used with this system to freeze a total ground mass volume of approximately 140,000 cubic yards.

SOURCE: Phil Rice, Parsons Brinkerhoff Quade and Douglas Inc., New York.

TABLE 2.3
ASCE Report Card for America's Infrastructure (Estimated Five-Year Need)

AREA	GRADE	TREND (SINCE 2001)	NOTE
Roads	D	↓	Poor road conditions cost U.S. motorists $54 billion a year in repairs and operating costs ($275 per motorist). Americans spend 3.5 *billion* hours a year stuck in traffic, at a cost of $63.2 billion a year to the economy. Total spending of $59.4 billion annually is well below the $94 billion needed annually to improve transportation infrastructure conditions nationally. While long-term federal transportation programs remain unauthorized since expiring on Sept. 30, 2003, the nation continues to shortchange funding for needed transportation improvements.
Bridges	C	↔	Between 2000 and 2003, the percentage of the nation's 590,750 bridges rated structurally deficient or functionally obsolete decreased slightly from 28.5 percent to 27.1 percent. It will cost $9.4 billion a year for 20 years to eliminate all bridge deficiencies. Long-term under-investment is compounded by the lack of a federal transportation program.
Transit	D+	↓	Transit use increased faster than any other mode of transportation—up 21percent—between 1993 and 2002. Federal investment during this period stemmed the decline in the condition of existing transit infrastructure. The reduction in federal investment in real dollars since 2001 threatens this turnaround. In 2002, total capital outlays for transit were $12.3 billion. The Federal Transit Administration estimates $14.8 billion is needed annually to maintain conditions, and $20.6 billion is needed to improve to "good" conditions. Meanwhile, many major transit properties are borrowing funds to maintain operations, even as they are significantly raising fares and cutting back service.

continued

TABLE 2.3 Continued

AREA	GRADE	TREND (SINCE 2001)	NOTE
Aviation	D+	↑	Gridlock on America's runways eased from crisis levels earlier in the decade because of reduced demand and recent modest funding increases. Air travel and traffic have reportedly surpassed pre-9/11 levels and are projected to grow 4.3 percent annually through 2015. Airports will face the challenge of accommodating increasing numbers of regional jets and new superjumbo jets.
Schools	D	↑	The federal government has not assessed the condition of America's schools since 1999, when it estimated that $127 billion was needed to bring facilities to good condition. Other sources have since reported a need as high as $268 billion. Despite public support of bond initiatives to provide funding for school facilities, without a clear understanding of the need, it is uncertain whether schools can meet increasing enrollment demands and the smaller class sizes mandated by the No Child Left Behind Act.
Drinking water	D–	↓	America faces a shortfall of $11 billion annually to replace aging facilities and comply with safe drinking water regulations. Federal funding for drinking water in 2005 remained level at $850 million, less than 10 percent of the total national requirement. The Bush administration has proposed the same level of funding for FY06.
Wastewater	D–	↓	Aging wastewater management systems discharge billions of gallons of untreated sewage into U.S. surface waters each year. The EPA estimates that the nation must invest $390 billion over the next 20 years to replace existing systems and build new ones to meet increasing demands. Yet, in 2005, Congress cut funding for wastewater management for the first time in eight years. The Bush administration has proposed a further 33 percent reduction, to $730 million, for FY06.

TABLE 2.3 Continued

AREA	GRADE	TREND (SINCE 2001)	NOTE
Energy	D	↔	The U.S. power transmission system is in urgent need of modernization. Growth in electricity demand and investment in new power plants has not been matched by investment in new transmission facilities. Maintenance expenditures have decreased 1 percent per year since 1992. Existing transmission facilities were not designed for the current level of demand, resulting in an increased number of bottlenecks which increase costs to consumers and elevate the risk of blackouts.
Hazardous waste	D	↓	Federal funding for Superfund cleanup of the nation's worst toxic waste sites has steadily declined since 1998, reaching its lowest level since 1986 in FY05. There are 1,237 contaminated sites on the National Priorities List, with possible listing of an additional 10,154. In 2003, there were 205 U.S. cities with brownfield sites awaiting cleanup and redevelopment. It is estimated that redevelopment of those sites would generate 576,373 new jobs and $1.9 billion annually for the economy.
Dams	D	↔	The number of unsafe dams has risen 33 percent since 1998. $10.1 billion is needed over 12 years to address all critical, nonfederal dams—dams whose failure would pose a direct risk to human life.
Solid waste	C+	↔	In 2002, the United States produced 369 million tons of solid waste of all types, only a quarter of which was recycled or recovered.
Navigable waterways	D–	↓	Nearly 50 percent of the 257 locks operated by the U.S. Army Corps of Engineers are functionally obsolete. By 2020, that number will rise to 80 percent.

continued

TABLE 2.3 Continued

AREA	GRADE	TREND (SINCE 2001)	NOTE
America's infrastructure GPA	D		
	• Total investment		$1.6 Trillion (estimated five-year need)

SOURCE: Adapted from the 2005 Report Card for America's Infrastructure, courtesy of the American Society of Civil Engineers (2005).

continued degradation over 2003, when it assigned grades between C and D to its 12 categories of infrastructure systems, with an aggregate grade of D and an estimated required investment of $1.6 trillion over the next five years to bring conditions to acceptable levels. Essentially these grades reflect no improvement since ASCE issued its first infrastructure report card in 1998 (ASCE, 1998) and a significant degradation in infrastructure quality from the 1988 National Council on Public Works Improvements report card (NCPWI, 1988).

In addressing this backlog of infrastructure needs, sustainable development considerations, including design for durability and longevity and for efficient use of construction materials, have taken on increased importance. An important manifestation of the growing emphasis on sustainable development is the trend toward locating or relocating more of our civil infrastructure underground to minimize the impact of our activities on the environment. This trend is one of the primary factors contributing to the explosive growth in the cost of some civil infrastructure development projects.

Important geoengineering issues for infrastructure systems include construction and reconstruction of urban centers to minimize use of resources and impact on the environment, improved modeling of environmental impacts of infrastructure development and improved approaches for mitigating these impacts, rehabilitation of existing geofacilities, and enhanced durability of civil construction. The challenges that must be addressed by the geoengineer in dealing with these issues encompass many of the same challenges facing the geoengineer in waste management, environmental protection, and other geoengineering problems. These challenges include seeing beneath Earth, both for subsurface investigation and for locating underground utilities and obstructions, management and remediation of contaminated soil and groundwater, the development of enhanced ground improvement and remediation methods, including passive and biostabilization techniques, and enhancing the durability of geostructures, including those that employ geosynthetic materials.

Sustainable development and improved environmental impact modeling will require large regional databases and data models, development of adaptive management techniques (i.e., application of the observational method), and associated developments in monitoring technologies. Infrastructure databases should include comprehensive inventories of underground facilities, reflecting the recognition of underground space as an important infrastructure resource. With respect to enhanced durability of underground facilities and components, biofilm technologies offer the promise of below-ground corrosion protection for steel and concrete components.

In addition to the traditional geomechanical and geoenvironmental issues discussed above, both life-cycle cost analysis and reliability analysis (see Sidebar 2.2) are playing an increasingly important role in infrastructure development and rehabilitation. The effective functioning of society—even the safety of its citizens—requires that roads, railroads, bridges, electric distribution networks, dams, power plants, harbors, buildings, and myriad other facilities operate reliably. Every sort of human activity is affected when civil structures fail. Civil engineering and related industries have done such a good job in providing reliable infrastructure that most people take for granted the civil systems on which they depend. An unintended consequence of the success of our profession in providing reliable infrastructure is that the public—and its political

SIDEBAR 2.2
Reliability

Engineers working on problems that involve geology and other earth processes (geoengineers) have always known that they deal with an uncertain environment and one in which the engineer cannot know everything needed to make firm, final decisions. Accounting for this uncertainty by employing large factors of safety is often not possible or would make the project prohibitively expensive. Geoengineers have traditionally used several stratagems to mitigate the effects of uncertainty on the cost and reliability of civil construction, most prominently the observational method (see Sidebar 4.4). In recent years formal reliability or risk methods have become increasingly applied to manage these uncertainties.

The application of reliability and risk analysis is well established in many fields, including management, engineering, and manufacturing. The essential idea is that the uncertainties that enter into the process in question are expressed in probabilistic form and the resulting distributions carried through an analysis of the process to arrive at a probabilistic description of expected outcomes. This then makes it possible to make decisions rationally on the basis of the probabilistic results. In civil engineering most of the applications of reliability analysis have been in hydraulic and structural engineering. In both these fields the major uncertainties lie in the loads (e.g., building occupancy loads, traffic loads, earthquakes, and floods). On the other hand, in geoengineering, major sources of uncertainty also arise in the response (resistance) of the system to these loads (e.g., in the properties of soils and rocks, their location, and their distribution). To apply reliability analyses to geoengineering problems, procedures developed to deal with uncertain loads must be modified to account for uncertain response of the systems themselves. Furthermore, each geological setting is unique, and it is often difficult to translate a description of the uncertainty at one site to the study of a project at another location.

Recent years have seen considerable progress in the application of reliability methods to geoengineering. Among the most notable are its widespread use in design and construction of offshore structures and the development of load and resistance factor design methods for transportation projects, especially for design of pile foundations. Reliability methods are particularly powerful when combined with observational methods to facilitate rational updating of designs and construction procedures. However, a great deal of practical research and teaching is needed before geoengineering practitioners are fully comfortable with the technology. For a recent description of the issues involved in probabilistic descriptions of geoengineering problems and the method involved in reliability approaches, see Baecher and Christian (2003).

representatives—often fail to provide adequately for maintenance, improvement, and expansion of these necessary facilities. This is especially true in times of financial constraint. The cost of replacing or repairing infrastructure in an urban environment while the city life goes on around it can be enormous. The pressures associated with increased financial constraints, including increased concerns over homeland security, have made formal reliability and life-cycle cost analysis of civil systems of increasing importance. Formal reliability and life-cycle cost analyses provide decision makers with a rational means of setting priorities and allocating resources.

The large uncertainties associated with the geotechnical components of a system often make geotechnical considerations a driving force in reliability analyses for many infrastructure systems. Increased attention to the sources of uncertainty in geoengineering (see Sidebar 2.3) and to methods for quantifying and reducing these uncertainties reflects a significant change in perspective since the 1989 report.

2.3 CONSTRUCTION EFFICIENCY AND INNOVATION

Cost-effective and sustainable construction, maintenance, and rehabilitation of civil structures remain vital to the economic and environmental health of society. Even a 10 percent reduction in the direct and indirect costs associated with foundation engineering, earthworks, and underground construction activities would provide billions of dollars annually in financial resources that could be dedicated to other purposes. A 10 percent reduction in costs on even one megaproject like the Central Artery/Tunnel Project in Boston (NRC, 2003a) would have provided over $1 billion in funds for other badly needed infrastructure projects. Such cost savings are well within the realm of possibility within the next decade, with sufficient investment in research and development in geoengineering.

The actions identified in the 1989 report to improve construction efficiency and stimulate innovation are just as important today as they were then. Improved site characterization methods and development of

SIDEBAR 2.3
Uncertainty in Geoengineering

Uncertainty is an essential and unavoidable part of geoengineering, but when we say that something is uncertain, what do we mean? One answer is that an uncertain event or condition is one that occurs at random with little or no external control, much like the throw of a pair of dice. If the dice are honest, no amount of additional information, such as the initial velocities of the dice, influences the probability of the outcome. It is truly a "throw of the dice." Many names been applied to this type of uncertainty, but use of the term aleatory, from the Latin for "dice thrower" or gambler, is especially widespread. An example of aleatory uncertainty in geoengineering is uncertainty with respect to the occurrence of a specific earthquake. On the other hand, an uncertain event may be one whose outcome is actually already determined but not known to the observer. For example, in a game of bridge the arrangement of cards in a deck is fixed once the deck has been shuffled and cut, but the players do not know what the arrangement is. Good play consists of applying various techniques to acquire knowledge and to deduce the arrangement of the cards. This type of uncertainty is often called epistemic, after the Greek for "knowledge." Our uncertainty about the location, extent, and properties of geologic strata is essentially epistemic. The configuration and properties of the strata are fixed but are uncertain to us; our uncertainty reflects our lack of knowledge.

It is clear that one deals differently with the two types of uncertainty. Additional information may reduce the epistemic uncertainty but not the aleatory uncertainty, for which additional information will only improve our understanding of the governing parameters. In actual applications there is a trade-off between the two types of uncertainty. Research can move some uncertainty from one category to another. For example, flood stages were once treated essentially as aleatory occurrences, but today they are often regarded as the results of models of storms and runoff patterns, whose uncertainty can be reduced by better knowledge. It is clear that the distinction between the two types of uncertainty is an important underlying issue in geoengineering and one that needs to be addressed when dealing with uncertainty.

A second important issue with respect to uncertainty in geoengineering concerns the meaning of probability. What does it mean to say that there is a certain probability of an event or condition? One position is that probability is an underlying property of the phenomenon and that statistical studies are aimed at identifying it. Thus, the results of tossing an honest coin or of repeated application of a certain drug reflect the underlying probabilities. The idea is that probability has to do with the frequency of occurrence, so this point of view is called the frequentist position. Alternatively, we could observe that many real situations do not involve frequency of occurrence. There is one geological profile. It is meaningless to talk about the frequency of occurrence of a liquefiable layer; it is either there or not there. However, we do often talk about the probability of finding a liquefiable layer. In these cases we are talking about our confidence in the existence of the layer; this position is called the degree-of-belief point of view. Probabilistic questions in most practical engineering contexts are best stated as issues of degree of belief; this school of thought has found greater acceptance in recent years.

A third important question regarding uncertainty in geoengineering concerns the appropriate statistical tools. Conventional statistical tools taught in most courses in statistics, including geostatistics, are basically concerned with determining the probability of observing the data if the model is true. Thus, a 20 percent probability from a statistical method such as discriminant analysis or logistic regression of liquefaction data means that there is a 20 percent probability of observing the data, given that the soil is liquefiable. What the engineer wants is a 20 percent probability of liquefaction if the data are observed. The latter type of output requires a Bayesian approach, in which probabilities are updated on the basis of new information. This is becoming a popular approach in many fields, such as industrial management, process control, and even drug testing. It is, of course, completely consistent with the ideas behind the observational approach in geoengineering.

In any particular situation the approaches to the above three issues can be combined in many ways. One can apply Bayesian approaches with a frequentist view of probability and so forth and so on. It is becoming increasingly clear that much of geoengineering involves a large component of epistemic uncertainty, addresses the engineer’s degree of belief, and requires Bayesian updating. This suggests that research and education regarding uncertainty in geoengineering should be concerned with improving the techniques for employing these approaches and with educating engineers in their practical implications.

innovative equipment and technology remain critical needs for improving construction efficiency. More energy- and cost-efficient means of ground improvement, particularly with respect to wet and weak soils, and development and implementation of remotely controlled, automated construction equipment are also areas where significant improvement is needed. Adaptive management of urban construction (e.g., using automated monitoring systems to facilitate application of the observational method) also offers the promise of significant savings in geotechnical construction. New equipment and methods are continually introduced by contractors and suppliers (e.g., laser-guided earthmovers and graders and handheld global positioning system devices for survey control) (see Figure 2.4), although most improvements in equipment and methods have been incremental.

Advances in site characterization technology since 1989 have also been limited; most site characterization programs are conducted in the

FIGURE 2.4 Laser-guided earthmover (photo courtesy Lecia Geosystems, http://www.leica-geosystems.com).

same manner today as they were in 1989, or in 1974 (NRC, 1974). However, use of geographic information systems has improved our ability to store, retrieve, and display large quantities of diverse types of information on projects covering large areas (see Sidebar 2.5).

One of the most significant recent changes in the construction industry has been the development of new project delivery systems. Design-build and build-operate-transfer projects have become established means for delivery of public works projects. These methods have provided incentives for innovation and have reduced delivery time for major projects (see Sidebar 2.4). However, much of the geoengineering on a project occurs during the preliminary pre-tender phase, and geoengineering during the design phase is often still performed on a fee-for-service basis, even when design-build and build-operate-transfer project delivery systems are used. Therefore, incentives for innovative geoengineering are often lacking on these projects. Because the rewards for construction innovation tend to go to the contractor and project financier, as they are the team members who take the financial risk, the geoengineer often will not get a proportional reward for any risk taken or for innovation. To provide incentives for geotechnical innovation, mechanisms are required that will allow geoengineers to benefit proportionally from the risks they take.

Geoengineering issues related to construction efficiency and innovation include development of more efficient and economical underground construction techniques, minimizing environmental impacts of construction activities, and development of more efficient and less disruptive ground improvement techniques. Underground construction is the area that often incurs the greatest capital costs and thus has great potential for savings in infrastructure development. The direct costs of underground construction, including costs for excavation and support of the underground openings and foundation construction for aboveground structures, can be equaled and exceeded by the indirect costs associated with location and relocation of underground utilities and repair of underground and aboveground facilities damaged by construction activities, whether or not their location was known prior to the start of construction. The potential

SIDEBAR 2.4
The Alameda Corridor

The Alameda Corridor is a 20-mile freight rail expressway between the neighboring ports of Los Angeles and Long Beach and the transcontinental rail yards and railroad mainlines near downtown Los Angeles. The centerpiece is the Mid-Corridor Trench, a below-ground railway that is 10 miles long, 30 feet deep, and 50 feet wide. By consolidating 90 miles of branch rail lines into a high-speed expressway, the Alameda Corridor produced the following benefits:

1. Reduced traffic congestion on surface streets by eliminating conflicts at 200 street-level railroad crossings, where cars and trucks previously had to wait for long freight trains to slowly pass;
2. Cut by more than half, to approximately 45 minutes, the time it takes to transport cargo containers by train between the ports and downtown Los Angeles;
3. Slashed emissions from idling cars and trucks by 54 percent;
4. Cut emissions from locomotives by 28 percent; and
5. Increased efficiency of the cargo distribution network to accommodate growing international trade.

The project was constructed at a cost of $2.4 billion by the Alameda Corridor Transportation Authority, a joint powers agency known as ACTA and governed by the cities and ports of Los Angeles and Long Beach and the Los Angeles County Metropolitan Transportation Authority. The ACTA employed design-build contracting for the construction of the mid-corridor segment of the project. The mid-corridor encompasses 10 miles of depressed

FIGURE: Mid-corridor track construction (image courtesy of the Alameda Corridor Transportation Authority).

rail through Alameda Street in the cities of Compton, Lynwood, South Gate, Huntington Park, and Vernon. The use of design-build required special enabling legislation by some of the ACTA member cities. Design-build shortened construction time by more than one year. The Alameda Corridor opened on time and on budget on April 15, 2002.

FIGURE: Map of the Alameda Corridor (image courtesy of the Alameda Corridor Transportation Authority).

for large indirect costs associated with damage to adjacent facilities often leads to construction schemes that are excessively conservative and costly, at least with respect to the vast majority of their applications.

The high capital cost of underground construction not withstanding, many communities are demanding that new infrastructure facilities be placed underground in order to mitigate their adverse impacts on urban and suburban areas (e.g., visual impacts, noise, dust, vehicle exhaust, and other traffic impacts, such as grade crossings). A good example of these community demands is the $2.4 billion Alameda Corridor Project, a dedicated rail corridor designed to facilitate the transfer of goods from the ports of Los Angeles and Long Beach to inland distribution points, not only reducing shipping costs and improving the flow of commerce but also removing a significant traffic load from congested freeways (see Sidebar 2.4). During project planning, several of the small local communities along the route threatened to block the project unless it was put below ground through their communities (at significant additional expense). The proposed CenterLine Light Rail system in Orange County, California, provides another example of a project whose segments are being forced below ground at significant additional capital cost owing to community demands (Harper, 2003).

Perhaps the most significant contribution geoengineering can make to construction efficiency is through improved site characterization, as unanticipated site conditions still represent the most common and most significant cause of problems and disputes that occur during construction. Regional infrastructure databases and data models, discussed in the previous section of this chapter, offer the potential for reduced cost, increased coverage, and reduced uncertainty in subsurface characterization if extended to include geotechnical and geological subsurface information. Although some private-sector owners will likely be reluctant to share subsurface information that has traditionally been treated as proprietary, participation in development of these databases could be made mandatory anytime a permit or public agency approval is required for a project. Compilation of comprehensive geological and geotechnical databases and data models can lead to development of advanced algorithms for planning and interpretation of geological and geotechnical investigations and for evaluation of the reliability of the constructed system, taking into account the geological context of the site and the specific sensitivities of a particular project to geological and geotechnical conditions.

Even with development of comprehensive databases and advanced algorithms for data interpretation, uncertainty over underground conditions and material response will remain a significant issue for the foreseeable future. The logical response to this uncertainty is the use of adaptive management and observational approaches to construction activities to minimize the impact of uncertainty, maximize efficiency, and enhance reliability. Trenchless technologies for minimizing construction impacts in urban areas and biotechniques for ground improvement are areas where geoengineering can also make significant contributions to construction efficiency through innovation, minimizing the social and economic disruption associated with infrastructure construction, and rehabilitation in urban areas.

2.4 NATIONAL SECURITY

The national defense-related imperatives identified in the 1989 report (e.g., hardening, hiding, and limiting access to facilities by placing them underground; detecting underground facilities, activities, and caches; and monitoring for underground and surface activities) remain an important component of geoengineering's roles in today's society. The beginning of the twenty-first century has been marked by increased concern over threats to U.S. facilities at home and abroad from both foreign and domestic terrorism. In this context the focus on security issues has shifted in recent years from national defense to homeland security. Geotechnology can play a major role in ensuring the safety of civil structures under attack, particularly with respect to underground construction. More cost-efficient underground construction techniques will allow certain critical facilities to be placed underground, where they may be easier to protect against terrorist threats. Geotechnology can also play a role in detecting unwarranted intrusions (e.g., seismic devices for listening through the ground), in hardening both underground and aboveground facilities against ground shock and other blast or weapons effects, in developing means for penetrating underground facilities, for vehicle mobility, for expedited construction of airfields, harbors, and other base facilities during rapid deployment, for protection of aboveground facilities (e.g., with earthen berms), and for detection and removal of unexploded ordinance, both during hostilities (e.g., clearing mine fields) and after hostilities (e.g., spent ordinance).

In 1989, critical geoengineering contributions to national security included weapons effects and ground shock predictions. Progress with weapons effects has been made (e.g., the development of bunker buster bombs that can penetrate soil cover to attack buried targets) but advances in this technology may simply drive the intended targets deeper underground, negating any strategic advantage. Increases in computational power and constitutive modeling for soil and rock have improved our ability to predict ground shock effects. Continued improvement in predicting weapons effects and ground shock effects is to be expected as computation schemes become more efficient and the necessary intensive computation become faster and more economical.

One major change in national security priorities since the 1989 report has been the focus on homeland security. As this focus on homeland security evolves from response to prevention, geotechnical engineering and, in particular, underground construction can play an important role in reducing the vulnerability of critical infrastructure systems from attack. The benefits of underground construction with respect to securing critical facilities have long been recognized by the military. From rudimentary fortified caves to modern underground command centers like Cheyenne Mountain, the military has placed structures underground to harden them. Similar benefits with respect to homeland security can be realized by placing civil works underground. For instance, the seemingly intractable task of protecting thousands (if not hundreds of thousands) of kilometers of aboveground oil and natural gas pipeline against an attack that could come anywhere along its route becomes significantly more tractable if the pipeline is buried. Burying a pipeline or any other linear system, such as a utility corridor or highway, reduces both vulnerability and fragility, as the ground limits access and buffers the line against impacts and explosions. Although aboveground "point" facilities, such as power stations, switching yards, and pump stations, are somewhat easier to control with respect to access, there is little doubt that placing them, or any other potential target, underground hardens the facility.

In many cases, appropriate geoengineering solutions for sensitive facilities, such as underground placement, will augment efforts to create more secure and more resilient infrastructure. It must be kept in mind though that security and resilience are the desired systems characteristics, and geoengineering will only be a part of the relevant system. The primary barrier to placing critical facilities underground in order to harden them against terrorist attack is cost, which can be a very significant barrier. Costs associated with underground construction include not only the actual excavation and construction costs but also investigation costs, costs associated with utility location and relocation (and the failure to do so), and costs associated with the protection of adjacent facilities from the effects of excavation. Thus, important to the increased use of underground space for securing civil facilities are improvements in excavation and support system technology, including geologic and geotechnical characterization and in situ ground stabilization and improvement; improved capabilities for detection of underground objects and obstructions; and a more comprehensive system of cataloging and archiving the locations of known underground conditions and facilities.

Improved detection of underground obstructions and underground activities may also play an important role in enhancing homeland security. Although access to underground facilities is limited, they are not impenetrable. Along with providing protection and limiting access, the subsurface can also shield terrorist activities and objects from detection. So, monitoring for and detection of underground intrusions and caches is important to homeland security. In particular, monitoring along the route of linear facilities (e.g., tunnels, pipelines, and power lines) for intrusive activities from fixed listening points and monitoring from moving vehicles, aircraft, and space for buried caches and underground activities can provide important contributions to homeland security. Fixed listening posts may also be able to detect certain types of threats to aboveground facilities (e.g., approaching vehicles and attempts to undermine foundations).

From a global perspective, geoengineering can provide a means for proactively addressing some of the root causes of terrorism and international conflict. Providing adequate, appropriate, and reliable civil infrastructure for everyone everywhere can help reduce these threats to national and global security. Furthermore, global climate change represents a significant threat to both national and international security. It could disrupt food resources and affect international trade. Through the development of technologies for minimizing global climate impacts, such as underground carbon sequestration, geoengineering can make perhaps its most significant contribution to our national security. Until the threats are eliminated, geoengineering must also be concerned with securing civil infrastructure against external threats. Improved threat detection and protection (e.g., hardening of civil infrastructure and other facilities against threats from terrorism and international conflicts) will remain an important element of geoengineering for the foreseeable future.

2.5 RESOURCE DISCOVERY AND RECOVERY

The 1989 report identified continued discovery and recovery of natural resources as a critical national need. Demand for most natural resources has increased steadily with population growth, industrialization, and urbanization. Furthermore, resource recovery becomes more challenging as the readily accessible supplies of raw material are recovered. An improved ability to see into the Earth was identified in the 1989 report as crucial to development of cost-effective approaches to resource discovery and recovery in the United States. Resource exploration relies more on geophysical methods, including downhole, airborne, and satellite systems, than most other geoengineering endeavors. The mineral resource industry also makes greater use of statistical techniques for data evaluation and for planning invasive exploration programs (NRC, 2002c). This may be attributed to the significantly larger rewards to risk ratio for resource discovery compared to other geotechnical endeavors. The reward for successful investigation generally means discovery of a new, economically viable resource deposit that has a tangible economic value, while failure during natural resource exploration generally results solely in a direct expended cost with no return rather than in both direct and indirect costs associated with loss of life or disruption of services.

The biggest change in our perspectives on resource discovery and recovery since the 1989 report is the growing focus on sustainable development (see Sidebar 4.2). Although the 1989 recommendations focused on more efficient engineering and construction techniques to locate and extract resources from Earth, sustainable development requires that we develop the resources required to support our population (energy, water, and minerals) in an environmentally responsible manner, with a minimum of disruption and waste. Sustainable development also dictates that renewable substitutes be developed to replace nonrenewable resources and practices that are employed currently.

Energy may be foremost among sustainable resource development considerations. Richard Smalley stated that of the various resources used to sustain our population, energy is the most important (Smalley, 2003). If enough energy can be provided without harmful emissions or other negative environmental impacts, then most other problems, such as the provision of adequate supplies of potable water or mineral resources, can be solved. Geotechnical inputs are a critical part of locating, developing, and extracting fossil fuels. Offshore methane hydrate deposits are a major potential source of energy for the years ahead. At low temperature and under high pressure (e.g., water depths greater than 300 meters) methane hydrate is a crystalline solid consisting of a methane molecule surrounded by a cage of water molecules. At higher temperature and lower pressure, the crystalline form of methane hydrate becomes unstable, greatly complicating recovery. Approximately 60 percent of the world's fossil fuel resources (including coal and petroleum) is known to be contained in methane hydrate form. Safely and economically recovering methane hydrates from the relatively deep and unstable underwater environment in which they are found is a major geoengineering challenge (NRC, 2004a).

The recent focus on hydrogen as a fuel is based on the fact that burning hydrogen emits no carbon dioxide. The problems to be solved to develop hydrogen as a viable energy alternative include finding sources for hydrogen, storing the hydrogen, and developing low-cost reliable hydrogen fuel cells. Of these problems, finding sources for hydrogen will involve geoengineers. Possible hydrogen sources include mining of clathrates,[1] conversion of natural gas or coal with CO_2 sequestration, and conversion of seawater using geothermal, wind, solar, or nuclear power. Each of these solutions will require geotechnical problem solving (NRC, 2004b). Increasing attention is also being focused on sources of energy that are renewable and generate no emissions. Geothermal energy taps the heat sources of Earth, either directly for heating and cooling, or to make electricity. Vast amounts of energy are stored in Earth, as 99 percent of Earth is at a temperature greater than 1,000 degrees Celsius. Geothermal reservoirs can be characterized and managed using geoengineering.

In addition to its role in developing new energy sources, geoengineering plays a critical role in efforts to minimize and mitigate the environmental effects of current energy production technologies, including fossil and nuclear energy production and energy resource extraction. Safe and environmentally protective coal waste impoundments (NRC, 2002b) and tertiary recovery methods for oil, drilling, and extraction of gas from complex three-phase reservoirs are just two examples of the many energy resource problems needing geotechnical input for their solution. Approximately 20 percent of our electric power still comes from nuclear power plants (EIA, 2004), and there appears to be a resurgence in interest in nuclear power plant development. The mining of uranium, management of mine wastes, and storage of the resulting nuclear waste are all geotechnical problems.

---

[1] A clathrate is a chemical substance in which one molecule forms a lattice around a “guest” molecule without chemical bonding. Methane hydrate is a natural form of clathrate hydrate where the guest molecule is methane and the lattice is formed by water (NRC, 2004a).

Given the dramatic increase in atmospheric concentrations of carbon dioxide caused by fossil fuel burning, there is increasing interest in enhanced sequestration of carbon (CCSP, 2003). Secretary of Energy Spencer Abraham focused the Department of Energy on an energy future that uses abundant coal as a source of energy, using clean coal technology coupled with CO_2 sequestration (DOE, 2003b). Schemes for CO_2 sequestration such as deep injection or engineering large-scale formation of $CaCO_3$ will require geotechnical solutions (NRC, 2003b). There is also renewed interest in nuclear power as a means of meeting our energy needs. Resumption of construction of nuclear power plants will mandate a solution to the problem of nuclear waste disposal, discussed elsewhere in this report.

In addition to energy development, resource recovery concerns involving geoengineering include providing safe water supply, developing mineral resources, and improving the energy efficiency of both the development of urban infrastructure and the infrastructure itself. Provision of abundant and safe water is among the most critical needs in many parts of the world. Of Earth's some 6 billion people, at least 1 billion do not have access to adequate supplies of healthful water and 2.4 billion people lack access to basic sanitation (Gleick, 2003, p. 1525). Water tables are dropping on every continent while 60 percent of water use is for agricultural irrigation. Regions of the world with the highest populations seem to have the most water shortages. In Asia, which has the most population and two-thirds of the irrigated lands, 85 percent of the water is used for irrigation. Food shortages due to lack of irrigation water are becoming a major recurring problem that has affected the stability of societies (Diamond, 2004). Several of our major rivers are totally used before they reach the sea, notably the Colorado River, which is a source of interstate conflict, as well as international conflict between the United States and Mexico. Egypt is planning to use approximately 85 percent of the flow of the Nile, but has no agreement to that effect with upstream countries. Turkey has dammed the Euphrates without agreements with the downstream countries of Iraq and Syria. Rising sea levels due to climate change will exacerbate these problems because of increases in seawater intrusion into important aquifers along coastal regions. Important aquifers are also increasingly contaminated with sewage, nitrates from fertilizers, heavy metals, and other industrial wastes. Climate change is causing glaciers to melt and threaten water supplies. In the western United States, climate change may reduce or eliminate the winter snowpack that serves as an important storage mechanism for the water supply.

Water managers need better data and understanding of our water cycles and systems. Better ways are needed to provide water services that meet the needs of society with less water. For example, geoengineers can play a role in developing efficient irrigation schemes that do not salinate the soil. Remediation and prevention of water pollution are critical. Mitigation of saltwater intrusion and recharge of groundwater aquifers are important problems. Water engineers will have to manage the storing of water underground when it is plentiful so that it can be withdrawn when needed. Geoengineering can play an important role in each of these tasks through development of new and improved methods for water collection, storage, and irrigation and better understanding of water infiltration, groundwater flow, and evapotranspiration processes.

Mineral resources, including various metals and industrial minerals, are essential to sustaining our current standards of living. In addition to the “conventional” geomechanical issues associated with economic extraction of mineral resources, geoengineering is squarely in the middle of environmental issues related to mining that range from developing new methods of mining that do not cause pollution or visible changes to the landscape to remediation and closure issues. To the extent that these environmental issues affect the social license to mine, geoengineers must participate in a dialogue with the public and regulators about management and mitigation of these impacts of resource recovery, including mine waste piles, subsidence, water pollution, large mine pits that may fill with toxic water, and tailings ponds (NRC, 2002b).

Equally important is the location and development of gravel pits and rock quarries, as large quantities of these common construction materials are essential for virtually all transportation systems and other constructed facilities. Opening and operating these “local mines” can be among the most difficult projects to permit, owing to the many regulatory constraints and the NIMBY (not in my back yard) societal mind-set.

An important problem related to many important mineral resources is that this country is strongly dependent on foreign sources. The U.S. Bureau of Mines (USBM) effectively supported and managed domestic and foreign policy relative to these resources until the bureau was disbanded in 1998. In the absence of coordinated policy for finding and developing new mines, and owing to complex environmental regulations, private developers are often discouraged from developing domestic reserves. There is no governmental agency or funding for developing more innovative technology for resource recovery from domestic sources. If U.S. policy is to move in the direction of less foreign dependence, some federal direction is called for. The National Science Foundation could serve as a catalyst for this by stimulating and funding research on better, more efficient, and environmentally protective mineral recovery.

In summary, geoengineering inputs are an essential element of locating, developing, and recovering the natural resources necessary to sustain our standard of living. They are also part of the critical efforts to prevent and mitigate the environmental effects of resource extraction. Energy and water are perhaps the two most important classes of natural resources for sustaining our civilization. Abundant energy supplies can be used to mitigate many of the other resource recovery issues, including mitigating the environmental impacts of resource recovery and providing abundant supplies of natural resources. Providing adequate supplies of water for human consumption, agriculture, and industrial uses is of paramount importance to maintaining our standard of living, and improving the standard of living in developing countries.

2.6 MITIGATION OF NATURAL HAZARDS

Much of the work of the geoengineering community is directed at characterizing, evaluating, mitigating the risks from, and recovering from the effects of natural hazards and disasters. Geoengineering plays essential roles in identifying and describing the destructive forces and effects of extreme events, such as landslides and debris flows, earthquakes, floods, tsunamis, expansive and collapsing soils, volcanoes, and even wildfires. The world saw a direct example of the need for geoengineering to play these roles in the December 26, 2004, tsunami disaster. Geoengineering is important in evaluating the resistance of the natural ground; assessing the risks of loss of life and property; evaluating and choosing among acceptable risk mitigation, emergency response, and disaster recovery alternatives; and the development of hazard and disaster-resistant designs. On average, natural hazards (landslides, avalanches, erosion, subsidence, swelling soils, floods, earthquakes, volcanic eruptions, high winds, and tsunamis) cause numerous casualties (deaths and injuries) and billions of dollars a year in damage (USGS, 1995). Related to these, although not *natural* hazards per se, are a variety of dam, embankment, and surface impoundment geohazard issues, including seepage, piping, erosion, settlement, and slope stability. These hazards demand greatly improved prediction, prevention, mitigation, and post-event recovery strategies and methods.

The 1989 report called for more effective application of technology to reduce losses, both in lives and monetary costs, resulting from natural hazards. Geotechnology has been effectively applied over the past 15 years for natural hazard reduction. An excellent example of such an application is the Hong Kong Slope Stability Warning System, wherein state-of-the-art geographic information system technology is integrated with automated data acquisition and geoengineering information of landslide triggering to issue a “landslide warning” and facilitate emergency response (see Sidebar 2.5).

Adoption of statewide landslide and liquefaction hazard maps for California and their incorporation into local building codes and the widespread use of ground-shaking maps developed under the National Earthquake Hazard Reduction Program (NEHRP), with the incorporation of its methodology for developing site-specific earthquake response spectra into the International Building Code are other examples of

SIDEBAR 2.5
Hong Kong Slope Stability Warning System

A substantial portion of the dense urban development area of Hong Kong is built on steep hillsides. Heavy rainfall triggers, on the average, approximately 300 to 400 landslides each year in these areas. To mitigate the substantial risk to life and property these landslides create among the 7 million residents of Hong Kong, the Geotechnical Engineering Office of the Civil Engineering and Development Department of the Hong Kong Special Administrative Region government has employed state-of-the-art technology to develop a sophisticated geographic information system (GIS) database to identify, register, and collect information on the approximately 57,000 slopes in the area. The GIS integrates photographs, text, and graphical information into a Slope Information System (SIS). An important component of the SIS is a sophisticated landslide warning system. The SIS is also used to facilitate maintenance planning and to coordinate emergency response.

The landslide warning system is based on studies that correlate locally heavy rainfall with the occurrence of landsliding in the region. Both observed and forecasted rainfall is employed. Initially, a Landslip Warning was issued when the 24-hour rainfall was expected to exceed 175 mm or the one-hour rainfall was expected to exceed 70 mm. In 1999, enhanced criteria that take into account the size of the area receiving heavy rainfall were implemented. A total of 110 rain gauges are automatically monitored throughout the region as part of the system. In addition to data from rain gauges, radar monitoring and high-resolution meteorological satellite images are used to provide input to the landslide warning system.

Three to four Landslip Warnings are issued each year. When a Landslip Warning is issued, local radio and television stations are notified and are requested to broadcast the warning to the public at regular intervals. Information is also available to local residents online and by telephone. A Landslip Warning also triggers an emergency system in various government departments that mobilizes staff and resources to deal with landslide incidents.

In an emergency, the SIS provides real-time information to government agencies through an intranet. The system can be used to generate maps to show the location and seriousness of the landslides and assist an emergency controller in monitoring the situation and allocating emergency resources. The SIS also allows users to run spatial query functions and to extract slope-relevant information for planning and maintenance activities. Information in the SIS is also available to owners.

The Geotechnical Engineering Office has recently implemented a mobile mapping application system (MMAS) in conjunction with the SIS. The MMAS integrates state-of-the-art mobile computing, wireless telecommunication, a global positioning system, and mobile GIS technologies into a handheld package to improve the efficiency and cost-effectiveness of geotechnical fieldwork by integrating positioning, surveying, geotechnical mapping, and data processing capabilities and to facilitate decision making under emergency situations (e.g., a serious landslide).

advanced geotechnology applied to hazard mitigation. While regional hazard maps have been incorporated into codes, zoning laws, and land use planning in some areas, many communities are still at risk and continued research and development is needed. Furthermore, there is an increasing susceptibility to natural hazards owing to increased urban growth. There is also a need for development of hazard assessments and mitigation measures for developing countries that are less complicated and more easily understood and applied than those used in the United States (e.g., the NEHRP methodology).

There has also been increasing interest in applying formal risk assessment (see Sidebar 2.2) to geohazard mitigation, though it is not yet general practice. The adoption of reliability-based load and resistance factor design by the American Association of State Highway and Transportation Officials for its standard specifications for highway bridge construction (AASHTO, 2003) represents an attempt to move in this direction. However, most of these codes, standards and land use measures address new construction. Application of these hazard mitigation technologies to existing facilities remains a major issue that involves public policy as much as geoengineering.

There have been several important initiatives for major field and laboratory experimentation relevant to geohazard assessment and mitigation since 1989, as called for in the 1989 report. These initiatives have included the establishment of seven National Geotechnical Experimentation Sites (http://www.unh.edu/nges/desc.html), the $88 million National Science Foundation-funded Network for Earthquake Engineering Simulation (http://www.nees.org), and the Federal Highway Administration-funded Interstate 15 test bed for highway research projects in Utah (Utah Department of Transportation, 2003). Geoengineers have continued to develop new technologies and enhance existing technologies for hazard mitigation. GIS are being used with increasing frequency for regional hazard assessments (Rosinski et al., 2004; Hilton and Elioff, 2004). Sophisticated numerical analyses for hazard evaluation (e.g., nonlinear earthquake site response analyses and stress deformation stability assessments) are being applied with increasing frequency. Among more recent developments, automated landslide warning systems that employ time domain reflectometry and in-place inclinometers combined with automated data acquisition and interpretation and cellular or satellite communications systems are now being deployed to protect lives and property (http://www.iti.northwestern.edu/publications/tdr/1994_papers.html; Serafini and Fiegel, 2004; Kane et al., 2004). In addition to ground-based systems, airborne and satellite remote sensing systems are starting to be developed for both hazard identification and postdisaster response and recovery, though much work remains to be done in this area (Anderson et al., 2004).

While there have been significant advances in geohazard assessment and mitigation technologies, global climate change threatens to dramatically increase the severity of storms and extremes of hydrologic processes (NRC, 2002a). These extremes will have larger and more serious consequences, which in some cases may lie outside of previous experience. The potential consequences of these climate extremes, including landslides, floods, and erosion, is exacerbated by growing concentrations of population in cities that are home to more than 50 percent of the world's population (Cohen, 2003). Geoengineers will be involved in predicting these hazards and in developing mitigation plans through appropriate engineering and land use planning. However, mitigation is often linked to issues of sustainability, political and social policy, and economics. Even when the existence of a natural hazard and appropriate mitigation measures are known, political, social, and economic considerations may prevent appropriate mitigation measures from being applied. Witness over 30,000 dead in the Bam, Iran, earthquake of December 2003 with a 6.6 magnitude earthquake (USGS, 2003). Similar-size earthquakes in the United States have resulted in much less damage and loss of life (e.g., the Nisqually, Washington earthquake in February 2001, which resulted in only one death, a heart attack victim who was reported in the Seattle area [SCEC, 2001]). As with environmental protection and waste management, a major challenge for geoengineering is to develop appropriate methods for geohazard mitigation in the developing world.

As in other geoengineering endeavors, new and improved characterization tools are perhaps the most important need in improving our ability to identify and manage geohazards.

- Sensing, imaging, and geophysical techniques should ultimately enable reliable monitoring of ground movements;
- Identification of both old landslides and new landslides that are poised to occur;
- Identification of expansive and collapsing soils;
- Location of wet, weak, potentially unstable zones in embankment dams and other critical earth structures;
- Identification of potentially liquefiable or otherwise unstable ground during earthquakes;
- Rapid reconnaissance of ground failures following an earthquake; and
- Identification and mitigation of other conditions and situations leading to breakdown and loss of strength in earth materials that could result in loss of stability.

Regional databases and data models for geoinformation will facilitate the collection, interpretation, and dissemination of the information and algorithms required to accomplish these tasks.

Landslides and earthquake-related hazards are perhaps the most dramatic geohazards, but other more subtle geohazards, such as expansive and collapsible soils, also exact a large toll on our society. The annual cost of damage to constructed facilities in the United States attributed to expansive soils was estimated to be $9 billion in 1987 (Jones and Jones, 1987), more than the annualized cost of any other geohazard in that year. Furthermore, population growth and urban growth exacerbate the impact of these natural hazards.

In summary, critical issues in geoengineering for natural hazard mitigation include improved hazard monitoring and forecasting, implementation of land use planning, and development of appropriate hazard mitigation technology for developing countries. While geoengineers have become fairly adept at identifying geohazards, other societal imperatives make it unlikely that hazard avoidance is a viable strategy in many land use planning situations. Therefore, hazard mitigation, including ground improvement, hazard monitoring and warning systems, and facilitation of disaster response and recovery, will remain significant geoengineering activities. Remote sensing technologies and the development of regional databases and data models will play an increasingly important role in natural hazard mitigation in the future.

2.7 FRONTIER EXPLORATION AND DEVELOPMENT

Humanity has continued to stretch its reach into the deep oceans, polar regions, and outer space. Geoengineering inputs are essential for success in these endeavors. These geoengineering inputs include sampling, testing, and interpreting the results of soil and rock tests; developing advanced technologies for subsurface drilling; helping to solve trafficability and mobility problems in extreme environments; providing foundation support and developing below-surface storage; and the use of in situ materials in construction. The Apollo lunar landings from 1969 to 1972 provide a good example of how geotechnical inputs contribute significantly to the success of scientific investigations conducted in extreme environments. These lunar landings three decades ago, as well as the recent NASA landings on Mars, required consideration of vehicle mobility issues (see Figure 2.5).

Any attempt to build permanent bases on the Moon or Mars, or on the seafloor, will have to address geotechnical issues as seemingly mundane as foundation-bearing capacity. Remote sensing technologies developed for interplanetary exploration may have invaluable terrestrial applications for natural hazard mitigation and subsurface exploration. The need for basic research on seafloor sediments and extraterrestrial materials identified in the 1989 report continues unabated.

Exploration at the frontiers of the natural universe is considered by many a fundamental drive in human society. Frontier exploration is also often accompanied by the hope that it will lead to new frontiers for

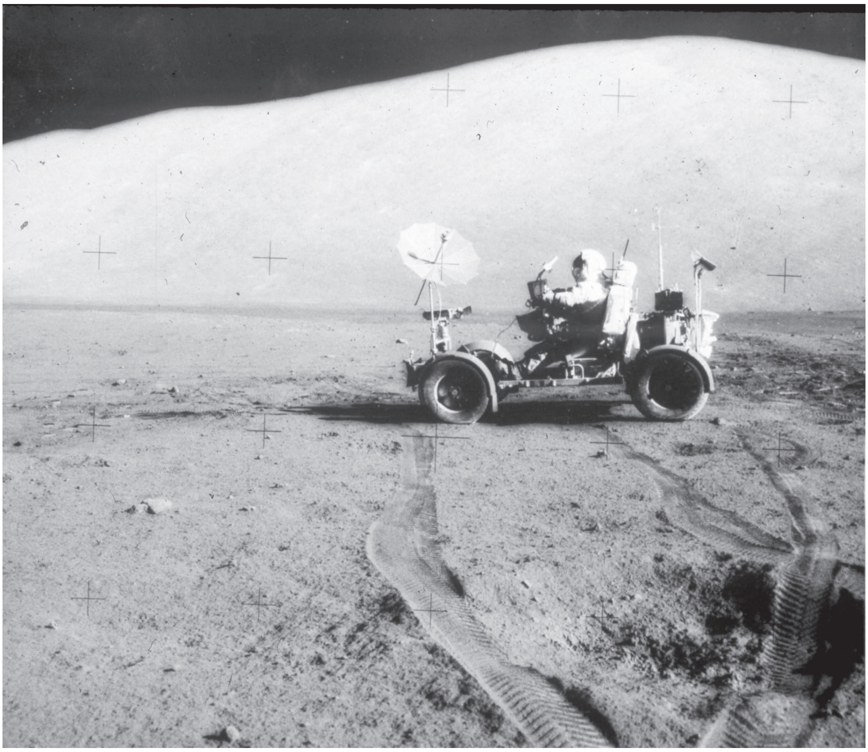


FIGURE 2.5 The Lunar Rover (NASA).

natural resource recovery and human habitation. Depletion of readily accessible natural resources has pushed us further and further into the frontiers of development in search of these resources (e.g., into the subarctic areas and deeper waters for mineral and hydrocarbon recovery). Inevitably, certain essential natural resources will become scarce on Earth (e.g., precious metals). Geoengineering issues are involved in both frontier exploration (e.g., vehicle mobility studies for lunar exploration and the Mars Rover) and ultimately in extraction of resources from these frontiers. Geoengineers should remain engaged in these activities as we stretch the limits of human experience and activities into these new frontiers.

2.8 REMAINING KNOWLEDGE GAPS

Considerable progress has been made in addressing geoengineering contributions to the societal needs identified in the 1989 report in the 15 years since the report was issued. However, much remains to be done to achieve the report's recommendations. In reviewing what needs to be accomplished, the committee identified specific geoengineering knowledge and technology gaps that must be closed. These knowledge and technology gaps include:

- Improved ability to "see into Earth." Faster, more rapid, more cost-effective, more accurate, and less invasive techniques for characterizing the subsurface is perhaps the most important need in geoengineering, irrespective of the specific problem to be solved.
- Improved sensing and monitoring methods, including improved geophysical and remote sensing technology, more reliable and accurate instrumentation, enhanced data acquisition, processing, and storage and incorporation of the collected data into appropriate information systems.
- Understanding and predicting the long-term behavior of constructed facilities and earth structures, including time effects in disturbed ground. Properties and conditions change with time; our ability to predict accurately what will happen over even short time frames is limited.
- Improved ability to characterize both the spatial variability of soil properties and the uncertainty in soil properties and soil behavior and the associated reliability of geosystems.
- Characterizing and engineering with materials that are in the range between hard soils and soft rocks. Shales, mudstones, decomposed granites, and other materials are often encountered for which a determination must be made as to whether to treat them as hard rock or soil. The consequences with respect to project cost and future behavior can be large.

- Understanding biogeochemical processes in soils and rocks. Meeting this need will serve two purposes: (1) It will provide better understanding of soil and rock composition and properties and how they may change with time and (2) these phenomena and processes can open the door to both new remediation processes for environmental applications and to innovative and sustainable ground stabilization and improvement applications.
- Improved soil stabilization and ground improvement methods. More than ever we are forced to deal with sites and subsoil conditions that are inadequate in their present state, especially in urban areas and the megacities in both the developed and developing parts of the world. Less expensive and more effective treatment methods are needed to improve soils and rocks for use both as foundation and construction materials.
- Improved understanding and prediction of the behavior of geomaterials under extreme loadings and in extreme environments. Understanding and prediction of behavior under extreme loading is essential to hazard mitigation efforts. Understanding geomaterials behavior in extreme environments, including the deep ocean, polar regions, the Moon, and now Mars provide new technical and scientific opportunities and challenges.
- Development of subsurface databases and data models, including geological and geotechnical data, information on the built environment (e.g., subsurface utility locations), natural resource and environmental data, and monitoring data for natural hazards and environmental conditions.
- Applications of information-enhanced computing power, information technology, and communication systems. These applications will impact both how and what research can be done because of the opportunities for linking facilities and real-time integration of concurrent experimental, computational, and prototype analyses and observations.

2.9 THE WAY FORWARD

Beyond the context that spawned the 1989 report there are new perspectives that have introduced new needs and shifted priorities. Some of these perspectives have been discussed in this chapter and more are discussed in Chapter 4. The globalization of the economy and of our political and social environment is also a major force driving these new needs and shifting priorities. For example, rather than focusing solely on discovery and recovery of U.S. natural resources, geoengineering today must focus on global resource recovery issues and global effects of resource use. The new emphasis on sustainable development reflects the growing recognition of the forces of globalization on society and the role of the engineer. None of these issues can be considered individually because of the complex interrelationships among them. For instance, pressures from globalization impact homeland security needs, and homeland security needs impact both infrastructure development requirements and the availability of resources for infrastructure development, rehabilitation, and maintenance. There remains a host of fundamental challenges in understanding the behavior of soils and rocks and of structures composed of soil and rock that need to be addressed by geoengineers in order to more effectively deal with these issues.

The United States and the world need geoengineers and need advances in their abilities to understand, manage and design in, on, and with Earth. Geoengineering is crucial to addressing essential national and global needs, including infrastructure development and sustainability, the availability and reliability of our civil structures, provision of homeland security, protection from natural hazards, and expanding our frontiers of knowledge. The following chapters will address this future. Chapter 3 examines the potential of new tools that might help to solve geoengineering problems in new and efficient ways. Chapter 4 looks at an expansion of the traditional geoengineering role into supporting the emerging fields of sustainability and Earth Systems Engineering (ESE). In Chapter 5 we examine the institutional issues at the National Science Foundation and universities that affect the attainment of the vision described in Chapters 3 and 4.

CHAPTER THREE

Meeting the Challenges With New Technologies and Tools

The seven areas of national need served by geoengineering and the associated critical issues identified in the 1989 National Research Council report on geotechnology (see Table 2.1) has helped the geoengineering community in the United States to define its research agenda for the last 15 years. The knowledge gaps and new realities discussed in Chapter 2 provide a basis for establishing the research agenda for the geoengineering community at the beginning of the twenty-first century.

In this chapter we present an overview of promising current and emerging technologies in various fields of engineering and science that have the potential to improve significantly the practice of geoengineering in the twenty-first century. Emphasis is placed on the emerging technologies that are focal areas for research expenditures nationwide, including bioengineering, nanotechnology, sensors and sensing, geophysical methods, remote sensing, and information technology and cyber infrastructure. National Science Foundation (NSF) priority areas and fiscal year (FY) budget requests for some of them are given in Table 3.1. Of special interest to geoengineering are Biocomplexity in the Environment, Mathematical Sciences, and Nanoscale Science and Engineering. Each section of the chapter consists of two parts. The first part presents a brief description of the technology designed for readers in the geoengineering research community; a short list of selected references is included to

TABLE 3.1 NSF Budget Request by Priority Area

PRIORITY AREA	FY 2005 REQUEST (IN MILLIONS)
Biocomplexity in the Environment	$100
Human and Social Dynamics	$ 23
Mathematical Sciences	$ 90
Nanoscale Science and Engineering	$305
Workforce for the 21st Century	$ 20

SOURCE: http://www.nsf.gov/about/budget/fy2005.

provide an entrée to the field for geoengineering researchers. The second part is intended to spark the imagination about the possible application of these technologies.

3.1 BIOTECHNOLOGIES

3.1.1 Background

The latter half of the twentieth century witnessed the transformation of biology from a descriptive science to a science that is fully able to describe the structure, mechanisms, and chemistry that control the behavior of living things. This transformation has led to an explosion of new applications in fields as disparate as medicine, agriculture, computing, and Earth processes. Applications to Earth processes in particular may provide exciting new avenues for geoengineering.

Initially, abiotic physical and chemical processes dominated the shaping of Earth. These same processes also led to the establishment of self-replicating molecules that started to exploit the residual stored energy in inorganic constituents using existing energy gradients and flux driven by the geoheat gradient and sunlight. From this aseptic beginning, life began to build more complex systems and initiate a radical reshaping of the geochemical and geological environment of Earth. The biologically induced changes are dramatic. For example, life has changed Earth's surface fundamentally from a highly reducing environment to an oxidized environment. The evolution of photosynthetic organisms beginning approximately 3.5 billion years ago established present-day oxygen concentrations and radically changed physical, geological, chemical, and biological processes on our planet (see Figure 3.1). Increased oxygen affected geologic processes by causing the oxidation of minerals as well as biology by creating conditions favorable for oxygen-breathing organisms. Life even affects the weather and helps to regulate the temperature of Earth. For example, some algae or phytoplankton in the ocean emit dimethyl sulphide that is capable of nucleating raindrops and causing rain. As the sun shines, more phytoplankton grow. These in turn nucleate clouds, which in turn control the temperature (http://www.oceansonline.com/gaiaho.htm).

Biological processes affecting Earth work on very small scales and in short time frames. It is the sheer magnitude of the amount of biomass and the cumulative effects of these processes over long time frames that shape Earth. It is estimated that the approximately 350 to 550 × 10^{15} grams

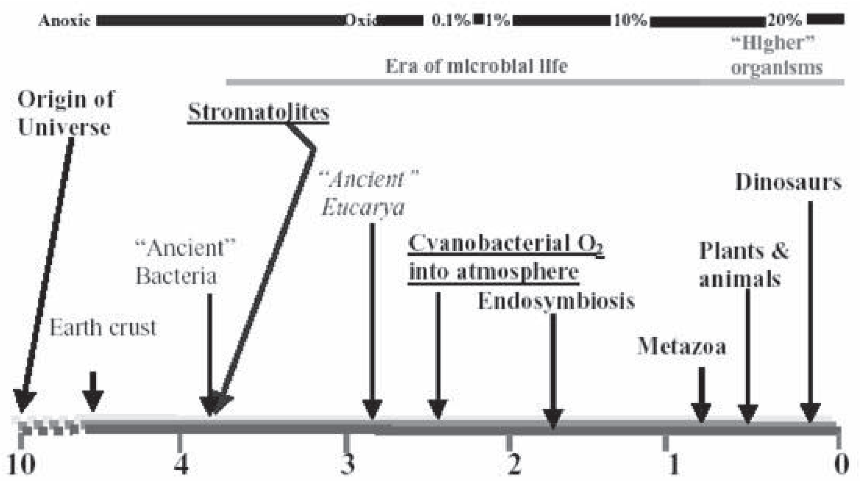


FIGURE 3.1 The biogeological time line. Approximate timing of major events (billion years from present day) in the history of life on Earth. SOURCE: Image courtesy of Dr. Bharat Patel, http://trishul.sci.gu.edu.au/courses/ss13bmm/introduction_MAM.pdf.

of carbon are stored in 4 to 6 × 10^{30} microorganisms, which represent 50 percent of the total amount of carbon stored in living organisms on Earth (Whitman et al., 1998). Assuming an average cell diameter of 1 μm, the surface area of 10^{30} microorganisms would amount to over 1 × 10^{13} square kilometers of a one-cell-thick live membrane acting as a biochemical factory. In contrast, Earth's surface is much smaller, only approximately 1 × 10^{8} square kilometers. Therefore, small-length-scale bioprocesses that work at the micro- to millisecond time frame can affect large areas and operate over millennia.

Biomediated geochemical interactions have a significant effect on the composition and properties of soil and rock near Earth's surface. Microbial life (or any biological activity, for that matter) requires a source of energy (sunlight or chemical reactions), a source of cellular carbon (inorganic or organic compounds), water, and an adequate environment for growth. Microorganisms can have a short reproduction period (10 minutes to an hour). These high-speed generation rates, mutations, and natural selection lead to very fast adaptation and extraordinary biodiversity and rapid propagation. Therefore, microbial activity can be expected everywhere in the near surface.

There are from ~ 10^{9} to 10^{12} microorganisms per kilogram of soil in Earth's near surface (upper few meters). Bacteria, the most common microorganisms in soils, are 0.5 μm to 3 μm in size, and spores can be as small as 0.2 μm. Thus, microorganisms are in the same size range as fine sand and smaller soil particles as shown in Figure 3.2. Most biological activity occurs in silt-size or coarser particles and rock fractures. Additional information on biological principles and biomediated geochemical processes, their role on the evolution of Earth, and their potential applications is in Chapelle (2001), Ehrlich (1996, 1999), Hattori (1973), and Paul and Clark (1996), among others.

3.1.2 Biology and Geoengineering

Given the ubiquitous presence of biological processes in the subsurface, it is surprising that only recently are geoengineers becoming

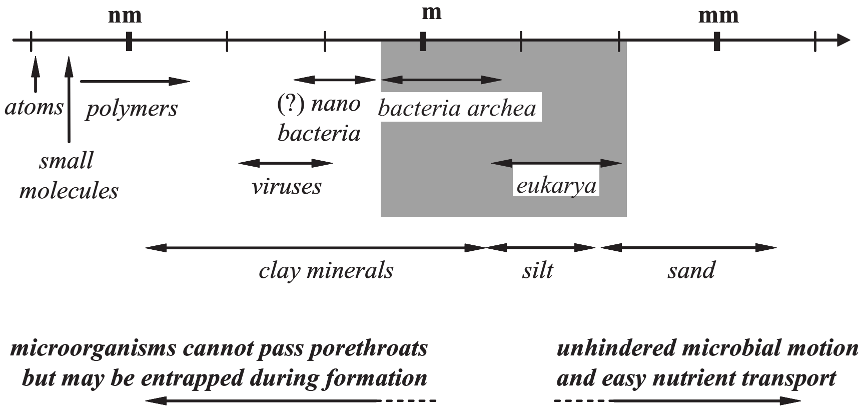


FIGURE 3.2 Comparative sizes of microorganisms and soil particles. SOURCE: Mitchell and Santamarina (2005); used with permission.

aware of them and are beginning to study their role in determining and controlling soil properties and behavior and exploiting them in engineering applications.

Geoenvironmental engineering applications. Perhaps the greatest progress in practical application of biological processes in geoengineering has been in bioremediation of contaminated ground, and much of this work has been under the purview of environmental engineers. Nonetheless, geoengineers have contributed significantly to these developments through their work on site characterization, developing means for bioaugmentation and biostimulation in the ground, the definition of seepage flows and pathways, the development and implementation of sampling and monitoring programs, and the design and construction of passive reactive barriers. A passive reactive barrier consists of a reactant-filled trench across which a contaminated seepage plume must pass. The reactants in the trench then neutralize the contaminants so that the seepage emerging from the trench no longer poses an environmental risk.

Even anthropogenic compounds in soil are broken down by many different microorganisms and plants. Chlorinated aliphatics and aromatics are readily degraded, as are such complex compounds as polychlorinated biphenyls (PCBs), dioxins, and chlorofluorocarbons (CFCs) (NRC, 1993). Microorganisms can also remediate contamination due to metals and radionucles (http://www.lbl.gov/NABIR/). The organisms take their energy and carbon from these compounds and grow on them. Bioremediation takes advantage of these microbial processes to transmute or immobilize harmful substances. Still incomplete, however, is detailed understanding of how microbes transform contaminants at the molecular level, the nature of bioavailability of contaminants to microbes, interactions between biological and geochemical behavior, and microbial community dynamics and ecology.

Geomechanical applications. Biomediated geomechanical processes can have significant impacts on the geomechanical behavior of Earth materials. Microorganisms can selectively pull or immobilize metals and other inorganic compounds from solution, release enzymes and proteins that change their environment (e.g., charges, cation capacity, and pH of soils), and cause the precipitation of inorganic compounds. Microbial activity can directly or indirectly affect the physical properties of soils on a permanent or a temporary basis. Conceivably, it could even be used for such purposes as producing self-healing infrastructure.

Consider, for example, the construction of a conventional, aboveground building with subsurface infrastructure that requires a supported excavation in sand. Traditionally, this construction would normally require the installation of sheet piling or other shoring techniques to prevent infiltration of groundwater, to control movement of soil into the excavation, and to minimize subsidence of other existing and adjacent structures. Imagine instead that six months before construction and excavation a solution of specialized or genetically engineered microorganisms, along with special amendments to sustain the microorganisms, was injected into the sand throughout the depths requiring soil improvement. Assume that these microorganisms then produced a polymer or resulted in the precipitation of inorganic compounds that cemented the soil particles together and made the soil very stiff and possibly even impervious to groundwater flow. A process of this type would also have application for the passive stabilization of loose saturated sands that are susceptible to liquefaction in seismic areas.

Or perhaps we could learn to grow foundations with biological processes much like trees grow roots. These foundations might require no disruptive excavation and might well provide the most appropriate support systems in unconsolidated soils. Applications of such stabilization technology might well also apply to tunneling, where biota could be called on to limit water inflows and prevent tunnel collapse. Even further, perhaps biological media would soften rock before it is excavated thus decreasing excavation costs and facilitating the use of the underground. Such techniques could result in faster excavation methods, and a reduction or elimination of excavation support and water control. These are only a few examples of the potential applications offered by a new paradigm of biomediated geochemical processes in geoengineering.

Even further, could biotechnology be developed such that a soil and microbial system could behave as a smart material responding to changing conditions such as occur during earthquakes or fires? Biotechnology is already used in resource recovery, with bioleaching being used to extract base metals, such as copper, zinc, and cobalt, and as a pretreatment process to enhance extraction of gold. Thus, the promise of biotechnology to improve geoengineering and construction is already being realized. It is on a steep slope of advancement, and as new information, understanding, and technology become available new applications can surely follow.

In mining, truly revolutionary developments could occur if microorganisms could be used in situ to increase permeability and porosity of hard rock, specifically a sulfide mineral deposit, to enable good solution contact between the mineralized material and the lixiviants used to solubilize the minerals. This development would enable in situ mining of base and precious metals, which would significantly minimize the environmental impacts of mining. As well, microorganisms could be used to create an impermeable cavity underground to contain and control solutions in situ so that metals dissolved in the lixiviant could be collected and to eliminate the possibility of contaminating groundwater in an in situ mining application.

3.2 NANOTECHNOLOGIES

3.2.1 Background

Nanotechnology deals with the structure and behavior of materials at a very small scale, typically from less than a micron down to submolecular sizes. Although perhaps never considering themselves nanotechnologists, soil scientists and engineers, with their interest in the study of clay-size particles (< 0.002 mm), are among the earliest workers in the field. Most material types and properties change with scale. For example, soil particles change in composition and shape from predominantly bulky quartz and feldspar to platy mica and clay over the range of particle sizes from sand and gravel down to silt and clay. A central challenge in geo-engineering is to understand the changes in properties and behavior in moving from large to small, whereas a central theme in nanotechnology is to take advantage of this transition and attain novel material performance through nanostructuring of new materials. Material properties may be affected or engineered using nanoscale building blocks, controlling their size, size distribution, composition, shape, surface chemistry, and manipulating their assembly. Building nanoscale structures requires a fundamental understanding of nanoscale processes. Sidebar 3.1 highlights events in the development of nanotechnology.

Several important effects relative to inter-particle interactions gain relevance at the nanoscale. Nanomaterials possess very high specific surface (ratio of surface area to mass), and chemical activity is specific surface dependent. For example, the specific surface of a 1 nm cube is about 2400 m^2/g. The maximum specific surface for bentonite clay (sodium montmorillonite) is about 800 m^2/g, and about half of the constituent atoms are exposed at the surface and thus available for chemical interactions. High specific surface means high adsorption capacity and great sensitivity of nano-size particles to specific adsorbed

SIDEBAR 3.1
A Brief History of Nanotechnology

1959	Richard Feynman addresses the American Physical Society with "There's Plenty of Room at the Bottom: An Invitation to Enter a New Field of Physics." He recognizes the potential for new, exciting discoveries, the possibility of fabricating new materials and devices at the molecular scale, and identifies the need for new equipment and instrumentation for manipulation and measurement.
1980s	Important advances in instrumentation (e.g., scanning tunneling microscopes, atomic force microscopes, near-field microscopes), and in computer capability that can support extensive simulation studies (e.g., molecular dynamics). E. Drexler (1986) in "Engines of Creation: The Coming Era of Nanotechnology" coins the term "nanotechnology."
2000	President Clinton announces a $500 million national nanotechnology initiative to generate breakthroughs in "materials and manufacturing, nanoelectronics, medicine and healthcare, environment, energy, chemicals, biotechnology, agriculture, information technology, and national security."[a]
2005	There are more than 30 centers dedicated to nanotechnology research at U.S. universities and industrial laboratories. The annual research and development funding approaches $1 billion (combining National Science Foundation, Department of Defense, National Institutes of Heath, National Institute of Standards and Technology, National Aeronautics and Space Administration, Environmental Protection Agency allocations), with similar investments in Western Europe and in Japan. Atomic force microscopes can reach a sensitivity of sub-attonewton (10^{-18}N) and deploy multiple parallel sensing probes for faster data gathering. Single-electron devices (transistors and memory) have already been demonstrated. Many commercial applications of nanotechnology research affect everyday life. The health risks of nanomaterials remain mostly unknown.

---

[a] Office of the Press Secretary. National Nanotechnology Initiative: Leading to the Next Industrial Revolution. Press Release, January 21, 2000. Available at: http://clinton4.nara.gov/WH/New/html/ 20000121_4.html. Accessed September 1, 2005.

materials. Interactions between nanoparticles are determined by interparticle electrical forces. The pH and ionic concentration of the aqueous pore fluid alter the surface chemistry through dissolution, protonation, and adsorption. Therefore, pore fluid characteristics affect the self-assembly of nanocomponents and their long-term stability.

Nanosystems exhibit phenomena not usually observed in continuous systems. Some salient comparisons between different types of behavior at macro- and nanoscales and how analysis and engineering are done at these two levels are summarized in Table 3.2. Among the challenges to be met in introducing nanotechnology into geoengineering is to be able to upscale the nano-level phenomena and process descriptions to the macroscale behavior, materials, and structures that are the usual end points of the engineer's efforts.

Current research in the nanotechnology field falls into three main areas:

1. *Fundamental issues* that are concerned with improved dimensional and structural definition, local chemistry control, and surface properties;
2. *Assembly, segregation, and aggregation; effective biological synthesis, self-replication, and assembly*; *and environmental effects and fabrication control.* Nanomaterials by design involve bottom-up fabrication, synthesis from solution rather than solid-state fabrication, short manufacturing times, and reproducibility.
3. *Application challenges.* Among the application areas receiving attention at the present are nanoelectronics, optoelectronics, and magnetics; microspacecraft; bionanodevices for detection and mitigation of health threats; healthcare, therapeutics and diagnostics healthcare; and energy conversion and storage.

Additional information on fundamental aspects of nanotechnology and its applications is given in Zhang et al. (2002), Wang et al. (2002), and elsewhere. Articles and keynote lectures by Ken P. Chong are readily found on the Internet and are excellent sources of information on nanotechnology and the National Science Foundation's vision for its future.

TABLE 3.2 Analysis and Engineering at Macro- and Nanoscales

	MACROSCALE ENGINEERING IS DONE CONSIDERING THAT	NANOSCALE ENGINEERING IS DONE CONSIDERING THAT
General properties	• Continuum behavior • Generalized constitutive models are applicable	• Analysis of discrete particle behavior • In terms of discrete atomic nature of matter • The discrete distribution of charges • Quantized energy • The failure of continuum theories at this scale
Magnetic properties	• Magnetic responses reflect the average of individual magnetic fields of a system's constituents	• Magnetic response reflects the electron's intrinsic spin • Quantum tunneling of magnetic moment is observed (nanomagnets)
Conduction and transport processes	• Flow is continuous according to Darcy's law, Ohm's law, Fourier's law, Fick's law, Advection-dispersion equation	• Mean free path of phonons becomes comparable to the prevailing scale • Transport is sporadic and irregular • Charge confinement and surface effects produce electronic density states (nanodots) rather than the continuum density state in bulk matter
Thermo-dynamic conditions	• Temperature and pressure are state parameters	• Thermodynamic limits are reached at the nanoscale • Brownian motion cannot be disregarded • Thermal energy can exceed other excitations • Nanodevices are very sensitive to thermal noise • Strong coupling effects can develop among all forms of energy (thermal, electrical, optical, magnetic, mechanical, chemical). For example, nanodots exhibit strong optical emission

3.2.2 Nanotechnology and Geoengineering

A comparison of scales in nanotechnology and geomaterials was noted above and is presented graphically in Figure 3.3. As this figure shows, the fundamental behavior of clays is a nanomechanics problem, suggesting that concepts and models developed in nanotechnology can provide new insights and enhanced understanding of the behavior of clay-size particles and, even more important, new means to manipulate or modify this behavior.

Soil and rock are the world's most abundant and lowest-cost construction materials. In some states (e.g., dense, dry, and cohesive) they are strong and durable. In others (e.g., loose, wet, and soft) they are weak and unsuitable. Is it possible or even conceivable that new knowledge and the development of processes at the nanoscale may someday transform these materials in ways that can make them even more useful and economical? The committee believes that investment in research on the possibilities should be a high priority.

In particular, developments in nanotechnology can aid in understanding the fundamental behavior of fine-grain soil at the particle level and lead to the development of engineered fine-grain soils. Readily available atomic force microscopes are now being used in mineral studies to explore local mineral variations in clays, such as surface charge and local hydrophobicity on mineral surfaces. Further developments will permit the use of nanomagnets to manipulate very small diamagnetic clay

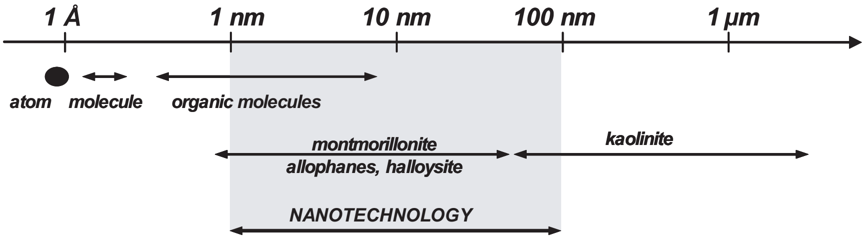


FIGURE 3.3 Length scales: Nanotechnology and clay minerals.

minerals and to study mineral surface reactions using chemical force microscopy.

Although most nanoscale phenomena have not been studied in the context of geomaterials, the self-assembly of nanoparticles in aqueous solutions involves particle-level phenomena similar to fabric formation by clay-size particles. Clay soil fabric formation is mineral and pore fluid chemistry dependent. Figure 3.4 shows a phase diagram illustrating the relationship between the chemistry (pH and concentration) of an aqueous solution and the type of fabric formed by clay particles sedimenting down through that solution.

Although nanotechnology applications in geoengineering are largely exploratory at present, other applications in geoengineering can be

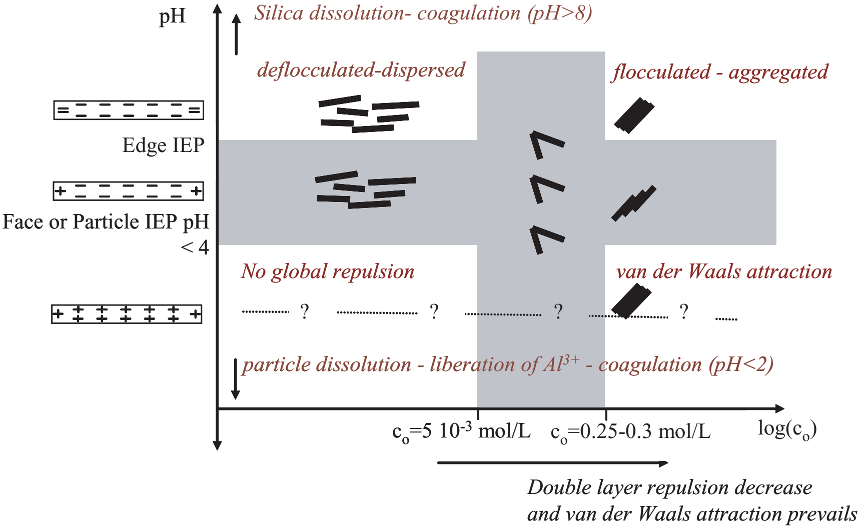


FIGURE 3.4 This fabric map for montmorillonite shows the inherent variety of self-assembly affecting clays. The states vary between repulsion dominated (dispersed fabric) and attraction dominated (aggregated fabric). These states reflect the balance between double layer/osmotic repulsion and van der Waals attraction. In turn, pH determines the charge of a particle, which changes from negative at high pH to positive at low pH (the transition point is called the isoelectric point, IEP, which takes place around the salinity of seawater in many clays). Combining the two regions in pH and concentration results in four states and transition regions. SOURCE: Modified from Santamarina et al., 2001.

imagined that will radically change practice. For example, imagine building clay liners, clay cores, and soil bases using engineered high-surface-area mineral particles consolidated from controlled self-assembled clay aggregates to obtain macroscale behavior resulting from exceptional mechanical properties (e.g., very high ductility); external friction control to facilitate compaction while increasing long-term strength, fluid-sensitive porous membranes, as well as special and unique chemical properties (e.g., specie-selective diffusion); engineered wetting conditions such as in NanoTurf; altered phase equilibrium for fluids in small pores; and specified electrical properties (e.g., exceptional magnetic and polar properties). Some of these developments are already taking place, for example, in the engineering of kaolin and precipitated carbonates for the paper coating and paint industries.

Nanoparticles might also be engineered to act as functional nanosensors and devices that can be extensively mixed in the soil mass or used as smart tracers for in situ chemical analysis, characterization of groundwater flow, and determination of fracture connectivity, among other field applications.

Although some of these applications seem almost magical in their potential, and many of those we can imagine will face some major unanticipated difficulties in reaching application, it behooves the geoengineering community to explore the possibilities of how the nanoscale material we know as soil can benefit from the nanoscale knowledge and new materials that are being developed by our colleagues in other disciplines.

3.3 SENSORS AND SENSING SYSTEM TECHNOLOGIES

3.3.1 Background

Microelectromechanical systems (MEMS) integrate mechanical elements, sensors, actuators, and electronics on a common silicon substrate using microfabrication technology, as described in Sidebar 3.2. Recent technological advancements in materials science, microfabrication of MEMS, and bioengineered systems have made the dream of inexpensive, powerful, and ubiquitous sensing an achievable reality for many applications. Potential examples of such applications include (1) smart airframes that can adapt their performance to applied stresses and movements and self-evaluating buildings and infrastructure that can assess their condition and provide real-time responses for natural hazard mitigation and (2) data acquisition for weather forecasting and self-organizing energy systems. These applications will probably require that MEMS-based sensors integrate with networking and computational capabilities.

The assembly techniques used to build MEMS (described in Sidebar 3.2) are based on the accretionary and etching technologies commonly used by the integrated electronics circuit industry, which allow for involved micron-scale machining. The basic material used, silicon, has excellent structural properties. It is easy to add complementary metal oxide semiconductor (CMOS) circuitry directly onto the silicon to form very small, low-power-consumption, accurate, and rugged sensing devices. For example, the Sensirion barometer module for atmospheric pressure measurement is only 5 mm × 5 mm × 3 mm and has integral linearization, temperature compensation, 16-bit analog to digital conversion, and a common digital interface. In mass production the cost of such a device is typically only a few dollars.

Common to all advanced sensing systems is the vast amount of data generated. Processing these data encourages development of sensor systems that preprocess data in order to return decisions and information directly to the user. Traditionally deployed sensors are a collection of individual components in which the data collected must be processed by additional hardware downstream. Networks containing preprocessing sensors could become powerful, dynamic, and user-friendly in comparison to the traditional sensor data.

Wireless communication offers important advantages in the development of sensing systems. A generic wireless sensor platform includes an antenna, a power supply, a transceiver, signal processing circuitry, and a microprocessor to run the sensing and networking software. Each of

SIDEBAR 3.2
What Are MEMS?

The following description of MEMS was taken from the MEMS and Nanotechnology Exchange at http://www.memsnet.org/mems/what-is.html:

Microelectromechanical systems (MEMS) integrate mechanical elements, sensors, actuators, and electronics on a common silicon substrate through microfabrication technology. While the electronics are fabricated using integrated circuit process sequences (e.g., CMOS, Bipolar, or BICMOS processes), the micromechanical components are fabricated using compatible micromachining processes that selectively etch away parts of the silicon wafer or add new structural layers to form the mechanical and electromechanical devices.

MEMS promise to revolutionize nearly every product category by bringing together silicon-based microelectronics with micromachining technology, making possible the realization of complete systems-on-a-chip. MEMS are an enabling technology allowing the development of smart products, augmenting the computational ability of microelectronics with the perception and control capabilities of microsensors and microactuators and expanding the space of possible designs and applications.

Microelectronic integrated circuits can be thought of as the brains of a system and MEMS augment this decision-making capability with eyes and arms to allow microsystems to sense and control the environment. Sensors gather information from the environment by measuring mechanical, thermal, biological, chemical, optical, and magnetic phenomena. The electronics then process the information derived from the sensors and through some decision-making capability, the actuators respond with actions such as moving, positioning, regulating, pumping, or filtering, thereby controlling the environment for some desired outcome or purpose. Because MEMS devices are manufactured using batch fabrication techniques similar to those used for integrated circuits, unprecedented levels of functionality, reliability, and sophistication can be placed on a small silicon chip at a relatively low cost.

SOURCE: Courtesy of MEMS and Nanotechnology Exchange, http://www.memsnet.org/mems/what-is.html.

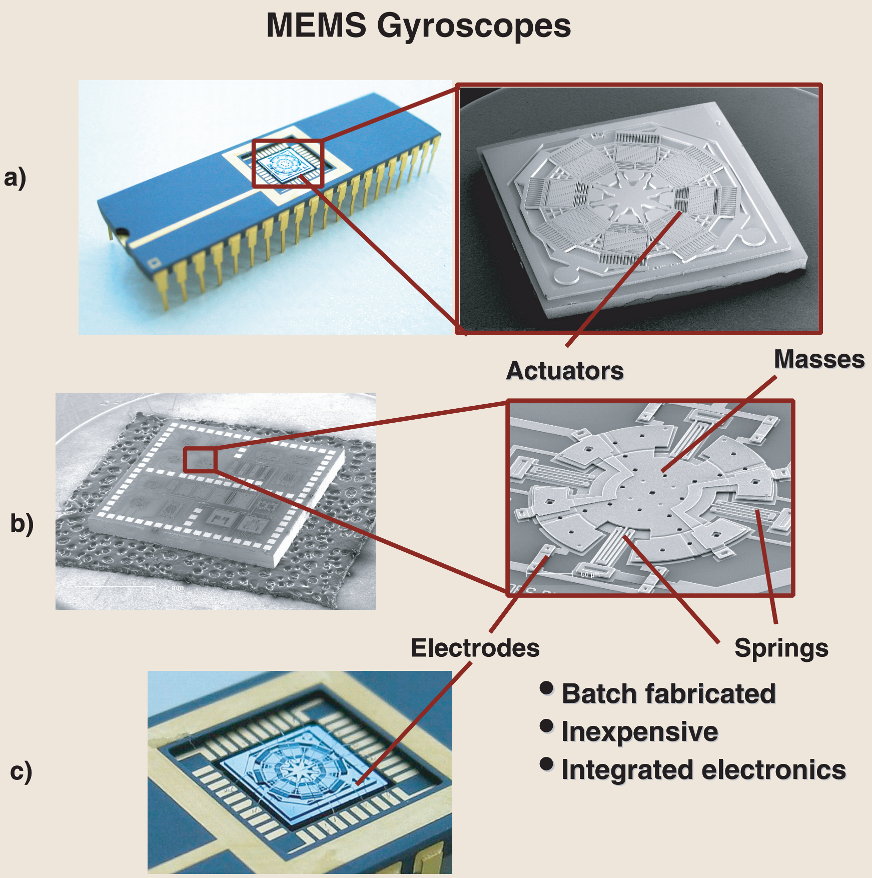


FIGURE: A MEMS gyroscope is shown as it (a) appears to the end user (as an integrated circuit [IC]), (b) the die within the chip and the micromachine within the die, and (c) a detail of the packaged die. This gyroscope has many common mechanical elements, and measures rate of twist around the normal to the plane of the device. The center of the gyro is a mass suspended on micromachined springs and damped by dashpots. The mass is resonated and the resultant Coriolis force, the same force that gives us the trade winds, is measured during motion (images courtesy of Andrei Shkel, University of California, Irvine).

these components presents design challenges and opportunities for MEMS applications. Limitations in wireless communication include power demand because radio frequency (RF) communication requires relatively large amounts of power compared to MEMS-based sensors; ensuring privacy of the data transmission; poor quality of low-power RF transmission that is susceptible to failure by seemingly insignificant changes in surroundings; and limited data transmission rates over low-power RF networks compared to the simplest wired bus. Furthermore, RF signals cannot be broadcast through soil, which limits their applications in geoengineering.

The very convergence of new sensor technologies, communications, and computing creates new potential. With the simultaneous use of these technologies, geoengineers could collect data over large time and space scales in a variety of materials and environments, analyze these data in situ, and make highly informed engineering decisions. Ultimately, the sensor and system (network) technology and devices must be inexpensive enough to allow their use in great numbers. Furthermore, the sensing systems must be easy to deploy, configure, and maintain so that researchers from disciplines other than computer science or electrical engineering can use them.

Current research themes in the Sensors and Sensor Networks Initiative at NSF (Liu and Tomizuka, 2003) involve sensor design for such purposes as biomimetic (life mimicking) applications, toxic agent detection, chip-based sensing systems, remote activation and interrogation, and self-calibration; sensor arrays and networks for multisensor monitoring, information transfer, ultralow power nodes, data management, distributed network control, and smart devices that self-assemble into networks; and information interpretation and use for decision and feedback, sampling, location optimization, monitoring, and diagnostic tools. MEMS research problems include identifying the optimal physical location of sensors to gather independent and complementary data, quantifying the uncertainties involved in measurements, developing autocalibration strategies, and validating sensor output using independent measurements.

Data interpretation requires knowledge of the uncertainties involved in taking the measurement. Hardware solutions to this problem must include autocalibration so that rational estimates of uncertainty can be made. System solutions must include sensor output validation with independent measurements and predictive modeling. The massive amounts of data that sensors gather must be manageable and interpretable to have any value. The user wants information, not numbers. One approach is to synthesize design models with the data to be collected (i.e., use sensing as a link between the real world and an abstract world). This synthesis leads to adaptive data interrogation systems.

Additional information on sensors and sensing systems is given in Kovacs (1998), Madou (2002), Petersen (1982), Elwenspoek and Wiegerink (2001), Ristic (1994), and Senturia (2001).

3.3.2 Sensing Systems and Geoengineering

Unobtrusive, smart, and inexpensive monitoring of geostructures can help greatly in providing knowledge and characterization of Earth through the four dimensions: the three spatial dimensions and time. Micron-scale sensors are being produced that measure displacements, strain, strain rate, tilt, location, species of gas and fluids, temperature, relative humidity, water content, fluid pressure, light intensity and spectral content, fracture growth, and other mechanical and chemical parameters. The integration of these new sensor technologies and systems into geoengineering research and practice must take into consideration the high cost of developing new sensors and sensor networks. Consequently, it is important to consider the use and adaptation of commercial off-the-shelf devices for geoengineering applications whenever possible.

The continuing revolution in sensing technology enhances our ability to see into Earth (NRC, 2000). The new technologies have dense sensor arrays that provide an order-of-magnitude increase in overall sensitivity over what was previously possible. These sensor arrays will have to be based on wireless communication and must incorporate in situ data reduction to minimize bandwidth requirements if they are to be practical. Potential users must consider the inherent physical limitations, such as the penetration depth of radio frequency signals through geomaterials. Advanced information technology will allow adaptive arrays that can function and react on multiple scales without direct human intervention.

Advances in sensors and sensing systems complemented with information technologies will allow advances in multivariate sensing and multiconstrained inversions. Imagine a dense dataset compiled from such methods as seismic, electromagnetic, gravitational, magnetic, and streaming potential. Each type of data contributes independent information. Together, these datasets can provide a comprehensive image of the subsurface, including the distribution of utilities and the spatial variability of the soil mass or rock structure.

Fiber optic seismic sensors are now available for boreholes that allow high-resolution imaging of the subsurface without interfering with the borehole. MEMS-based three-component accelerometers can provide high-accuracy digital data. High-resolution geophysical testing is complemented with microdrilling technology, which drills holes as small as 1.25 in to depths of 500 ft with the potential to maintain that hole size to depths of 5,000 ft (Shirley, 2003). The Badger Explorer (Bradbury, 2004) is a new rigless, battery-powered drill that carries sensors directly into the subsurface, collects data, and transmits the data to the surface. It measures shale volume, water saturation, porosity, bulk density, pore pressure, temperature, and acoustic velocity. In the coming decade, integration of autonomous sensing, computing, and communications systems—such as Smart Dust (http://robotics.eecs.berkeley.edu/~pister/SmartDust/) and downhole fiber optic, MEMS, or nanosensors—will be combined with information management technology to take us to a new level of data gathering and interpretation (also see Pister, 2003).

We can imagine geoengineering applications such as real-time monitoring of geostructures during occurrence of natural hazards (e.g., hurricanes, floods, and earthquakes) and the instrumentation of an earthfill dam with a network of devices so small that they do not have a structural effect but so ubiquitous that we can monitor seepage, piping, displacements, and dislocations throughout the structure in real time. If enough information can be gathered and analyzed in near-real time, it may be possible to deploy self-sealing technology to waste containment barriers where they are leaking, know where strain is accumulating along a fault zone to provide advance warning of seismic events, and image ahead of an advancing drill bit or tunnel machine to identify obstructions and hazards before they are encountered.

Integration of advances in wired and wireless communications protocols and hardware will put geoengineers in an entirely different position with respect to design and problem solving. Traditional geoengineering is predicated on not having complete knowledge of the underground. If the promise of MEMS is met, geoengineers could have the opposite problem of having more data than they know what to do with. Learning to use massive amounts of detailed information effectively and inexpensively could even introduce new challenges.

3.3.3 Human Factors

While this section of the report has focused on the potential contributions to geoengineering from new sensing tools, the importance of human factors in applying these tools and technologies cannot be overlooked. For instance, successful application of any monitoring program, whether using old established technology or new innovative sensors and networked instrumentation systems, depends on a variety of seemingly mundane tasks, including procurement, calibration, and acceptance of hardware and software, installation and baseline monitoring of equipment, maintenance and recalibration as needed, data collection and processing, and data interpretation with response actions as warranted. Without these steps, even the most advanced and sensitive instrumentation and monitoring system in the world could be rendered useless. While some of these functions can be built into a monitoring system (e.g., self-calibration, automated data collection and reduction), human interaction will still be required for proper interpretation and response.

3.4 GEOPHYSICAL METHODS

3.4.1 Background

Geophysical sensing involves using techniques deployed from the ground surface or a borehole to define soil and rock profiles and to determine physical, chemical, or biological properties of Earth materials. Geophysical sensing can be employed for infrastructure-related characterization, resource development (hydrocarbon, mineral, and water), and monitoring processes (construction, remediation). Most geophysical methods are based on detecting a physical property contrast in space or time. The target must have sufficient size or contrast to be detectable by the geophysical sensor, and there is an inherent tradeoff between resolution and target depth. Although geophysical measurements are often conducted at a boundary, they can be processed using inversion techniques to infer the field of the parameter away from the boundary.

An overview of geophysical methods and their underlying principles is presented in Table 3.3. These methods generally provide independent

TABLE 3.3 Geophysical Methods

METHOD	PRINCIPLE	TYPICAL MEASUREMENT	PHYSICAL PROPERTY MEASURED	INTERPRETED PARAMETERS
Airborne sensing	Detects reflected electromagnetic radiation	Aerial photography and remote sensing in several spectral bands	Spectral-dependent reflectance of electromagnetic radiation	Geologic lineations, variations in vegetation, surface disturbances
Electrical and electromagnetic	Detects current flow in subsurface materials	Currents, voltages, spatial locations	Electrical resistivity	Depth, Earth material resistivity, porosity, inferred fluid chemistry

TABLE 3.3 Continued

METHOD	PRINCIPLE	TYPICAL MEASUREMENT	PHYSICAL PROPERTY MEASURED	INTERPRETED PARAMETERS
Ground-penetrating radar	Transmits radio waves in the 10 MHz to 500 MHz band into subsurface and detects returning reflected waves	Distance, wave arrival times, and wave amplitude	Dielectric permittivity, electrical resistivity, magnetic susceptibility	Shallow interface depth and geometry, electromagnetic wave speed, electromagnetic wave attenuation
Magnetics	Detects local variations in Earth's magnetic field caused by magnetic properties of subsurface materials	Proton precession frequency	Magnetic susceptibility	Geometry and magnetic susceptibility of local subsurface features
Microgravity	Detects localized minute variations in the gravitational field of Earth	Displacement of a gravitational-force-sensitive mass	Mass density	Depth, geometry, and density of local subsurface features
Seismic methods	Source of seismic waves provides sampling of elastic properties in a localized volume of Earth	Distance, wave arrival time, and wave amplitude, different wave types	Speeds of compressional, shear, and surface waves; attenuation of these waves	Interface depth and geometry, elastic moduli, location of faults
Thermal methods[a]	Measures temperature and changes related to active or passive thermal sources	Temperature and temperature changes at specific locations	Thermal conduction, heat capacity	Density, moisture content, thermal anomalies, thermal sources, rate of geochemical reactions

[a] Thermal methods added for this report.

SOURCE: NRC (2000, 2001b).

information, which is analogous to the complementary nature of human senses, such as hearing (elastic waves) and seeing (electromagnetic waves). With respect to geoengineering, corresponding geophysical techniques (e.g., seismic methods and ground-penetrating radar) provide complementary information as well. It follows from this analogy that the best approach to looking into Earth is to use several different methods (including traditional geoengineering invasive techniques) and to consider the multiple constraints imposed by the results to limit and guide the inversion and interpretation process. In all cases, interpretation of the data requires proper understanding of the physical, chemical, or biological properties of Earth materials and their impact on the measured physical property.

The relationship of geophysics to geoengineering may be viewed from the perspective of the relationship of imaging technology to medical diagnosis. From this perspective the revolution in noninvasive medical diagnostic technology provides a guiding example for the geoengineering community, because it faces equally challenging diagnostic problems. Current medical imaging technology, such as computer-aided tomography (CAT), positron emission tomography (PET), magnetic resonance imaging (MRI), and ultrasound, can render both high-resolution and high-speed images that allow monitoring of subsecond-scale processes such as heartbeats. Recent extensions of medical imaging technology to the field of material science include very-high-resolution MRI and microcomputed tomography with micron-scale resolution. Additional information on geophysical methods, principles, and applications is given in Ward (1990), Yilmaz (1987), Telford et al. (1990), Aki and Richards (2002), and the Society of Exploration Geophysicists website (http://seg.org/publications/opubs/).

3.4.2 Geophysics and Geoengineering

The balance between the use of noninvasive geophysical methods and traditional invasive subsurface investigation methods reflects in part the cost of needed information that can be gathered with each technique.

This balance is different in geoengineering applications from that in medicine, mining, or petroleum applications (as suggested in Table 3.4), which may explain in part the delayed adoption of geophysical methods in geotechnical practice. In medicine the shapes, locations, and properties of the organs are usually known, and they can be imaged from all sides. In geoengineering applications there is limited access and the components of the systems, as well as the properties of the components, are not well known. Therefore, medical imaging is much more accurate than geoengineering imaging.

In addition, complexities in processing geophysical data associated with underlying physical concepts, mathematical modeling and inversion, and final interpretation have further deterred the direct involvement of the geoengineering community in the development and application of geophysical methods for near-surface applications. However, new, efficient geophysical sensing devices coupled with versatile modeling and inversion software that can run on personal computers facilitate the application of geophysical techniques and permit the real-time visualiza-

TABLE 3.4 Cost of Information Versus Extent of Application of Invasive and Noninvasive Methods in Various Fields

APPLICATION (MAIN CONSTRAINT)	RELATIVE COST OF INFORMATION (INVASIVE / NONINVASIVE)	CURRENT PRACTICE
Petroleum (target thousands of meters deep)	Very high	Mostly noninvasive
Medicine (human life)	High	Mostly noninvasive
Mining (aerial extent)	Intermediate	Mixed methods
Geoengineering (near surface, limited aerial extent)	Low	Mostly invasive

tion of subsurface conditions. These developments offer the promise of a shift in the balance between traditional invasive exploration techniques and geophysical methods.

Geophysical tools that can have the greatest impact on geotechnical engineering are related to

- delineation of stratigraphy and subsurface variability, including the detection and characterization of small but significant geologic structures such as thin clay seams;
- fracture network characterization in rock masses (dip, strike, spacing, condition) and soil classification and porosity (without nuclear sources);
- degree of aging and diagenesis, assessment of fluid conditions (chemistry, saturation, pressure), and hydrogeological characteristics (including water table depth and variability in hydraulic conductivity);
- small-strain parameters and anisotropy;
- the values of effective stresses; and
- detection and monitoring of movement of Earth and built structures.

As the presence and potential role of biological activity are recognized and better understood as important factors in geoengineering, geophysical sensing tools will be needed to assess metabolic activity and biomass distribution.

Wave propagation techniques based on electromagnetic waves (electromagnetic induction, ground-penetrating radar, and resistivity) or elastic waves (reflection, refraction, vertical seismic profiling, cross-hole, and spectral analysis of surface waves) are most efficient for near-surface applications. Electromagnetic methods provide information about the specific surface of the soil, the volume fraction of water, and the conductivity of the soil-water mixture. The effectiveness of noncontacting electromagnetic techniques remains unmatched by seismic methods; however, the limited penetration depth of electromagnetic waves in geomaterials often restricts their application. Sensor arrays (antennas for ground penetrating radar or coils in probes for electromagnetic surveys) have been coupled to state-of-the-art imaging and visualization software to produce very-high-resolution images of the near surface for utility detection in urban environments. Figure 3.5 presents an example of the application of high-resolution geophysical methods for locating subsurface utilities in West Palm Beach.

Seismic methods provide parameters that are more intimately related to the geomechanical properties of the subsurface than many of the other geophysical methods. For example, the shear S-wave velocity, V_s, is a direct measurement of the small strain shear stiffness, G_{max} (knowing the mass density), and stiffness anisotropy. The primary compression or P-wave velocity, V_p, indicates proximity to full saturation (critical for

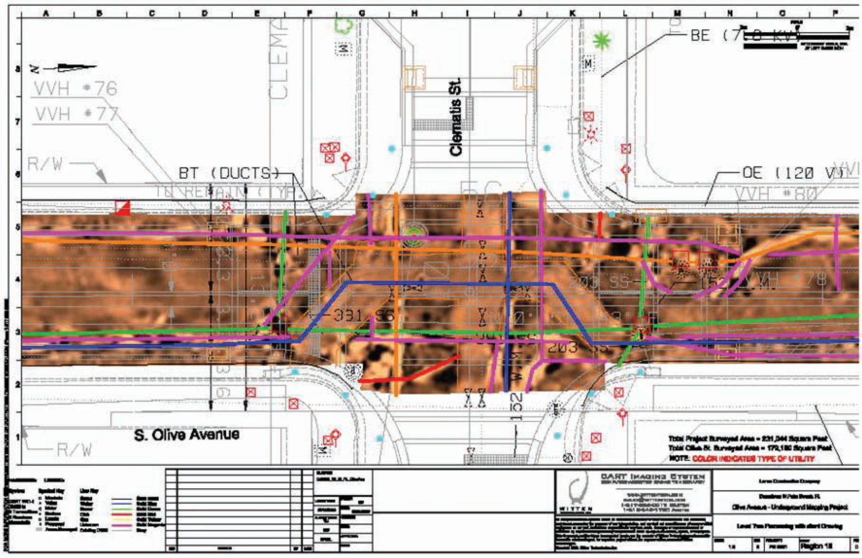


FIGURE 3.5 A plan-view 24-in depth-slice from imagery captured in downtown West Palm Beach, Florida, using radar tomography, an arrayed ground-penetrating radar technique used for shallow-subsurface 3-D surveying. This slice, which is one of 120 1-ft slices that make up a full "movie," has all (regardless of depth) utilities found overlaid, color-coded by facility type. This is a combination of radar tomography's two normally separate deliverables: PC video files and CAD drawings. (Copyright, Witten Technologies Inc.; used with permission.)

pore water pressure generation and liquefaction); when the soil is fully saturated, V_p and V_s can be used to infer porosity.

The importance of G_{max} in geomechanics stems from its ability to assess the skeletal stiffness even under saturated soil conditions. Seismic measurements of G_{max} can also detect the effects of aging and diagenesis on soil structure, effects that are destroyed by penetration-based testing or during sampling. Therefore, G_{max} measurements provide unparalleled information for cemented soil characterization, settlement computation, and even as an indicator of liquefaction potential (in particular for coarse deposits such as gravelly alluvium, where penetration testing can be either impossible or unreliable). Imagine deploying tomographic S-wave velocity systems beneath foundation systems prior to construction, behind retaining walls prior to excavation or in cross-sections prior to tunneling, and monitoring the evolution of soil stiffness (through changes in mean effective stress or loss of cementation) to help assess and monitor soil-structure interaction and its evolution in time.

There are important potential applications of geophysical techniques in laboratory studies as well. Imagine running a centrifuge-modeling experiment and assessing the evolution of the soil mass in the model with nonintrusive tomographic techniques; or monitoring the evolution of soil processes in laboratory cells while simultaneously gathering information with elastic and electromagnetic waves without perturbing the process (consider for example: consolidation, cementation, liquefaction, freezing, remediation, biomediated geochemical stabilization). Imagine using microtomographers (CAT and MRI) developed in medicine and material science to explore fabric evolution, mixed fluid flow, strain localization, and other microscale phenomena during laboratory testing. Imagine being able to determine the velocity and flux of fluids (water, oil, gas, injected CO_2) in the field without having to drill boreholes. These are not esoteric concepts; prototypes of such devices are already available and ready to be explored to address geoengineering needs.

Important research needs remain for near-surface geophysical technology, including better understanding of the effects of mechanical, electrical, chemical, thermal, and biological processes on geophysical and geotechnical parameters; the optimization of sensors and sources (arrays, permanent sensor deployment, embedded sensors in natural and built environments, sensor reliability, calibration, communication, power requirements, control, and data transmission); and adequate processing algorithms that reveal the inherent high gradients in stiffness, porosity, and saturation conditions in the near surface. These new techniques must address the need for high resolution compatible with engineering applications, the complementary nature of multiple geophysical methods, and the need for ground truth provided by invasive techniques.

3.5 REMOTE SENSING

3.5.1 Background

Remote sensing techniques involve noncontact observation, measurement, and recording from an airborne or space platform of electromagnetic energy reflected by or emitted from a target. Passive systems measure energy that is reflected or transmitted from an object on Earth's surface back to the sensor (e.g., satellites that record visible, near-infrared and thermal infrared wavelengths), whereas active systems generate energy and record the reflection from the body that it strikes (e.g., radar). The digital images captured by remote sensing systems can be manipulated and enhanced to highlight subtle features, such as vegetation type and density, water turbidity or pollutants, lithology and mineralogy, soil type and moisture, and many more features.

Space-based remote sensing systems deployed by governments or commercial enterprises are designed to make measurements of the land, atmosphere, and oceans. Starting with the Landsat series in 1973, a variety of space-based remote sensing systems have been deployed by the United States, Russia, India, Japan, and Canada. Numerous commercial remote sensing systems are now available.

The oil exploration industry offers an example of the potential for broader application of remote sensing in solving geoengineering problems. The demand for better petroleum reservoir characterization and management has transformed geophysics from an exploration tool to a drilling, development, and management tool. Some of the newer technologies have applicability to depths and scales important in geoengineering, and include time-lapse seismic imaging, measurement while drilling, geosteering for directional (e.g., lateral) well drilling, multicomponent seismic acquisition and processing (P-waves and S-waves in multiple directions), passive seismic monitoring, multifrequency and spectral measurements, through-casing borehole logging tools, and a wide variety of automated and semiautomated processing techniques involving artificial intelligence and advanced mathematical algorithms.

Visualization of large, complex datasets gathered by remote sensing can have a tremendous impact on our ability to understand, predict, and manage the subsurface. Development of software for visualization and management of these large data streams requires collaboration of interdisciplinary technical teams (engineers, geologists, geophysicists). Rapid simulation software allows what-if scenarios to be played out in advance. Autonomic computing involving the self-management, self-optimizing, self-configuring, self-healing, and self-protecting of data assets is only a few years from reality. But all these developments require very high data storage and computation power (see the section on information technology below).

Additional information on remote sensing and geoengineering applications is given by Short and Bolton (2004).

3.5.2 Remote Sensing and Geoengineering

The spatial and topographic resolution that can be attained with current remote sensing technology is relevant to many geoengineering applications. Two examples follow.

Synthetic aperture radar (SAR) uses antennas mounted on spaceborne, airborne, or ground-based carriers to generate high-resolution images by repeating measurements at selected spatial intervals along a straight trajectory. Attainable resolution is from 10 m to 25 m for satellite-based systems and from 1 m to 3 m for airborne systems.

SAR data consists of a grid of complex numbers (amplitude and phase); two SAR images gathered at different times can be compared to produce interferograms that display phase difference (i.e., changes in elevation). Spaceborne interferometric synthetic aperture radar (InSAR) can determine displacement as small as a few millimeters over hundreds of square miles. Interference images gathered with synthetic aperture radar are shown in Figure 3.6, with applications to ground subsidence and tectonic displacements. InSAR technology has started to see some commercial applications (e.g., detection and monitoring of ground subsidence due to groundwater extraction in Phoenix). However, the technology is not widely accessible to the practicing geotechnical engineer. Making remote sensing technologies more accessible through research, development, and training will facilitate both advancement of technology and application to engineering practice.

Light detection and ranging (LIDAR) is an exciting new development in remote sensing that can provide very-high-resolution imagery of geologic features by measuring the time it takes for a laser pulse to travel roundtrip from the laser source to a target and back to a sensor. LIDAR

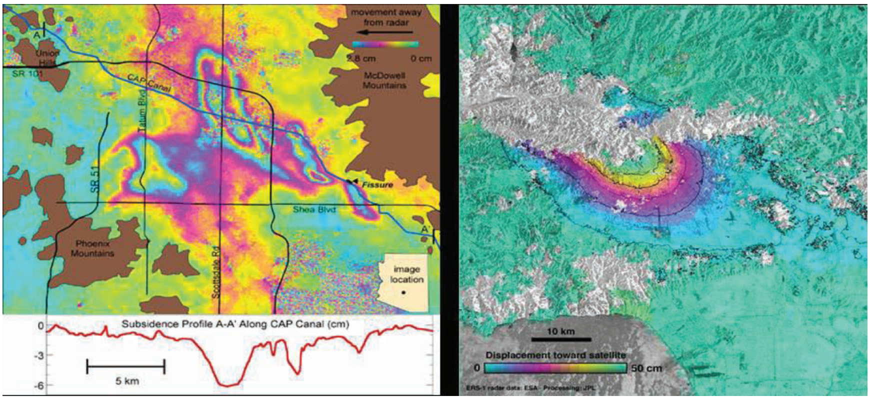


FIGURE 3.6 Synthetic aperture radar interferograms. (a) Ground surface subsidence induced by changes in groundwater in Phoenix, Arizona (Tatlow and Buckley, 2003; used with permission). (b) Tectonic displacement field after the 1994 Northridge earthquake (image courtesy of Gilles Peltzer, University of California, Los Angeles; used with permission).

has traditionally been employed from satellites and aircraft but can also be employed from a fixed station on the ground. LIDAR can produce high-resolution topographic maps over large areas with grid spacings as little as 0.3 m (see Figure 3.7). In forest terrain, LIDAR-based terrain maps can be more revealing than high-resolution photographs (NRC, 2004d). In urban areas recent advances in photogrammetry offer enhanced resolution in interpretation of high-resolution aerial photography. Landslide hazard maps, flood plain assessments, landslide prediction, monitoring, slope stability in mines and road cuts, and coastal erosion are a few of the geotechnical engineering applications that have used this remote sensing technology.

Potential applications of remote sensing in geoengineering are related mainly to large-scale projects and regional activities and planning. Examples include hazard forecasting, monitoring regional subsidence, disaster response and recovery management, infrastructure planning, avalanches and regional instability, near-surface resource characterization and mining operation monitoring, and coastal erosion. Imagine the ability to monitor the movement of large, active landslide complexes from space-borne platforms with sufficient accuracy and frequency to

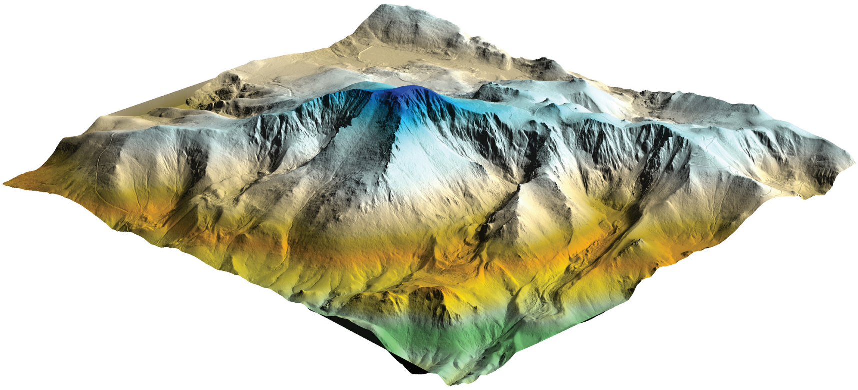


FIGURE 3.7 LIDAR 3-D topographic image of Pikes Peak. SOURCE: Data was developed using LIDAR methods by Merrick & Company in support of a project for El Paso County, Colorado. http://www.merrick.com/servicelines/gis/lidarsamples.aspx.

detect accelerating movements that could eventually lead to a catastrophic failure. Near-real-time processing of the data could be linked with preset alarm levels to provide early warning of impending disaster in sufficient time for evacuation or other emergency action, and perhaps even allow for remedial action to prevent it. Imagine post-event damage surveys performed by space-borne platforms that could be used to direct response and recovery efforts in the immediate aftermath of a catastrophic event such as an earthquake or terrorist attack. These types of systems are within the realm of existing technologies, and could become reality with appropriate investment in research and development.

3.6 INFORMATION TECHNOLOGIES AND CYBERINFRASTRUCTURE

3.6.1 Background

The staggering increases in computing power and communications capabilities over the past 50 years have led to the development of information systems unimaginable just a few decades ago. The evolution in computer simulation capability since 1993 is shown in Figure 3.8. The growth in computer power has been driven by energy, scientific, and engineering applications, and especially by defense applications such as the Accelerated Strategic Computing Initiative (ASCI), a project started in 1996 to replace traditional nuclear testing by highly tuned, massive computer simulations (Messina, 1999).

As shown in Figure 3.8, the performance of supercomputers evolves rapidly. Today’s fastest computers perform up to 71×10^{12} floating-point operations per second. A list of the fastest computers can be found on the Web at http://www.top500.org. In November 2004, the fastest computer was the Department of Energy/IBM BlueGene/L beta system, which has the record benchmark performance of 70.72 Tflop/s (“teraflops,” or trillions of calculations per second). It is closely followed (51.87 Tflop/s) by the Columbia system built by Silicon Graphics and installed at the National Aeronautics and Space Administration Ames Research Center

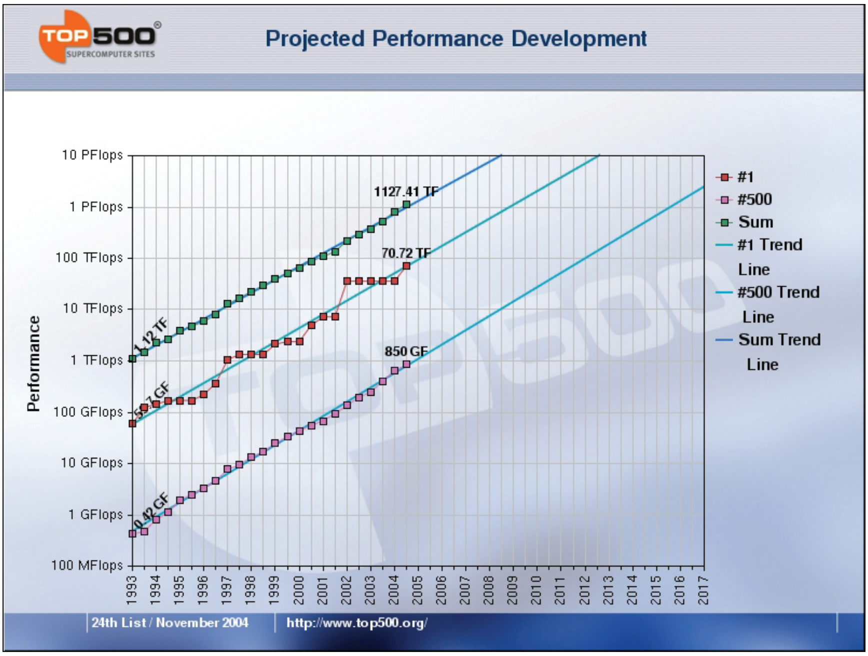


FIGURE 3.8 Evolution of fastest computer performance since 1993 (http://www.top500.org/lists/2004/11/ PerformanceDevelopment.php).

in Mountain View, California. Both computers recently exceeded the performance of the Earth Simulator supercomputer (35.86 Tflop/s) in Yokohama, Japan, which was the fastest computer between 2002 and 2004. These supercomputers are clusters of thousands of processors (Earth Simulator involves 5,120 processors). Even with this computing power, large-scale problems are still based on crude material models and employ simplified geometry and boundary conditions. Spatially varying material properties and geometries representative of actual in situ conditions would result in problems too large and complex for modern computers.

The integration of computer technology and communication networks has made distributed information systems possible. Unlike conventional networks that focus on communications among devices, the Grid harnesses unused processing cycles of all computers in a network for solving problems too intensive for any stand-alone machine. Grid computing is intended to provide extraordinary computational power by dynamically linking high-performance computational resources over wide areas, thus balancing supply and demand. Many large-scale computer simulations now use the Grid (Foster and Kesselman, 1999).

In a related initiative NSF has recently launched a middleware project to enable the seamless federation of resources across networks. Middleware software is an evolving layer of services that connects two or more separate applications across the Internet or local area networks. It resides between the network and more traditional applications for managing security, access, and information exchange.

The Grid and middleware are examples of current developments of the cyberinfrastructure. The term "cyberinfrastructure" refers to the "system of information and communication technologies together with trained human resources and supporting service organizations that are increasingly required for the creation, dissemination, and preservation of data, information, and knowledge in the digital age" (Atkins et al., 2003). Cyberinfrastructure is an enabler of research. It is recognized that an advanced cyberinfrastructure can be the basis for revolutionizing the conduct of scientific and engineering research and education, and it can have broad impact in many other knowledge-intensive domains. The creation and usage of the cyberinfrastructure requires synergy among the computer science, engineering, and science research communities.

Extrapolating in large part from prior NSF investments in cyberinfrastructure (including high-performance computing, networking, middleware, and digital libraries, trends in the information technology industry, and the vision and innovation coming from many research communities), the NSF Blue-Ribbon Advisory Panel on Cyberinfrastructure asserted in 2003 (http://www.cise.nsf.gov/sci/reports/toc.htm) that the capacity of information technology has crossed thresholds that now make possible a comprehensive cyberinfrastructure on which to build new types of scientific and engineering knowledge environments and organizations and to pursue research in new ways and with increased efficacy. Such environments and organizations enabled by cyberinfrastructure are increasingly required to address national and global priorities such as global climate change, protecting our natural environment, applying genomics and proteomics to human health, maintaining national security, mastering the world of nanotechnology, predicting and protecting against natural and human disasters, as well as to address some of our most fundamental intellectual questions, such as the formation of the universe and the fundamental character of matter. For additional information on information technology and cyberinfrastructure, see NRC (1993, 2001b,c).

3.6.2 Information Technology and Geoengineering

The importance of information systems and technology to advances in geoengineering cannot be overstated. Geoengineers will need to understand, implement, and benefit from such technology at all scales. For example, it will not just be that geoengineers will need more information about urban systems; urban systems will become characterized at all levels by the development of information systems: smart materials, smart buildings, smart urban geoplatforms, smart infrastructure, and the like. The twenty-first century should see the advent of smart geosystems: geoengineered systems with information structures built into them. These systems will not just talk hierarchically (that is, to geoengineers), but they will also be self-referential: self-defining, self-diagnosing, and self-healing. This is where communications networks have already gone, and where other infrastructure systems are heading. This has implications not only for research and innovation but also for geoengineering curricula and professional practice. The profession must address not just geosensing and monitoring, but also the evolution of information-rich, self-referential geosystems.

The explosion in information technology offers the potential for added value from existing hardware and software systems as well as for development of new hardware and software. Many (perhaps most) existing monitoring and sensing systems are easily integrated into an information-rich smart system context. There are more than 1,600 catalogued computer programs specifically written to solve geoengineering problems in soil mechanics, rock mechanics, engineering geology, foundation engineering, hydrogeology, geoenvironmental engineering, and environmental engineering. Some of these programs are capable of solving very complex nonlinear problems, time-dependent dynamic phenomena, including combined mechanical-chemical-thermal-biological processes and complex construction sequences (tunnels, foundations, excavations). State-of-the-art examples of computational geoengineering are illustrated in Figure 3.9 for multiphase flow (oil, water, and gas) and pollutant dispersion followed by biochemical reactions. The figure also illustrates the power of result visualization when interpreting the results of large, complex simulations.

Advances in computational geoengineering have benefited from multidisciplinary collaborations. For example, the Seismic Performance for Urban Regions (SPUR) project is designed to simulate the effects of earthquakes on urban regions, and is the collective result of structural engineers, computer scientists, and seismologists (ERC, 2005). Based on a distributed simulation framework and on advanced computational and

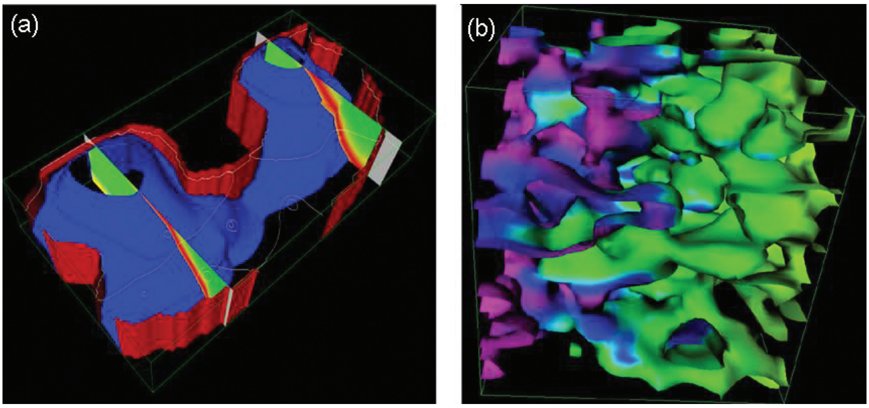
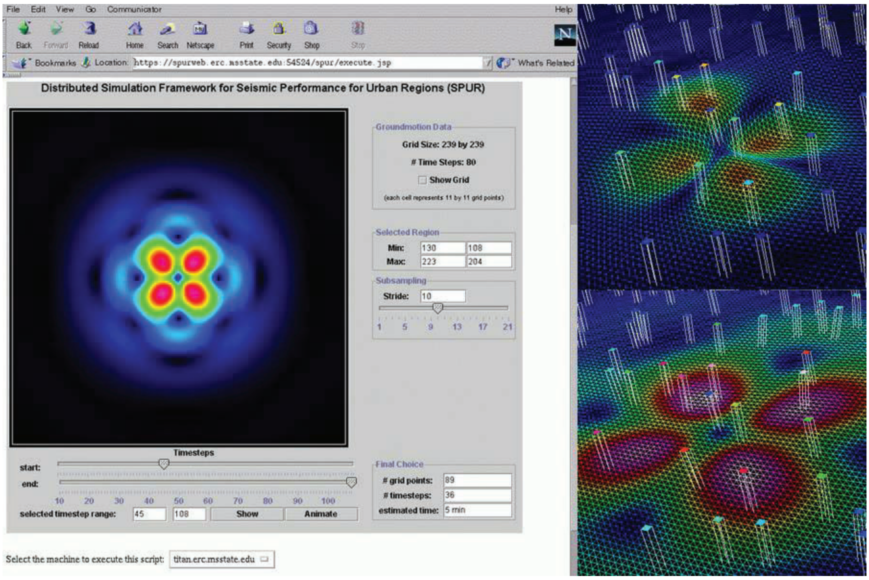


FIGURE 3.9 Computer simulations. (a) Oil production: 3-D maps of an oil reservoir and the flow of oil, water, and gas through a complex porous medium.
(b) Remediation: dispersion of pollutants in porous substrata where biochemical reactions are followed. Various species concentrations are shown using different colors. SOURCE: Oden et al. (2003). Reprinted with permission from Elsevier.

visualization methods, SPUR permits forecasting and visualizing the extent and distribution of damage to buildings, bridges, and lifelines caused by earthquakes of different magnitudes and depths (see Figure 3.10).

Geoengineers work extensively with spatial data. Databases that have the capability to code, store, manipulate, and display spatial data are herein grouped under geographic information systems (GIS). These systems gain critical importance in facilitating the identification of patterns and trends, in extracting information from massive datasets, and through valuable analysis and management tools, which include two- and three-dimensional displays and extensive imbedded modeling capabilities



Location: https://spurweb.erc.msstate.edu:54524/spur/execute.jsp

Distributed Simulation Framework for Seismic Performance for Urban Regions (SPUR)

Groundmotion Data

Grid Size: 239 by 239

Time Steps: 80

☐ Show Grid

(each cell represents 11 by 11 grid points)

Selected Region

Min: 130 108

Max: 223 204

Subsampling

Stride: 10

1 5 9 13 17 21

Timesteps

start:

end:

10 20 30 40 50 60 70 80 90 100

selected timestep range: 45 108

Final Choice

grid points: 89

timesteps: 36

estimated time: 5 min

Select the machine to execute this script: titan.erc.msstate.edu

FIGURE 3.10 Seismic Performance for Urban Regions (SPUR) simulation of regional effects after a large earthquake. (a) This image shows the intensity of earthquake shaking that originates from a fault rupture at depth. SOURCE: Java-based Web interface for earthquake ground motion simulation. Web interface: Tomasz Haupt, Engineering Research Center, Mississippi State University. Visualization: Joerg Meyer, University of California at Irvine; used with permission. (b) Images represent buildings (tall rectangles) that respond to the earthquake ground motion propagating across the city. SOURCE: Ground motion and structural response simulation in a 3-D virtual environment. Prashant Chopra and Joerg Meyer, University of California at Irvine; used with permission. Available at http://imaging.eng.uci/~jmeyer/SPUR/.

(e.g., statistical, logical, mechanical). GIS technology not only supports the geoengineer but also facilitates communication between researchers, practitioners, and the public. Current developments are oriented toward fully exploiting the capabilities of GIS with new sensor technology to allow us to capture and manipulate three-dimensional time-varying data.

The integration of sensor technology in geophysical measurements discussed above with visualization tools and data management that can be scaled to the types of problems encountered in the broader field of geoengineering provides an example of the role of information technology. Imagine the application of hybrid systems that will extensively combine dense sensor arrays with computer models to drastically increase the availability of data and decrease uncertainty in geoengineering applications, and allow the rational consideration of all available subsurface data in real-time decision making. While current GIS technology may be employed for developing smart sensor networks for data management, to take full advantage of their database capability current two- and three-dimensional databases must evolve into true geologic data models in which data is stored and interpreted in a geologic context and with multidimensional modeling and interpretation capabilities integrated into the data management, manipulation, and display schemes.

In the future, geoengineering researchers and practitioners will be able to implement complex computer models and examine multiscale and multiphysics phenomena, examine the complete range of physical phenomena at all applicable spatial and temporal scales, integrate computational models with large datasets originating from dense sensor arrays and satellite remote sensing, and examine uncertainties of computer simulations through realistic modeling. They will be able to conduct these analyses and control laboratory and field testing remotely, in cooperation with other colleagues in interdisciplinary teams pulling together human, technological, and computational capabilities in the cyberinfrastructure. Information technology will enable geoengineers to mine and analyze the voluminous information produced by field and airborne sensors. Using advanced computer networks, geoengineers will query and scrutinize gigabytes of information. They will construct efficiently realistic computer models of geoengineered structures that include detailed information on geometries and material properties. They will have a large digital library of in-depth case histories to train students in geoengineering. They will have the opportunities to make more educated real-time decisions based on the realistic computer simulations and rapid exchanges of information.

3.7 THE POTENTIAL OF THE NEW TECHNOLOGIES FOR ADVANCING GEOENGINEERING

A comprehensive and complete understanding of soils and rocks and the development of effective, efficient, and economical new solutions to problems in geoengineering must consider not only mechanical interactions but also interactions with all forms of energy: mechanical, thermal, chemical, and electrical. New ways of obtaining and processing information about soils and rocks have the potential to revolutionize our engineering capabilities. Some of the ways that the new technologies we have discussed in this chapter may make this happen are summarized in Table 3.5. Application of all these new technologies and the need to incorporate more electronics, biology, chemistry, material science, and information technology into geoengineering has major implications for education as well as practice, and these issues are discussed in Chapter 5.

The committee sees tremendous opportunities for advancing geoengineering through interaction with other disciplines, especially in the areas of biotechnology, nanotechnology, MEMS and microsensors, geosensing, information technology, cyberinfrastructure, and multispatial and multitemporal geographical data modeling, analysis, and visualization. Pilot projects with vertical integration of research of multiple disciplines—perhaps including industry, multiple government agencies, and multiple universities—should be explored as alternatives to more traditional interdisciplinary proposals.

The importance of the human factors discussed earlier in this chapter should not be neglected in the application of advanced technology, whether it be advanced sensors, geophysical exploration, remote sensing,

TABLE 3.5 The Potential of New Technologies to Advance Knowledge and Practice in Geotechnology

DISCIPLINE	POTENTIAL IMPACT ON GEOTECHNOLOGY	TIMING	REQUIRED KNOWLEDGE FOR GEOENGINEERS
Biotechnology	High • improved understanding of Earth material behavior • new construction materials • applications for in situ ground remediation of contaminated soil and groundwater will increase • passive methods for ground stabilization may be possible • better resource recovery methods may develop	Mature concepts permit high impact in the short-term.	• biology • geochemistry
Nanotechnology	Medium to Low • nanotechnology is a recognized part of soil technology • enhanced understanding based on more study of reactions at the nanoscale • new materials and methods • solutions looking for problems at this stage?	Field in early stages of development. Its full impact in geotechnology should be expected in the long term.	• physics • chemistry
Sensors and sensing systems	Medium to High Depending on whether the promise of MEMS is met, MEMS developers should be connected to geotechnical problem solvers (see Chapter 5). • will require geoengineers to increase their knowledge of electronics • proper integration can revolutionize laboratory measurement through noninvasive sensing • can make geophysical methods cheaper and more pervasive • integration of development work by other industries essential	Revolutionary developments in progress. Sensors already available and systems can have high impact in the short term.	• electronics • signal processing • inversion math

continued

TABLE 3.5 Continued

DISCIPLINE	POTENTIAL IMPACT ON GEOTECHNOLOGY	TIMING	REQUIRED KNOWLEDGE FOR GEOENGINEERS
Geophysical methods	High • will require increasing the benefit-cost ratio • noninvasive methods need more development • new data acquisition and processing methods enhance applicability • tomographic methods allow 3-D characterization	Revolutionary and mature tools available. Further emphasis on high-resolution near-surface characterization will have renewed impact in the mid-term.	• electronics • signal processing • inversion math
Remote sensing	High • ongoing, fruitful area for research and development • ground-truthing observations remain a research issue • research could address the potential for real-time decision making	A new family of unprecedented tools will have significant impact in the short term.	• signal processing • data management • computer science
Information technology	High • ongoing developments • provides a mechanism for collaboration • requires synergy among the computer science, engineering, and science research communities for fruition • aspire to 4-D GIS for real-time decision making • development of self-referential smart geosystems with built-in information structures	Its critical role in sensing systems, geophysics, and remote sensing will determine their impact in the short term. Smart infrastructure systems are already on the drawing board and under development. Existing geosensing and monitoring devices are available and ready for integration with these systems.	• data management • computer science

information technology, or some other technological advancement. Such issues as procurement, calibration, validation, data collection, and data interpretation remain vital to successful implementation of new tools and technologies.

We conclude that many of the most important tools for achieving major advances in geoengineering are likely to come from forward-looking, creative, and inspired individuals working alone or with one or two colleagues in related disciplines. We urge, therefore, that NSF increase its investments in this type of research, including especially the support of a greater proportion of projects that may be classified as high risk but high reward.

CHAPTER FOUR

Geoengineering for Earth Systems and Sustainability

Previous chapters looked at the traditional roles for geoengineering and suggested how they could be affected by new tools and technologies. This chapter looks beyond the traditional roles for geoengineers and projects how they might respond to the new compelling imperatives the world faces. It examines the relationships between geoengineering and sustainability and Earth Systems Engineering (ESE) and then describes how a new Geoengineering for Earth Systems (GES) initiative might be structured in response to these imperatives. There is a compelling leadership role for geoengineers in addressing these new problems, given that the focus of these problems is the health of Earth and that engineering in, on, and with Earth is what geoengineers do.

4.1 SUSTAINABLE DEVELOPMENT

The latter part of the twentieth century was marked by increasing attention to sustainability (i.e., to the question of whether our society can maintain the current quality of life we enjoy in developed countries while raising the quality of life in developing countries). A variety of definitions have been proposed for sustainability and sustainable development. For the purpose of this report, the committee has adopted the definition of sustainable development put forth by the American Society of Civil Engineers (ASCE) and presented in Sidebar 1.1.

An increasing focus on sustainable development is one of the major changes in the practice of civil engineering since the 1989 report. Sustainable development has become generally recognized as an important consideration in civil engineering practice (see Sidebar 1.1). ASCE, in Policy Statement 418, states that "the demand on natural resources is fast exceeding supply in the developed and developing world. Environmental, economic, social and technological development must be seen as interdependent and complementary concepts, where economic competitiveness and ecological sustainability are complementary aspects of the common goal of improving the quality of life." (ASCE, 2004a). In short, the civil and environmental engineering profession in the twenty-first century faces a new imperative that can no longer be ignored: the incorporation of social issues in addition to the environmental and economic dimensions when developing engineering solutions to societal needs. The simultaneous optimization of these three objectives has been called the triple bottom line of sustainable development.

Research in the discipline of geoengineering has already begun to broaden from its traditional emphasis on the highly focused science of the specifics of soil and rock mechanics in response to this new imperative of sustainable development. Now we are concerned with the life cycles of the materials we use, the long-term environmental effects of our choice of energy supply, and the availability of potable water. Importantly, these issues are considered not just at local or regional scales but at global scales. As noted at the National Academy of Engineering symposium on ESE, Norman Neureiter, former science and technology adviser to the U.S. Secretary of State, said in his remarks titled "It's the World, Stupid!" (NAE, 2002), "The problems we face—climate change, disaster mitigation, the spread of infectious diseases, safe drinking water, food security, the dramatic loss of species, protection of critical infrastructure, terrorism, proliferation of weapons of mass destruction—do not stop at anyone's border." One important implication of this global focus is that we must be concerned not only with advanced technology but also with appropriate technology (e.g., identifying the most appropriate solid-waste management technologies for developing countries where construction of advanced geosynthetic liner systems may not be feasible and may also not be warranted by the waste stream).

Many of the concerns associated with the sustainable development are directly related to geoengineering, including problems related to environmental health, resource conservation and availability, safe disposal of chemical and nuclear wastes (see Sidebar 4.1), clean up of contaminated sites, sequestration of CO_2 to mitigate climate change, and the natural resource needs of the developing world. The developing world is projected to be the source of most of the population growth in the next half-century and this growth is expected to occur almost exclusively in megacities. Basic needs in these megacities—such as water, energy, and sanitation—will be among the most pressing requirements. Therefore, geoengineering will play an important role in the movement toward sustainable development in the twenty-first century (see Sidebar 4.2).

Effective waste disposal and reuse or recycling of the components of obsolete engineered structures are increasing challenges requiring consideration of the full life cycle of facility construction. Solutions to these needs in developing countries should be low in cost to be realistic, and they might well be labor intensive, but they will not necessarily be low tech. Geoengineering for sustainable development must therefore be concerned with reducing the environmental impact of both existing and new facilities and operations in the engineered environment in the developing world.

Sustainable development and concern with the triple bottom line are also becoming important considerations in mining and mineral resource development. In an important two-year study commissioned by the World Business Council for Sustainable Development, the International Institute for Environment and Development (IIED) examined the role of the mining and mineral resources industry in global sustainable development (see Sidebar 4.3). Geoengineering will play an important role in addressing the many challenges identified in this study, including the control, use, and management of land and the impact of mining and mineral recovery on the environment and local communities.

SIDEBAR 4.1
Nuclear Waste Storage—A Cautionary Tale

Nuclear waste storage is an example of a problem with interdependent political, social, economic, and technical aspects. In this country, as in nearly every country facing the need to store spent fuel from reactors, the solution of choice is geologic storage. Geologic storage is not, however, just a geotechnical problem. The choices must be technically sound, but the way that we reach a decision about what to do is governed by national legislation (Nuclear Waste Policy Act and amendments) and affected by social acceptance. The cost is borne by utilities that pay one mil per kilowatt hour into the Nuclear Waste Fund. The current venue for high-level nuclear waste storage in this country is Yucca Mountain in Nevada. However, this project faces delays and legal obstacles promoted by the state government and the Nevada delegation to the U.S. Congress. A lack of consensus on the concept of the project has led to a lack of agreement about the technical and legal approach.

The reasons for these difficulties can probably be traced to the Nuclear Waste Policy Act and its amendments. The original act lays out a process for down-selecting from eight pre-chosen sites, then to five, then to three, and then one based on technical merit. The amendments override the last down-select process and anoint Yucca Mountain as the one and only site. This process created an environment and project culture, including the Yucca Mountain Project, where each of the Yucca Mountain site contractors tried to show their site was appropriate; in other words, they did not try to find out what might be wrong with the site. The amendments were viewed by the state of Nevada as 49 states ganging up on one, and the sense of unfairness that evolved has dominated the state's response ever since.

Some of the original ideas about why Yucca Mountain might be a good site turned out to be technically complicated. Yucca Mountain was thought to be quite dry and thus waste would not contact water, which could dissolve and transport it. Yucca Mountain is the only repository in the world being considered above the water table. It turns out that the predicted behavior of the hydrologic system over the lifetime of a heat-producing repository in fractured rock that is variably saturated with water is extremely difficult to validate. The above-the-water-table environment is oxidizing and the spent fuel is much more soluble in an oxidized state.

A legal challenge from Nevada has now resulted in the courts vacating the standard that is to be used for licensing the facility. A new standard must be developed that goes beyond a 10,000-year performance period and sets limits on the maximum risk whenever it occurs, a time period expected to be on the order of hundreds of thousands of years. The project continues to have budget problems with vastly different amounts proposed by the administration, the U.S. Senate, and the U.S. House. Utilities see the lack of progress as a major obstacle to the pursuit of future nuclear power. The future of this project is not clear.

Both the United Kingdom and Canada have faced similar obstacles to their nuclear waste programs for similar reasons. However, some countries have done a better job at integrating social, economic, and political concerns on this issue. Perhaps the exemplar is Finland, where an extensive process was used to obtain public agreement about the goals of the nuclear waste program and the need for storing waste in a geologic repository. Once this was accomplished, a plan to choose a site based on predefined technical criteria and local acceptance was developed and executed. Sites were eliminated that did not meet the criteria. The local community of the final site was engaged to develop a clear package of benefits. The program is progressing smoothly and may well be the first high-level waste repository to be commissioned.

SOURCE: Long and Ewing (2004).

SIDEBAR 4.2
Engineering for the Developing World—Challenges and Opportunities

The Challenge

With a current population of 6 billion people, the world is becoming a place in which human populations are more crowded, consuming, polluting, connected, and in many ways less diverse than at any time in history. One may question whether it is possible to satisfy the needs of a growing population and the needs of developing countries while preserving the carrying capacity of our ecosystems, biological diversity, and cultural diversity.

In the next two decades, almost 2 billion additional people are expected to populate Earth, 95 percent of them in developing countries. This growth will create unprecedented demands for energy, food, land, water, transportation, materials, waste disposal, earth moving, healthcare, environmental cleanup, telecommunication, and infrastructure. Engineers will be critical in fulfilling those demands since most of the growth will take place in large urban areas of the developing world. Today it is estimated that up to 2 billion people live in some type of city slum, and the urban share of the world's extreme poverty is about 25 percent. If engineers are not ready to fulfill the demands of the developing world, who will?

It can take as much as 10 years for a new U.S. engineering graduate to become an engineering manager. Therefore, current graduates will be called upon to make decisions in a sociogeopolitical environment quite different from that of today. In addition to having strong technical skills, tomorrow's engineers will need to be facilitators of sustainable development, reconstruction, and of social, cultural, and economic changes.

The engineering profession must begin preparing younger engineers to address the needs of the most destitute people on our planet. Problems include water provisioning and purification, sanitation, power production, shelter, site planning, infrastructure, food production and distribution, and communication, among many others. An estimated 20 percent of the world's population lacks clean water, 40 percent lacks adequate sanitation, and 20 percent lacks adequate housing.

It is clear that there is a demand for educating a new generation of engineers who can better meet the challenges and needs of the developing world. The challenge is to educate engineers who (1) have the skills and tools appropriate to address the issues that our planet is facing today and is likely to face in the next 20 years; (2) are aware of the needs of the developing world; and (3) can contribute to the relief of the endemic problems afflicting developing communities worldwide.

continued

SIDEBAR 4.2 Continued

Meeting the Challenge

Since 2001, Engineers Without Borders–USA (EWB-USA) has been working toward meeting the aforementioned challenges. EWB-USA is dedicated to helping disadvantaged communities improve their quality of life by implementing environmentally and economically sustainable engineering projects, while developing internationally responsible engineering students. Projects are initiated by, and completed with, contributions from the host communities, which are then trained to operate the implemented engineering solutions without external assistance.

All EWB-USA projects are carried out by groups of engineering students under the supervision of professional engineers and faculty. The students select a project and go through all phases of conceptual design, analysis, and construction during the school year; implementation is done during academic breaks and summer months. By involving students in all steps of the projects and through experiential learning, students become more aware of the social, economic, environmental, political, ethical, and cultural impacts of engineering projects.

Currently, EWB-USA has about 50 engineering projects in 22 countries. In 2003 alone, more than 50 students from various U.S. schools and 20 professionals were involved in projects in Mali, Mauritania, Senegal, Thailand, Haiti, Belize, Nicaragua, Afghanistan, and Peru. Project description reports can be found at http://www.ewb-usa.org (project pages). All projects are reviewed for quality control by teams of professional engineers before being accepted. EWB-USA has 1,000 members with 69 percent from academia (students and faculty) and 31 percent from practice. EWB-USA is also developing strong collaboration with engineering societies and organizations such as the American Society of Civil Engineers, American Society of Mechanical Engineers, National Society of Professional Engineers, World Federation of Engineering Organizations, and the Association of Soil and Foundation Engineers (ASFE).

Clearly, engineers have a collective responsibility to work toward meeting the Millennium Development Goals set by the United Nations General Assembly (UN, 2000). Appropriate and sustainable solutions are needed to meet the basic needs of all humans for water, sanitation, food, health, and energy while protecting cultural and natural diversity. Improving the lives of the 5 billion poor people whose main concern is staying alive each day is no longer an option for the engineering profession; it is an obligation.

EWB-USA and its partner organizations present many opportunities for professional engineers to become intimately involved in engineering education through projects in developing communities around the world (including the United States). It provides an innovative way to educate young engineers interested in addressing more specifically the problems faced by developing countries and communities.

SIDEBAR 4.3
Breaking New Ground: Mining, Minerals, and Sustainable Development

A two-year project undertaken by the International Institute for Environment and Development (IIED) and commissioned by the World Business Council for Sustainable Development (WBCSD), *Breaking New Ground: Mining, Minerals, and Sustainable Development*, sought to identify the challenges faced by the mining and minerals sector in contributing to global sustainable development. It lays out a vision for the sector to provide mineral services that will leave a community better off than when a mining project began.

Breaking New Ground begins with the idea that simply meeting market demand for mining and minerals is not a sufficient goal for the industry; it should instead strive to maximize its contribution to sustainable development to the benefit of both the industry and the global community. At the outset the report notes that the mining and minerals industry has one of the worst reputations of any industrial sector, especially in terms of environmental impact and human and local community rights, and "is seen as failing in its obligations and is increasingly unwelcome."

Starting in April 2000, IIED project teams in London, in concert with teams in the four key regions of southern Africa, South America, Australia, and North America, worked to meet four broad objectives:

1. To assess the global mining and minerals sector in terms of the transition to sustainable development;
2. To identify how the services provided through the minerals supply chain can be delivered in ways that support sustainable development;
3. To propose key elements for improving the minerals system; and
4. To build platforms of analysis and engagement for ongoing communication and networking among all stakeholders in the sector.

The Mining, Minerals, and Sustainability Project (MMSD) defines the goal of sustainable development as "integrating economic activity with environmental integrity, social concerns, and effective governance systems." The two-year research and consultation projects of MMSD identified a collection of challenges to sustainable development that the minerals sector faces that include viability of the minerals industry; control, use, and management of land; mining, minerals, and the environment; and local communities and mines.

The report outlines four major categories of actions that can be taken to integrate many of its suggestions on how to support sustainable development in the minerals sector:

continued

SIDEBAR 4.3 Continued

1. Increase understanding of sustainable development;
2. Create organizational-level policies and management systems for implementing the principles of sustainable development;
3. Collaborate with others with common interests to take joint steps toward sustainable development; and
4. Increase our ability to work toward sustainable development at the local, national, and global levels.

Groups affected by initiatives of integrating mining and sustainable development include policy makers, business leaders, public interest campaigners, people working in mines, local communities, and consumers. *Breaking New Ground* stresses that implementing sustainable development solutions can help reverse the minerals industry's checkered legacy, which will enable the industry to move forward with greater trust from the communities in which it operates. All parties, from consumers to business leaders, will benefit socially and economically. In addition to addressing a negative legacy, the report calls for other specific actions, including:

- An industry protocol for sustainable development;
- Supporting the legalization of artisanal and small-scale mining;
- Integrated management of the full minerals chain (exploration, extraction, smelting, refining, fabricating, manufacturing, use, reuse, recycling, and disposal, where applicable);
- More effective government management of minerals investment; and
- A more equitable international trade regime for minerals.

As a result of the North American Regional Process of MMSD, an approach was developed to test the sustainability of the contributions of mining and minerals activities (IISD, 2002a). A multi-stakeholder work group was asked to

> "collaboratively develop a set of practical principles, criteria, and indicators that can be used to guide or test the design, operation, and monitoring of performance of individual, existing or proposed, operations in terms of their compatibility with concepts of sustainability" (IISD, 2002b).

The seven questions that were formulated have much wider applications than just mining and minerals activities. They can also be applied to all development projects that have local and regional social, environmental, and economic impacts. From the seven questions comes a hierarchy of objectives, indicators, and metrics. Simultaneously, the starting point for assessing the degree of progress is provided by an "ideal answer" to the initial question. The seven questions are:

1. **Engagement.** Are engagement processes in place and working effectively?
2. **People (Human Well-being).** Will people's well-being be maintained or improved during and after the project or operation?
3. **Environment (Ecological Well-being).** Will the integrity of the environment be maintained or improved as a result of the project or operation?
4. **Economy (Market Economy).** Is the economic viability of the company assured; is the community and regional economy better off not only during operation but also postclosure?
5. **Traditional and Nonmarket Activities (Nonmarket Economy).** Is the viability of traditional and nonmarket activities in the community and surrounding area maintained or improved with the project or operation?
6. **Institutional Arrangements and Governance.** Are the rules, incentives, and capacities in place now and as long as required to address project or operational consequences?
7. **Synthesis and Continuous Learning (Continuous Learning and Adaptive Management).** Does a synthesis show the project to be net positive or negative for people and ecosystems? Is a system in place to repeat the assessment from time to time?

MMSD presented *Breaking New Ground* at the World Summit on Sustainable Development in Johannesburg, South Africa, at an interactive information session in August 2002. MMSD has also published four project follow-up reports that synthesize the results of their commissioned research:

1. Finding the Way Forward: How could voluntary action move mining towards sustainable development? (2002)
2. Artisanal and Small-Scale Mining: Challenges and opportunities (2003)
3. Room to Manoeuvre? Mining, biodiversity and protected areas (2003)
4. Finding Common Ground: Indigenous people and their association with the mining sector (2003)

Breaking New Ground and the other outputs of the MMSD project can be viewed at http://www.iied.org/mmsd/.

4.2 EARTH SYSTEMS ENGINEERING

We are increasingly aware that we are living in a tightly integrated Earth system where anthropogenic activities have a noticeable, and even dominant, effect on the planet. Accumulations of local activities have an effect on the large-scale behavior, and there are no isolated activities. The recognition of the importance of these phenomena has led the Earth science community to identify a new discipline: Earth Systems Science (ESS). ESS links the biosphere (all life on Earth), geosphere (the rocks, soil, water, and atmosphere of Earth), and anthrosphere (political, economic, and social systems) in order to understand and predict the behavior of Earth systems. From the engineering perspective, each design decision may have systems consequences in other parts of the world, and sometimes these consequences are large, sudden, and unanticipated. Geoengineers need to understand and appreciate the natural interrelationships that tie Earth systems together, and the feedback that is inherent in these systems. As Sarewitz (NAE, 2002) points out, it is a mistake to consider these problems only as scientific issues in which action depends only on gaining fundamental knowledge. Rather, as Sarewitz continues, owing to their global importance we would do better to consider these issues as engineering challenges.

The increasing importance of sustainable development, including the growing recognition that the quality of our engineering directly affects the quality of society and the lives of future generations—combined with the recognition that many engineering decisions cannot (or at least should not) be made independent of the context of the surrounding social systems—has lead to the emergence of ESE as a corollary to ESS. ESE was described by William A. Wulf, president of the National Academy of Engineering (NAE, 2002), as “an emerging multidisciplinary area based upon a holistic view of the interactions between natural and human systems. ESE addresses global, complex, multiscale, multicycle phenomenon, such as climate change, as well as problems of global importance such as urban design.” ESE is the tool, or collection of tools, for helping to achieve sustainable development on regional and global scales, and geoengineering is an essential component of ESE. Sustainable development is the engineering objective driving the development of ESE. Whereas ESS seeks to understand and predict, ESE seeks to understand and manage Earth systems problems.

Every year, the National Academy of Engineering hosts a public symposium at its annual meeting on a topic it considers crucial to the national welfare. ESE was chosen as the topic for the 2000 symposium in recognition of its importance. John Gibbons, chair of the NAE Technical Symposium on Earth Systems Engineering in 2000 (NAE, 2002), states that "the goals of ESE are to understand the complex interactions among natural and human systems, to predict and monitor more accurately the impacts of engineered systems, and to optimize these systems to provide maximum benefits for people and for the planet." Because of its focus on the behavior of natural systems (and the impact of human activities on these systems), geoengineering plays an important role in the development of ESE. In fact, with training in both geological science and engineering mechanics and with a civil engineering sensitivity and responsiveness to the needs and demands of society, geoengineers are well positioned to take a lead role in developing ESE.

Geoengineering roles in infrastructure development and rehabilitation, environmental remediation and waste management, and natural resource development are all essential to the development of ESE. However, traditional geotechnical engineering generally considers only the relatively local direct engineering impacts of these activities. ESE demands consideration of the impact of these activities not only on a local scale but also on regional and global scales, as well as in terms of both direct engineering consequences and indirect social and socioeconomic consequences.

Speaking of ESE, Gibbons notes that "many of the science, engineering, and ethical tools we need to meet this enormous challenge have yet to be developed." While many tools are available for the assessment of the response of individual Earth systems on local scales, there is still a critical need for development of new and improved models for the physical behavior of Earth systems components. Basic research is needed at the level of individual soil particle interactions (e.g., research on the erodability of soils). On regional and global scales, assessment of impacts will require application of advanced technologies in sensing, systems modeling, and information technology (e.g., satellite-based remote sensing, three-dimensional relational data models). Corresponding advances will be required in the understanding of our social (human) systems and their interactions with natural systems. Furthermore, the uncertainties associated with predicting the regional and global impacts of technologies mandate application of adaptive management techniques (i.e., the observational method) in ESE (see Sidebar 4.4). No other discipline is better positioned than geoengineering to undertake many of the engineering challenges of ESE.

4.3 GEOENGINEERING FOR EARTH SYSTEMS

We agree with the importance attached to ESE by the NAE and see the emergence of a new metadiscipline of GES as a subset of ESE. We define GES broadly as the integration of all disciplines related to geoengineering for earth systems, at all scales. Our definition therefore includes (1) microscale phenomena that affect bonding, conduction phenomena, and other particle-level interactions; (2) the midscale behavior of particle assemblages, including shear strength, dispersion of contaminants in Earth materials, erodability, and hydraulic conductivity; (3) macroscale behavior, such as slope stability and surface water infiltration; (4) megascale phenomena such as regional sediment transport and groundwater aquifer recharge; and (5) engineering required for mitigation on global climate change.

GES encompasses all of the seven areas where geotechnology contribute to national needs identified in Chapter 2: (1) Waste management (and environmental protection); (2) infrastructure development and rehabilitation; (3) construction efficiency and innovation; (4) national security; (5) resource discovery and recovery; (6) mitigation of natural hazards; and (7) frontier development and exploration. However, by definition and by necessity the GES perspective on these issues is a global systems perspective.

SIDEBAR 4.4
The Observational Method and Adaptive Management

The observational method describes a risk-based approach to geoengineering that employs adaptive management, including advanced monitoring and measurement techniques, to substantially reduce costs while protecting capital investment, human health, and the environment. Development of the observational method in geoengineering is generally attributed to Terzaghi (Casagrande, 1965; Peck, 1969). The method consists of the following steps (Peck, 1969):

- Assess probable and adverse outcomes;
- Establish key parameters for observation;
- Calculate observational parameters under probable and adverse conditions;
- Measure observational parameters and compare to calculations;
- Compare predicted and measured parameters; and
- Change the design as needed.

The observational method has several caveats. One must be able to define an action plan for every conceivable adverse condition. The method cannot be used if you cannot develop a predictive model for the behavior (i.e., you must have a model that can calculate the parameters you will subsequently observe). You must be able to monitor the parameters you can predict. This is not a trivial problem as often we can measure what we cannot calculate and vice versa. This means that the monitoring plan must be chosen very carefully with a good understanding of the significance to the problem. Mistaken preconceptions about the dominant phenomena that control system behavior can lead to choosing irrelevant observational parameters and cause the method to fail.

Casagrande (1965) described limitations to the use of the observational method in his classic geotechnical paper on "The Role of the Calculated Risk in Earthwork Engineering." Casagrande postulated that risks inherent to geotechnical practice include engineering risks and human risks, calculated risks and unknown risks, and voluntary risks and involuntary risks. Calculated risks are risks based on uncertainties associated with engineering analyses of known phenomena. Casagrande called for the use of the observational approach (i.e., an adaptive management method employing instrumentation and monitoring) to manage calculated risks.

The observational approach is also embodied in what is sometimes referred to as "adaptive management," or "staging," approaches to complex engineering problems. Like the observational method, adaptive management is designed to be used on problems where it is not possible to definitively predict the outcome of engineering choices because the system is too complex, the processes are not well enough designed, or the systems cannot be characterized adequately. The use of adaptive management to deal with a seemingly intractable geoenvironmental problem is discussed with respect to the Yucca Mountain Project in the NRC report *One Step at a Time* (NRC, 2003c). The method is most applicable when the project is one of a kind, the methods and the outcomes are controversial, and the consequences of the project will take a long time to evolve.

The committee believes that the geoengineering community faces at once a challenge and an opportunity to participate and lead in initiatives that can reconcile the often conflicting demands of GES. Efforts are needed to understand these complex systems and successfully manage human interaction with Earth's environment.

4.4 GEOENGINEERING FOR AN EARTH SYSTEMS INITIATIVE

The Geotechnical and Geohazards Program in the National Science Foundation (NSF) is advantageously positioned to play a major role in developing a major initiative in ESE with a large component for GES. An ESE or GES initiative should reflect the breadth of the issues involved and

- encompass efforts from the nano- and microscale behavior of geomaterials to the global scale;
- include data collection, management, interpretation, analysis, and visualization;
- include the development of geosystems models, place-specific mesoscale investigations (Harte et al., 2001), and models to support policy decisions and adaptive management of environmental problems.

A GES initiative should also help define the design equations and approaches for Earth systems and their interactions in an effort to develop systematic new approaches to these problems. These points are discussed below.

4.4.1 The Scope of a GES Initiative

It is not possible to list every problem that could be included in a GES initiative, but it is possible to describe the scope generally and to point to a few important areas. A GES initiative should include any research problem that (1) involves geotechnology, and (2) has Earth system implications or exists in an Earth system context. In this regard, Earth systems have components that depend on each other (i.e., the outcome of one part of the problem affects the process in another part of the problem). There are feedback loops and perhaps dynamical interactions. The parts of an Earth system come from the biosphere (all life on Earth), geosphere (the rocks, soil, water, and atmosphere of Earth) and anthrosphere (political, economic, and social systems) as well as individual components in these spheres.

ESE problems are large in scope, have long-term consequences, and are clearly appropriate subjects for research. However, beyond the issues discussed below, NSF should be open to proposals that identify additional ESE issues.

The first problem is energy. Over the last hundred years, population growth and industrialization, coupled with the availability of inexpensive fossil fuel has increased the concentration of carbon dioxide in the atmosphere by nearly 30 percent. Global climate change is occurring and there is a consistent interpretation that the magnitude of the change cannot be explained without including anthropogenic effects (Mitchell et al., 2001; Santer et al., 2003, 2004). Figure 4.1 shows the carbon dioxide concentrations over the last 100 years compared to the mean temperature of Earth.

Two distinct energy problems must be solved. First, we have the legacy of the last 100 years of energy use. Second, we have to reach a future where emission-free energy is available in sufficient quantity to allow the work of the world's economies to be done. Both these imperatives are Earth system problems with important geoengineering components.

The legacy problem includes dealing with the effects of greenhouse gases that are currently in our atmosphere and will remain on the order of 100 years, even if we could stop producing greenhouse gas emissions today (IPCC, 2001). Some key areas with geoengineering components will include

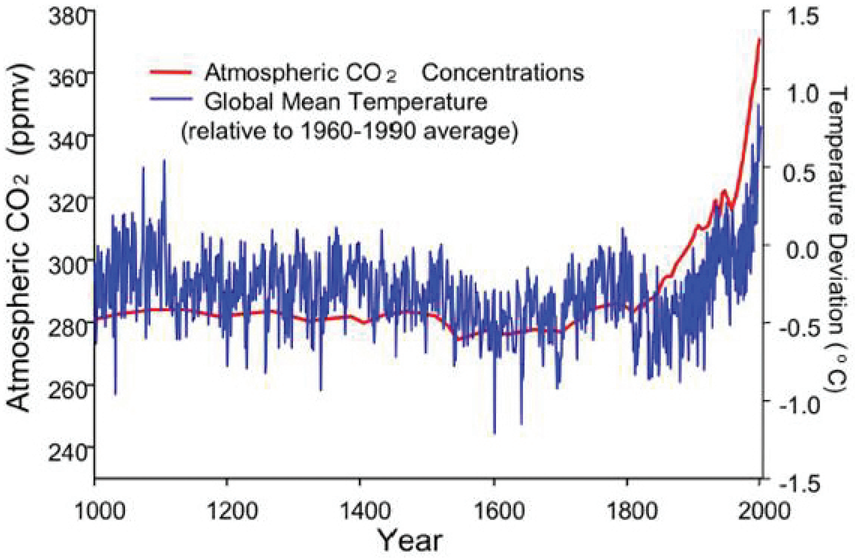


FIGURE 4.1 Increased CO_2 emissions causing a rise in atmospheric CO_2 associated with a rise in global temperature (SOURCES: CO_2 data from Ethridge et al. (2001) and Keeling and Whorf (2002). Temperature data from Jones et al. (1998) and Peterson and Vose (1997). Image from DOE, 2003a.

- Carbon sequestration: Can we find ways to inject CO_2 in the underground safely and economically and in sufficient quantities to make a difference? (Ten gigatons per year must be sequestered to stop emissions with the current energy-use pattern [see Caldeira et al., 2003].)
- Water supply: Extreme weather patterns due to climate change are stressing an already stressed water supply problem in the world. Large populations exist where water supplies are low and water tables are dropping. Creative water conservation methods need to be developed (e.g., soil modification to reduce irrigation demand). Aquifer management is critical as well.
- Natural hazard mitigation, particularly in urban environments: Extreme weather patterns also result from climate change and create greater hazards from flooding and landslides.

The future supply of emission-free energy is a grand challenge that is perhaps the ultimate systems problem. Solar radiation, Earth's geothermal capacity, and tidal energy theoretically provide many times more energy than will be needed in the next 100 years (http://smalley.rice.edu and Caldeira et al., 2003). However, the use of these energy sources is not now economical. Policy and economics will play a huge role in transitioning to an emission-free energy portfolio. Geoengineering will have a role in making these technologies more ubiquitously and economically available while not creating any new environmental problems. Geothermal energy is perhaps the best example of a geoengineering problem where the issues include finding new, hidden geothermal reservoirs with sufficient heat and fluid to be produced. The grand challenge, however, will be to find a way to use geothermal energy when the heat is present and when water or steam are not present to transfer the energy to the surface (called Enhanced Geothermal Systems). Geoengineering also has a role in the siting of wind farms, the use of tidal energy, and the appropriate use of hydropower.

A second problem with geoengineering aspects is dealing with the growth of megacities. Megacities are responsible for the largest anthropogenic affects on Earth. Heat and pollution generated by cities change the weather and draw resources (materials, air, water, and energy) from the rest of the world (Bugliarello, 1999, 2000, 2003). Risks from natural hazards are exacerbated in cities. Floods, earthquakes, volcanic eruption, and landslides all have magnified risk in areas of human concentration. The requirements for infrastructure to handle sanitation, energy, water, and transportation needs new creativity, particularly in the developing world. Beyond basic needs, cities will need to be livable spaces that are intelligently planned and agreeable to be in. These problems are not isolated engineering problems. The social, economic, and environmental aspects are daunting.

A third problem is a cross-cutting problem first clearly articulated by C. P. Snow in *The Two Cultures* (1959). If we are to succeed in ESE, the sciences and engineering will need to successfully interact with the social and political worlds. The implementation of any grand schemes to sequester carbon or manage the weather cannot even be conceived of without interaction and approval by society. It may well be that the economic and policy aspects of the energy problem dominate the technical problems. As Snow pointed out, these cultures do not communicate easily. NSF could address this issue directly by sponsoring institutes and workshops or by funding social scientists and physical scientists to work together.

An ESE program clearly would include biogeotechnology and we have seen in Chapter 3 a clear role for geoengineering in using biotechnology. If we are to release new bioengineered organisms to remediate waste or secure foundations, there will be significant systems implications requiring attention. What biogeoengineered systems are possible? How can we design biogeoengineering systems and how can we ensure their safety and develop social acceptability for their use? These are highly appropriate topics for a GES initiative.

The sustainability of human life on Earth is strongly affected by the sustainability of life in the developing world, which is home to most of humankind. The developing world's burgeoning population also requires and desires significant improvements in their standards of living. A GES initiative should include research to develop solutions to natural hazards, environmental degradation, energy, sanitation, water supply, and transportation problems in the developing world. These solutions will also have to be environmentally acceptable and economically possible.

These GES imperatives are not all-inclusive, but they do give an idea of the critical importance of the ESE issues that will involve geoengineering. There are many important problems involving geoengineering that affect sustainability.

4.4.2 Material Behavior and Data Compilation and Interpretation Methods

Cross-cutting the topical areas discussed above, a GES initiative should encompass efforts from the nano- and microscale behavior of geomaterials to the global scale; data collection, interpretation, analysis, and visualization; and the development of geosystem models, place-specific mesoscale investigations and models to support policy decisions and adaptive management of environmental problems.

To understand complex interactions between geomaterials and the environment and to develop efficient and effective methods to manage and control these interactions, an improved understanding of nano- and microscale behavior of soil and rock masses is required. These interactions include geochemical and biological phenomena. In fact, the committee perceives the investigation of biological interactions with soil and rock for the purpose of modification and control to be an important component of GES, with potential applications in both developed countries for infrastructure construction and rehabilitation and in the developing world as cost-effective appropriate technologies.

Enormous amounts of geographically referenced data, including geological, geotechnical, and hydrological data, will be required to understand the spatial and temporal changes of Earth systems. The GES initiative should fund research to develop databases and data models and associated applications to support meso-, macro-, and global-scale Earth systems analysis and to collect data to populate the databases.

In terms of data collection and management, a number of federal agencies are already managing components of the systems. For example, the National Aeronautics and Space Administration (NASA) and National Oceanic and Atmospheric Administration (NOAA) collect important remote sensing data that bear on integrated monitoring of a large number of Earth processes. The Department of the Interior (DOI), Department of Energy (DOE), and the Department of Agriculture (USDA) include several agencies that have primary responsibility for Earth resources (e.g., the U.S. Geological Survey, Bureau of Land Management, Fish and Wildlife Service of the U.S. National Park Service, Office of Fossil Energy of the Department of Energy, and U.S. Forest Service). Collaboration between these federal agencies in developing systems analysis approaches to geoengineering could include the following actions:

- Development of a roundtable to facilitate coordination;
- Cooperative agreements to share and jointly archive information

for pertinent databases, which should be extended to private developers as much as possible;

- Integration and coordination of data collection efforts; and
- Collaboration to develop tools specifically tailored toward ESE data needs (NASA, NOAA, Council of Europe, U.S. Bureau of Reclamation, USDA, Federal Highway Administration, DOE, and Department of Defense (DOD), including the Army Corps of Engineers).

Such coordination creates the possibility that other disciplines may join in addressing the challenges of GES, and that geoengineers will be leaders in defining the challenges not only of GES but also of many aspects of the emerging metadiscipline of ESE as well.

Modeling will play a major role in all aspects of GES. A GES initiative should include the development of systems analysis models for the problems encountered in geoengineering. The definition of the relevant Earth systems and how they interact is itself a research question. Which system components interact and how? Investigators should be encouraged to develop engineering models that recognize the hierarchy of interactions of the various components under different engineering design choices that can and should influence policy choices. This hierarchy must ultimately incorporate systems models at process, urban, regional, and global scales. These models could encompass civil infrastructure, transportation, energy and environment, mineral and water resources, air quality, climate change, waste management, and sociological and economic factors, as well as national security and defense. They could include aspects of the environment as simple as the migration and dimensions of sand dunes advancing on agricultural lands or as complex as the interaction of global carbon cycles, energy-use patterns, and climate. They will require substantial data collection, management, and processing and must include the incorporation of uncertainty.

It is likely that one of the more fruitful approaches to modeling human interaction with the environment will be on the mesoscale, that is, at a particular location where complexity is present and yet when small-scale phenomena can be identified and characterized, where the boundaries of the system are known and where hypotheses about the mesoscale behavior can be tested.

One of the critical tools for geoengineering will be a hierarchy of models that calculate the interactions of the various components under different policy and engineering design choices. These models will aspire to predict the behavior of the complex, interacting system components. Entirely new types of modeling that emphasize the interaction without losing fidelity in representing the components may be required. Models of dynamical systems, chaotic behavior, and emergent phenomena certainly have a role.

4.4.3 GES Design Approaches and Management Methods

The essence of engineering as opposed to science is the focus on design and management. In this light, the focus of an ESE or GES initiative is the eventual production of design approaches and management paradigms that address highly interactive Earth systems where anthropogenic effects play a dominant role and where the overall objective is sustainability. ESE presents a scope and complexity that has never before been addressed by engineers. In some cases, we may be able to extrapolate and modify engineering methods of the past. However, there is no accepted—or even tried—engineering methodology for problems as complex as global change. In fact, Allenby conjectured that ESE will not even be engineering in the usual sense in that it will be less management per se and more purposeful decision making (Personal communication from Brad Allenby to the committee, September 2003). The requirement for social and economic acceptability to this purposeful decision making about Earth will be profound. Many engineering projects have faced and solved what are considered the constraints imposed by the environment and social concerns with varying success. Case studies will show a wide variety of successes and failures in this regard. However, much more remains to be done to learn how to include and, as much as possible, formalize social concerns in design and to make the triple bottom line (economic, environmental, and social) the normative goal.

One of the most important geoengineering approaches to Earth systems analysis and design will be adaptive management (see Sidebar 4.4). For example, one of the largest current GES projects in the world is the rehabilitation of the Everglades. Adaptive management is a large part of this program (NRC, 2003d). In adaptive management, mitigation is designed, the outcome predicted, and then the outcome following a specific action is measured. Once the measurements are in hand, the predictions are compared to the measurement in order to determine if the engineering approach should be modified. This is philosophically much easier to describe than it is to do. In practice, it is extremely hard to know what to predict, what to measure, and how to compare these two types of quantities. NSF should invest in research to develop the techniques for integrating measurements with model predictions for adaptive management to update Earth systems models, especially for urban, regional, and global applications. This research should include the development of sustainability indicators and the use of these in evaluating the effect of engineering measures.

4.5 SUMMARY

If Chapter 3 presented an exciting vision for a new way to tackle geoengineering problems, this chapter has put those problems in a new global systems context. This new context will force geoengineers to think and act differently and to approach their work as part of a system that has social, environmental, and economic components. Geoengineers clearly have a crucial role in sustainability and ESE, which NSF, universities, and industry can begin to foster. The institutional needs required by the vision presented in Chapters 3 and 4 are described in Chapter 5.

CHAPTER FIVE

Institutional Issues for the New Agenda in Geoengineering

In previous chapters we gave an overview of the current state of geoengineering knowledge and its applications, the knowledge needs and gaps that must be addressed to advance the profession, new tools and scientific advances relevant to geoengineering, and the emerging discipline of Geoengineering for Earth Systems (GES). These topics constitute an agenda for advancing the field of geoengineering to enhance its contributions to our society in the beginning of the twenty-first century. This agenda for the field reflects recognition of both the expanded scope and complexity of the problems geoengineers must address in the future and the new and powerful tools that are available to geoengineers to address these problems.

This chapter examines some of the institutional issues that must be dealt with by the National Science Foundation (NSF), universities, and the geoengineering industry to advance this agenda and create a new vision for geoengineering. In some cases these institutions may have to change the way they do business to advance this agenda (i.e., to resolve critical knowledge gaps, advance the use of new tools in geoengineering, and expand geoengineering practice to address the complexity of current problems). This chapter first discusses how the committee believes that NSF can better foster the innovative, interdisciplinary, and cross-disciplinary work necessary to achieve these objectives. Second, this chapter considers the institutional issues associated with enhanced university support for interdisciplinary research and education relative to geoengineering. The third set of institutional issues relate to the geoengineering industry, including both private engineers and constructors and government agencies. This chapter also presents the case for development of a more diverse workforce to achieve our new vision for geoengineering.

5.1 NATIONAL SCIENCE FOUNDATION ISSUES

5.1.1 Investigator-Driven Research

The committee discussed at length the merits of sole investigator and small investigator projects versus large directed research (research initiatives) and large collaborations to accomplish research advances in geoengineering. The committee was deeply concerned about what it perceives as a continuing trend in NSF toward more foundation-directed research initiatives and away from investigator-driven research. At least in geoengineering the funds available for unsolicited investigator-driven research appear to have diminished almost to the point of disappearance. In fiscal years 2003 and 2004, the geomechanics and geohazards programs at NSF funded only 29 and 14 unsolicited proposals, respectively, with a success rate of 16.1 percent and 8.8 percent, respectively, for unsolicited proposals. This is among the lowest success rate of any program in the engineering directorate and NSF as a whole. The diminishing of resources available for unsolicited proposals is counter to the general trend of increased funds for engineering directorate research over those two years and reflects an overall trend in NSF toward foundation-directed research initiatives (e.g., sensors, nanotechnology, and biotechnology). Geoengineers should participate in these initiatives. In fact, one of the major initiatives that has drained funds from the unsolicited proposal program is the Network for Earthquake Engineering Simulation (NEES) initiative, in which geoengineers play a major role. The committee believes that the balance between directed and investigator-initiative research has become inappropriate and a larger portion of civil and mechanical systems resources must be committed to the unsolicited proposal program.

The committee believes strongly that NSF funding of research projects initiated and conducted by individual investigators and by small groups of investigators is an essential mechanism for maintaining and enhancing strength in all engineering disciplines, including geoengineering. This position is entirely in keeping with the 1987 NRC report *Directions in Engineering Research*, which states that "the very nature of engineering research is such that many long-range advances have been made only through the vision of individuals who are not allied with the mainstream of the industrial process or the current conventional wisdom. This type of research is a key to the health of the overall engineering research environment, and it is not likely to be sustained by 'trickle-down' support filtering through the large, heavily funded activities. Consequently, the Board urges that the general scheme of NSF sponsorship should continue to provide a major explicit emphasis on encouraging the individual engineering researcher, in balance with the new thrusts emphasizing cross-disciplinary research" (p. 62).

5.1.2 Interdisciplinary and Cross-Disciplinary Research

Advancing our agenda for geoengineering, particularly with respect to development of new tools and the emerging discipline of GES, clearly requires integrated, interdisciplinary problem solving. We begin with the position that funding proposals that use new tools and integrate knowledge from different scientific disciplines can maximize the likelihood of research breakthroughs. The committee also echoes the finding from the NRC report *Basic Research Opportunities in Earth Science* (NRC, 2001a) that "strict disciplinary divisions are recognized to be artificial, and an increasing number of investigator-initiated 'small science' projects span two or more disciplines" (p. 91). While various NSF programs are formulated to cross disciplinary lines, and while cross-disciplinary research is encouraged by NSF, cross-disciplinary activity does not appear explicitly as a proposal evaluation consideration. The geoengineering research agenda presented in this report will be enhanced to the extent that NSF can provide evaluation guidelines that encourage both proposers and reviewers to consider integration of knowledge and research approaches from different disciplines in proposal preparation and evaluation.

Cross-disciplinary research is also more likely to be recommended by reviewers if multidisciplinary review panels are assembled by inviting panelists from associated but nongeoengineering disciplines to join geoengineering proposal review panels. There is a perception among some committee members that cross-disciplinary work is sometimes downgraded because of a lack of understanding or the absence of an advocate for the cross-disciplinary work among panelists. Composition of cross-disciplinary panels may also create new opportunities to coordinate both panel reviews and funding with other related NSF programs. It may be beneficial to include program directors from other federal research-funding entities in panels as this could facilitate leveraging NSF program funds by cofunding research with other federal and state agencies. These enhancements to panel composition offer an added potential benefit in that NSF-funded basic research in geoengineering will become more visible to those agencies and their associated researchers, opening new doors now all but shut to geoengineering researchers. Committee members recognize the difficulties in assembling qualified panels to review proposals in a timely fashion, and thus offer these suggestions as guidelines rather than mandates.

5.1.3 Collaborative Research

It is clearly in the interest of NSF and of the geoengineering community to promote collaboration in research. The committee's perspective is that the most effective forms of sharing and collaboration grow out of personal exchanges, which can be encouraged through workshops and private investigator meetings. Organizations such as the Earthquake Engineering Research Institute, the Department of Energy, and the Department of Defense regularly organize meetings to describe current research programs and progress, and these provide a model of success. To mitigate costs the workshop could be a virtual workshop, with an abstract and presentation slides submitted electronically and published on the Internet. The committee feels that person-to-person interaction provides added value to such a workshop, and personal exchanges and research cooperation of all sorts, including sabbatical visits and research cooperation between researchers and with practitioners, should be encouraged and viewed favorably in the proposal review process.

Opportunities to build on the research of other researchers could also be improved if NSF were to set out expectations or even requirements for researchers to share their findings in a timely, accessible manner. This could include a requirement that researchers make available to other researchers their data, analytical models, and in certain circumstances, their equipment. The protocols for archiving and sharing experimental data being developed for the NEES initiative (http://www.nees.org) provide a template for such sharing of data. Specifics of data availability could be required to be spelled out in proposals, and "results of prior research" documentation could be required to indicate whether that had been achieved in previous research awards. Specifics could include, for example, dates by which data would be available, procedures for accessing results, formatting of data, and incidental or overhead costs associated with such transfers or access. NSF expectations, standardized data dictionaries and formats, and other protocols to facilitate sharing of data should be defined, including development of incentives for encouraging such exchanges and procedures for accountability.

The trade-off between large-team collaborative research, including collaboratories (see Sidebar 5.1), and small projects that might have smaller impact but lower individual funding requirements, was one of the more controversial topics in the committee's deliberations. The committee recognizes that collaboratories have proven useful in various disciplines, particularly where they enable the sharing of large, expensive, centralized equipment and facilities. Such collaboratories may also increase the visibility of the research effort and broaden public support for NSF-funded research. In fact, through both the National Geotechnical Experimentation Sites (NGES; http://www.unh.edu/nges/) and NEES, the geoengineering community has been a leader in develop-

SIDEBAR 5.1
Collaboratories

Collaboratories are a concept formally introduced at NSF in 1989 to cultivate collaborative research. The concept of co-laboratory, or collaboratory, is a laboratory without walls built upon distributed information technology. As stated in the NRC report on collaboratories, "The fusion of computers and electronic communications has the potential to enhance dramatically the output and productivity of U.S. researchers. A major step toward realizing that potential can come from combining the interests of the scientific community at large with those of the computer science and engineering community to create integrated, tool-oriented computing and communication systems to support scientific collaboration. Such systems can be called collaboratories" (NRC, 1993).

The earliest example of a shared-use collaboratory in geotechnical engineering is the National Geotechnical Experimentation Sites (NGES) program. NGES comprises six sites available to geoengineering for the purposes of large- or full-scale field testing in areas such as in situ testing, field instrumentation, prediction of soil behavior, and foundation prototype testing. The several well-characterized sites will stimulate the development and evaluation of new geotechnical tools and techniques, improve geotechnical practice and research, and promote educational opportunities. The NGES database (http://www.unh.edu/nges/) is designed to search and retrieve test site data, such as generalized soil conditions and representative soil properties; test data; site conditions and services; and published references. Creation of that database was accomplished principally through NSF funding. The database is continuously updated with data supplied by the site managers and users. Remote testing and data sharing in real time were not designed to be part of the system. Sites are maintained by individual site managers with little or no outside maintenance funding. A fee is negotiated for researchers to conduct a field test at a site. Researchers may budget for testing fees in NSF proposals.

A more recent example of a larger collaboratory, in which geoengineering at NSF has taken a leading role, is the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES), initiated in 1999. NSF notes that

> when fully operational in October 2004, the NEES program will provide an unprecedented infrastructure for research and education, consisting of networked and geographically distributed resources for experimentation, computation, model-based simulation, data management, and communication. Rather than placing all of these resources at a single location, NSF has leveraged its investment and facilitated research and education integration by distributing the shared-use equipment among nearly 20 universities throughout the United States. To insure that the nation's researchers can effectively use this equipment, equipment sites will be operated as shared-use facilities, and NEES will be implemented as a network-enabled collaboratory. As such, members of the earthquake engineering community will be able to interact with one another, access unique, next generation instruments and equipment, share data and computational resources, and retrieve information from digital libraries without regard to geographical location. (http://www.nees.org)

Features of NEES include telepresence (the ability to control and monitor an experiment from a remote location), public-access data archives that will use a common data dictionary, and provisions for piggy-backing by secondary investigators on NEES experiments, in which secondary investigators can install instrumentation packages and collect data for their own purposes on a primary experiment. In return for providing substantial funds for facility development, NSF requires that there be no fee for using NEES sites. At this stage NEES is itself an ambitious experiment in big science research that will educate the community regarding pitfalls and successes in both current and future collaboratory development and management.

ment of this collaboratory concept. However, because of the large commitment of funds required to maintain the NEES collaboratory (an annual overhead cost of approximately $20 million, much of which was diverted from other civil and mechanical systems programs, including geomechanics and geohazards), the committee was divided on whether these were positive developments in an age of limited resources for geoengineering. In fairness, it must be noted that overhead costs for the NGES sites is significantly less than for NEES and does not come entirely from NSF funds.

In light of these observations, it seems prudent for NSF to establish a set of criteria to evaluate when collaboratories are appropriate compared to other methods of fostering collaboration and to generate reports on successes and opportunities for improvements in their development. The following questions should be included when evaluating the benefits of funding investigator-driven research versus funding a collaboratory:

- Is solution of the research problem important enough to society that it merits the required funding and focused efforts of some significant portion of the research community by formation of a collaboratory?
- Is a collaboratory feasible? Do the key components already exist, such as a distributed computing infrastructure?
- Would the development of a new, complex collaboratory distract researchers from making progress on the research problem to be solved?
- Is a collaboratory an optimal way to address the research problem?
  - Is the research problem well defined at present? Research challenges and the ways to address them that are well defined are better candidates for collaboratories than ones that are emerging, with paths of research concentration that are not yet established.
  - Does the project require large, expensive, or unique equipment or facilities? If not, then institution of a collaboratory may be unnecessarily constraining.

  - Will a collaboratory lead to better and faster advances than alternative methods of collaboration at a lower cost?
  - Is the project multidisciplinary? Will it benefit from creation of large research teams drawn from different disciplines using these facilities? Will those researchers want to use the collaboratory?
- How will it affect research in the research community in general?
  - Will the collaboratory create opportunities for many investigators, or only a few?
  - Will it eliminate or substantially diminish support for other important research addressing the same research problem?
  - Will the collaboratory stimulate development and use of new tools, techniques, and improved practice?
  - Will it build capacity by creating new educational opportunities?
- How will the collaboratory be managed?
  - Is there a realistic plan for management that facilitates the research objectives? Does the plan include a vision of how to achieve effective integration of capabilities developed by other disciplines such as computer science? Does it include a realistic time schedule?
  - Is there a realistic vision of a mechanism to share and to maintain equipment, facilities, data, and results both during and after the project?
  - Will use of the collaboratory be affordable to researchers and do the operational costs justify the benefits?

NSF has an opportunity to advance the development of new tools, including both laboratory devices and sensors, essential to realizing our agenda for geoengineering. One way to accelerate this process would be to include both the developer of the device and participants from the user community on projects for developing new tools. For example, a sensor developer working in isolation from potential users increases the probability that an innovation in sensor technology will go unused and that the needs of experimentalists and practitioners may go unmet. While recognizing that the role of NSF is basic, rather than applied research, panel members felt that NSF should include collaboration between new tool developers and tool users as a discriminating criterion in proposal evaluation. This collaboration could extend beyond the pure development phase into actual application and testing, whether funded by NSF or some other entity.

5.2 UNIVERSITIES

5.2.1 New Approaches to Geoengineering Education

The challenges the geoengineering profession faces in reforming geoengineering education should not be underestimated. The best and brightest students will be attracted to areas of science and engineering where they believe they can make new discoveries and inventions. Increasing the breadth of disciplines integrated into geoengineering education at both the undergraduate and graduate levels will be an important first step in attracting top students to the field. The profession also needs to work through education to "aspire to a future where engineers are prepared to adapt to changes in global forces and trends and to ethically assist the world in creating a balance in the standard of living for developing and developed countries alike" (NRC, 2004c). For this to be achievable there must be greater flexibility in engineering education that engages previously untapped populations of university students. Educational expectations have changed for both the new postsecondary school attendees and the traditional college attendees and the engineering profession and engineering educators should capitalize on these expectations.

At the undergraduate level, issues surrounding changes in curriculum are complex. The report *The Engineer of 2020: Visions of Engineering in the New Century* (NAE, 2004) states that the expanding role of engineers in dealing with more complex problems requires additions to an already full curriculum:

> The options would seem to be: (a) cutting out some of the current requirements, (b) restructuring current courses to teach them much more efficiently, or (c) increasing time spent in school to become an engineering professional. All three may need to be done to some extent, but it is worth noting that all professions except engineering—business, law, medicine—presume that the bachelor's degree is preceded by a nonspecialist liberal arts degree, so it is also not clear that just adding two years or so to a traditional engineering B.S. degree will raise engineers to the professional status of managers, lawyers, and doctors. Nonetheless, while it cannot be mandated instantly and could require radical restructuring of the present approach to engineering education, by 2020 engineering could well follow the course of the other professions. Doing so may be part of the competitive advantage of U.S. engineers. (NAE, 2004, p. 41)

This sentiment is not out of line with the current movement in the profession to recognize the master's degree as the first professional degree. In the geoengineering field this is already recognized de facto in most parts of the country. Despite the American Society of Civil Engineer's (ASCE) recent endorsement of this concept, this remains a controversial topic, with many civil engineers, particularly in the municipal sector, opposed to it.

Students who begin their undergraduate programs without a commitment to study engineering already in place or who are reluctant to forego the intellectual excitement and freedom of a general education are at present simply dismissing engineering as a career choice. The options adopted by the architecture profession (see Sidebar 5.2) present one possible model to offer different paths to professional practice in engineering. Expansion of options that engage the most educated portion of the population, a portion that is both inclined and trained to think across disciplines, is encouraged. The profession can also benefit from the influx of more mature and potentially more broadly educated students. This can be attractive in particular to women and underrepresented minorities who are more likely to choose engineering later in their academic careers.

SIDEBAR 5.2
Paths to Professional Practice in Architecture

In the United States there are three usual educational avenues through which one may approach professional registration and practice as an architect. These include a bachelor of architecture degree, typically a five-year program; a two-year master of architecture degree, which is designed for those students who possess a bachelor of science in architecture degree (distinct from the bachelor of architecture degree); and a three to three-and-one-half year master of architecture degree, which is designed for those students who possess a baccalaureate degree in a discipline other than architecture. The emphasis in these three degrees is preparation for professional practice and registration. Students who know as they begin their undergraduate educations that they wish to practice architecture are provided with a clear, and highly focused, five-year educational path to professional practice in the bachelor of architecture program, although it is frequently the case that even these students still plan to complete a program of study that includes a master of architecture degree. Students with different academic and life backgrounds, arriving at the decision to begin architectural training at later stages in their lives, are readily accommodated by this system, and their other degrees are respected by this system; students are not required to forego the freedom of a liberal arts and science undergraduate education as they emerge from high school.

In addition to these architecture degrees, there are two other, nonpractice degrees. The bachelor of arts in architecture degree and the bachelor of science in architecture degree are designed to familiarize students with architecture but do not train them for registration and practice. These students may choose to continue on to graduate studies in architecture, but students who do not intend to practice architecture may nonetheless undertake undergraduate study in architecture that they can use as a foundation for other careers. The benefit of this system to the profession is that architecturally inclined students who choose not to practice as architects can carry into their other professional lives both an understanding and an appreciation of the discipline.

Innovation in the undergraduate curriculum even in the traditional four-year undergraduate program faces impediments to implementing change. In 2000, the Accreditation Board for Engineering and Technology (ABET, 2000) asked that engineering programs specify their own goals and objectives and provide evidence that they were continually improving their attempts to meet these goals. Accreditation of engineering programs is jointly managed by ABET and traditional professional societies, for example, by the American Society of Civil Engineers for geotechnical engineering and the Society for Mining Metallurgy and Exploration for geological engineering. These two participants in accreditation are designed to complement each other, but they also conflict in that engineering programs need both to define themselves to meet the ABET standards and to fulfill prescriptive requirements to satisfy the professional societies. Although the recently completed American Society of Civil Engineers report *Body of Knowledge* (ASCE, 2004b) addresses undergraduate curriculum, it is still developed in the context of a traditional four-year undergraduate program.

It is beyond the scope of this report to address accreditation problems in engineering. However, NSF is encouraged to keep opportunities open for experiments in education, beginning with convening roundtables to generate truly innovative concepts. NSF could also work to support interdisciplinary undergraduate programs much as they do graduate programs with the Integration Graduate Education and Research Traineeship and might consider developing an Interdisciplinary Undergraduate Engineering Education program. A number of universities have general engineering degrees that are accredited by ABET but are not required to satisfy the special criteria determined by professional societies. Most universities consider this a less desirable degree, but it may well be the easiest path to achieving truly interdisciplinary education and become a much more valuable degree.

Transitioning undergraduates in their thinking from learning textbook material to beginning to ask and answer unsolved questions is encouraged already through undergraduate research opportunities supported by most institutions, although not required of all students.

Research Experiences for Undergraduates, among other NSF programs, has played an important role in facilitating that connection. The Engineers Without Borders program is another way to cultivate new approaches to engineering, in addition to developing appreciation of the critical importance of sustainability in engineering design. New and innovative approaches are required to make geoengineering more enticing and more accessible to students.

5.2.2 Interdisciplinary Studies

In the last 20 years or so, many university faculty members have recognized that solving the high-level problems we face requires more than a single traditional discipline, however most interdisciplinary efforts have been ad hoc arrangements. These ad hoc arrangements often carry with them problems associated with financial and scholarly credit for the resulting research. Junior faculty members attempting to cross disciplinary boundaries run the risk of lack of recognition for their efforts and contributions, while university financial systems are often not set up to properly account for shared overhead for laboratory facilities.

To address the agenda for geoengineering we have laid out, it is important for universities to find ways to go beyond traditional and ad hoc arrangements for interdisciplinary research. It may be fairly straightforward for a civil engineering department to grant a Ph.D. degree to a candidate who has discovered a way to use microbiology to remediate a contaminated site. It may require more imaginative innovation to create a program that can accommodate students crossing traditionally less compatible disciplines, for example, a Ph.D. program in Earth Systems Engineering (ESE) that requires integration of policy, economics, and engineering to address a problem of renewing infrastructure in urban environments. These programs also have the potential to attract different sorts of students: students who are interested in pursuing engineering science in their careers but will not practice engineering; and students who are interested in engineering as a first degree but who will choose nonengineering degrees for a second degree.

5.3 INDUSTRY'S ROLE

There are two issues related to the role of industry in meeting the challenges of advancing the state of the practice in geoengineering. The first issue is that the current state of the practice does not match the current states of knowledge and understanding. The second issue is that industry, in general, does not play a very active role in advancing either the state of practice (at least from a technological viewpoint) or the states of knowledge and understanding. There are several seemingly simple and straightforward measures that can address these issues, but institutional inertia and a perceived lack of economic benefit create powerful barriers to implementation. For instance, continuing education plays an important role in facilitating the incorporation of new knowledge and technology into practice, thereby closing the gap between the state of the practice and the states of knowledge and understanding. Because they fail to perceive any economic benefit for their firms, many employers are reluctant to pay the total cost of continuing education for their employees, including both the direct cost of registering for courses and workshops and indirect costs associated with release time from work, travel, and other associated expenses. In the absence of any regulatory mandate for continuing registration (e.g., in order to renew a professional license), many employers will continue to resist paying for continuing education until it becomes an economic imperative. Professional societies can play an important role in establishing this imperative by continuing to lobby for such best practices as qualifications-based selection (QBS) for engineering services as well as mandatory continuing education for license renewal. ASCE Manual 45, which provides recommendations for QBS for engineering services, is one example of the role professional societies can play in advancing the field (ASCE, 2003). Other important initiatives that professional societies like ASCE, Association of Soil and Foundation Engineers, and American Rock Mechanics Association can use to help close the gap between the state of knowledge and the state of practice include the use of quality criteria in awarding construction contracts and peer review and value engineering design practices.

Geoengineering professionals must also demonstrate the advantages of employing state-of-the-knowledge technologies to their colleagues, employers, and clients.

The support and active engagement of the geoengineering industry, including engineering consulting firms, contractors, municipal agencies, professional societies, and other stakeholders is also essential to continued advancement of the state of knowledge of geoengineering and fulfilling our vision for the future of geoengineering in ESE. Industry must actively endorse the value of geoengineering research from a total life-cycle cost perspective and embrace application of new tools developed in geoengineering research. If industry does not embrace the new tools developed by researchers, their efforts will be wasted. GES, by its very nature a hybrid of public policy and technical analysis, requires the support of the geoindustry. However, there are long-standing structural and cultural barriers that impact the ability of industry to embrace the new agenda. Traditional design-bid-build contractual arrangements are widely acknowledged as a barrier to innovation, particularly in public works contracting that makes up the largest segment of the civil construction industry, and geoengineers are often unable to participate fully in newer design-build and build-operate-transfer arrangements. Many engineers still embrace the ethic that their job is not to influence public policy directly but merely to provide impartial analysis and present the facts and let the decision makers guide the course of public policy.

Because NSF's role is to fund basic research and innovations but not necessarily the implementation of new technologies, industry must be relied upon to bridge the gap between technology development and its implementation. Implementation of new technology often requires research and development in its own right, and spending on applied research by the geoindustry in the United States lags behind many other industrialized countries, due in large part to the failure of the industry to perceive any benefit from funding the research. One role NSF can potentially play in furthering the implementation of new technologies in geoengineering is by funding studies that demonstrate the direct and indirect benefits of the application of advanced technology in geoengineering.

Specialty contractors have been a significant source of industry support for research and technology innovation in the United States. While specialty contractors have been a source of several important developments in geoengineering practice, commercial imperatives understandably tend to focus contractor-funded research and development on the downstream end of the process (i.e., on ready-to-be-commercialized processes). Midstream technological developments that do not have readily apparent commercial advantages, such as advanced methods for site characterization, and wider noncommercial applications, such as satellite-based monitoring of landslide activity, are typically not funded by this sector of industry. Even with respect to commercially viable innovation in geoengineering, the United States lags behind Europe and Asia in research and development of new technology.

Financial support for geoengineering research and development from the engineering design and consulting sectors of U.S. geoengineering industry is at best insignificant. This subject has been discussed at length in recent years in panel discussions at conferences (e.g., at the recent Pan American Soil Mechanics Conference in Boston in 2003) and in professional journal papers (Goodings and Ketcham, 2001). The consensus seems to be that financial pressures on consulting firms forced to compete for work on a low-bid basis and the design-bid-build contractual arrangements, wherein risks associated with a failed design innovation are passed on to the innovator without commensurate reward for success, are the primary hindrances to innovation under this contractual arrangement.

In design-bid schemes the designer and constructor are separate entities with sometimes conflicting interests. A different model is used in Europe and Japan, where the designer and constructor are often the same entity. There is now a trend toward more design-build and build-operate-transfer arrangements in the United States as a means of encouraging innovation. While this trend has met with some notable success, it is still prohibited by law for many public works and infrastructure development projects, requiring special enabling legislation to use this approach (see Sidebar 2.4), and geoengineers are often not in a position to capitalize on their innovation or assumption of risk by virtue of their role as an owner's representative at the initiation of a project or because they do not have a direct financial interest in the project. Thus, a geoengineer who comes up with an innovative means of supporting an excavation or constructing a foundation that saves an owner millions of dollars may have had to assume all the risk associated with its implementation and may be rewarded solely with a thank-you and an invitation to bid competitively on the next project. For this reason geoengineers who do come up with innovations invariably form construction firms to capitalize on their commercial potential.

Significant structural changes in the way risks and rewards are shared by innovators, constructors, and owners are required to spur innovation in geoengineering industry in the United States. The logical agents for such changes are the professional societies that represent the geoengineering community (e.g., ASCE and its Geo-Institute, American Rock Mechanics Association, Deep Foundations Institute, and the Association of Soil and Foundation Engineers). NSF can facilitate these changes by funding studies and workshops on barriers to innovation and by leveraging research funds to engage design and consulting engineers in geoengineering research and development projects. These societies themselves must all become advocates for changes that are required to spur research and innovation in geoengineering practice. The committee urges ASCE to coordinate this important effort and for practitioners to press them to do so.

Traditionally, most industry-supported geoengineering research in the United States has been through public and quasi-public entities, including the U.S Army Corps of Engineers, Federal Highway Administration, Transportation Research Board (through the National Cooperative Highway Research Program), and various state transportation departments. However, many of these agencies, faced with decreasing budgets and an increasing backlog of projects, have dramatically reduced their research and development efforts. For instance, the U.S. Army Corps of Engineers Waterways Experiment Station in Vicksburg, Mississippi, once a key source of funding for geoengineering research on infrastructure development projects through the Casagrande Geotechnical Laboratory, has essentially eliminated all external sponsored research in geoengineering, cut back internal research in geoengineering, and now must seek funding from other sources (e.g., the Environmental Protection Agency) to sustain some of its staff and facilities.

The mineral extraction industry is a major end user of geotechnology, but its involvement in geoengineering research has been restricted to development of equipment and technology for the sole purpose of reducing the cost of mineral extraction. The increased emphasis on sustainable mining (see Sidebar 4.3), along with lingering environmental issues associated with past practices, may make the mineral extraction industry more amenable to supporting broader geoengineering research initiatives. The geoengineering community must find a way to engage the extractive industries in broad research relevant to their concerns.

Public agency support for research and development becomes all the more important in noncommercial activities, such as GES, which have no direct financial benefit. Support for geoengineering research on regional and global environment issues is more a public policy issue than a commercial issue (as opposed to support for geoengineering research on infrastructure construction). In fact, the essence of ESE, of which GES is a component, is the marriage of public policy with environmental science and engineering technology. Thus, for the vision of ESE to become a reality, engineers must become engaged in public policy debates on regional and global environmental issues. Once again, the professional societies that represent the geoengineering community must play an important role in engaging geoengineers in these debates and mobilizing support for geoengineering research in ESE and sustainable development.

The Earthquake Engineering Research Institute (EERI) provides perhaps the best example of how a professional society can influence public policy and mobilize support for investment in research and development. EERI played an essential role in the creation and reauthorization of the National Earthquake Hazard Reduction Program (NEHRP), a primary means of support for earthquake engineering research for over 20 years, and in the allocation by Congress of $88 million for initial funding of the NEES program. EERI and NEHRP include social scientists as well as engineers and focus on societal issues of response, recovery, disaster planning, and community resilience, as well as hard engineering technology and geological science issues. The success of EERI and associated societies (e.g., the Geological Society of America) in mobilizing public support for earthquake engineering research and hazard mitigation efforts is a model for both integration of technology and public policy and for mobilization of public support for research and development.

There are also some excellent models for integrating research with practice in traditional infrastructure development. U.S. transportation research infrastructure serves as one impressive example of a successful model. One important component of this model is the National Academies' Transportation Research Board, which creates in its annual meetings opportunities to focus on research and its implementation in practice. In these meetings practitioners can define their engineering challenges in terms that make sense to researchers, and at the same time researchers can come to appreciate the practical constraints practitioners face in implementing research. After the development of research ideas, and ideally of research partnerships, there must be a follow-up in the form of research funding. The American Association of State Highway and Transportation Officials and the National Cooperative Highway Research Program define and fund research programs that are developed from these forums. Transportation research is also conducted by 33 university transportation centers created by the 1998 passage of the Transportation Equity Act for the Twenty-first Century. These centers, 23 of which are earmarked for funding in the bill and 10 of which are awarded competitively, are eligible for up to $500,000 per year in federal funding provided matching funds can be raised for the proposed transportation research. In this way the research conducted is dictated largely by the sponsor providing the matching funds, which is typically a state department of transportation. The Federal Highway Administration has in the past funded geotechnical-practice-oriented research at its discretion.

Key to the continued advancement of geoengineering through research and development is a substantial and continuing commitment of funding. This requires both maintenance of existing sources of funding, which are primarily through government agencies, and development of new sources of funding in both government and industry. With respect to government funding, engineers must be involved in public policy decisions if they are to influence the allocation of funds for geoengineering research. The professional societies may be the most effective agents for engineers to make themselves heard in this respect. However, broad recognition by both researchers and practitioners of the importance of the need to engage in public policy debates and influence funding decisions is equally key to a solution. The professional societies representing the geoengineering community must become involved in a concerted effort to engage industry in supporting research and development.

With respect to industry funding, the financial benefits of geoengineering research, including the benefits of both closing the gap between research and practice and additional research, must be made apparent to the entire geoengineering community. Again, professional societies can play an important role in this task through recommendations and guidance for continuing education, qualifications-based selection for both design and construction services, and best practices such as peer review and value engineering. In addition, design-build and other innovative contracting methods wherein geoengineers can share in the fruits of their innovations without assuming disproportionate risk can play an important role in encouraging industry support of research and innovation. Much of the responsibility will still lie on geoengineers themselves who have a desire to improve the state of practice and provide the best possible solutions to their clients' problems.

5.4 DIVERSIFYING THE WORKFORCE

Geoengineering faces important professional issues that go beyond redefinition and integration of science developed in other scientific disciplines. These issues are related to the engineering profession's own sustainability and its ability to develop effective solutions to complex, multifaceted problems. Advancing toward meaningful solutions to technical problems with social dimensions requires that those who will undertake research into these engineering problems and who will implement the solutions in practice are representative of the society that experiences the problems. Whereas the profession has advanced significantly in issues of diversity compared with the situation 30 years ago, the faces of the profession still do not reflect the faces of our population. NSF, historically a key player in invigorating action related to issues of workforce diversity, must work in new ways to remotivate the geoengineering community to address this problem.

NSF has supported and strongly encouraged diversity through its program expectations and its funding priorities for the last 30 years, with a commitment that has exceeded any other federal research funding entity. Nonetheless, career paths of women and minorities through undergraduate and graduate education and through faculty careers in science and engineering have not led to the progress toward equity and representation that had been envisaged (Nelson, 2002). William Wulf, president of the National Academy of Engineering, argued that it is not merely a case of fairness to open the engineering profession to the full population. Nor is it merely the need to draw from the largest possible pool of high academic achievers in our society. He argued that "one's creativity is bounded by one's life experiences" (http://www.brynmawr.edu/womeninscience/keynoteaddress.html). Diversity in the engineering workforce, where diversity is defined both in visible measures (racial and gender diversity) and in invisible measures (through diverse life experience), is key to optimizing engineering solutions to increasingly challenging problems. If engineers expect to be the creative leaders in addressing society's problems, it is imperative that society draw from and retain the broadest possible pool of engineers, enriching its traditional pool of students, and ultimately practitioners, with the nontraditional engineer, its educational practices, its professional registration practices, and its commitment to invest in diversity.

The competitive edge of a diverse engineering workforce has been established by *Land of Plenty*, the Report of the Congressional Commission on the Advancement of Women and Minorities in Science, Engineering, and Technology Development (CAWMSET, 2000), but commitment both by the engineering profession and by educational institutions has waned. That report, confirmed by results of Cook and King's study (2004, pp. 14-15, 39) identifies broad action items to advance this agenda. Two things are clear: (1) continuing the efforts in effect now will not advance us to the next level of success; and (2) passive acceptance of these presently underrepresented groups in the profession is not sufficient to attract and retain them, nor does it maximize their contributions to the profession. In terms of maximizing results from measures undertaken in colleges and universities, the data of 30 years of NSF programs may be a rich resource to begin to understand what new measures should be undertaken to support advancement toward those goals, especially if evaluation of programs in other agencies and in other developed countries is included in that study. It is beyond the scope of this report to evaluate and recommend measures to be implemented, however the urgency for new efforts is clear. The composition of the industry workforce still does not represent the composition of society as a whole. Renewed effort and innovative approaches are required to create a diverse geoengineering workforce representative of the general population.

5.5 INSTITUTIONAL ISSUES FOR A NEW AGENDA IN GEOENGINEERING

This chapter spelled out some of the institutional issues associated with achieving our vision for geoengineering in the twenty-first century and makes recommendations for actions NSF can take to overcome some of the barriers created by these issues. The role played by other groups in realizing this vision, including professional societies and various sectors of the geoengineering industry, is also addressed herein. The leadership of each group has already awakened to the realization that the vibrancy of the geoengineering profession depends on innovation. The 2004 ASCE *Body of Knowledge* report opens with a quote from William Jennings Bryan: "Destiny is not a matter of chance, it is a matter of choice." The committee embraces this philosophy for geoengineering.

NSF, the sponsor of this study, is unrivalled in its capacity to explore, support, and lead in initiatives that can (and have) enriched the profession. NSF has been influential in developments in geoengineering and it will have an even greater role in the foreseeable future. Universities are key players because of their responsibility for much of geoengineering research and education. Universities must dedicate themselves to innovation in interdisciplinary inquiry in order to address both continuing and new challenges in geoengineering; and they will need flexibility and resources to experiment with new approaches in education that will not only change what geoengineering graduates know and how they think about problems, but as importantly, who will choose to study and practice geoengineering. Geoengineering practitioners have the opportunity to make geoengineering a leadership profession in engineering. Bold projects that address pervasive societal imperatives will attract excellent practitioners and daring students.

This agenda requires fresh thinking and serious commitment to change on the part of each group. The first step has already been achieved: The leadership of each group has recognized that more of the same will not move the profession forward. The catalysts for change are new opportunities for breakthroughs and new compelling problems on which to work.

CHAPTER SIX

Findings and Recommendations

In preceding chapters the committee highlighted some important new imperatives and some exciting new technologies affecting geotechnology. It looked at opportunities that should be seized now and envisioned a future quite different from today. The committee also examined how geoengineering addresses societal needs now, and how geoengineering can address these needs better in the future.

From its deliberations the committee developed three categories of findings and recommendations. The first category includes knowledge gaps to address the critical issues and societal needs identified in the 1989 report *Geotechnology: Its Impact on Economic Growth, the Environment, and National Security* (NRC, 1989), gaps not yet satisfactorily resolved by the geoengineering community. This category addresses how new tools and technologies can be used to fill in these knowledge gaps and to tackle new applications in geoengineering. The second category is a compelling new imperative for Geoengineering for Earth Systems (GES). By GES we mean a systems engineering approach to geoengineering problems in the context of complex social, environmental, and economic factors. GES is an approach to sustainable development of our infrastructure and resources. The third category relates to changes in interdisciplinary research and education necessary to ensure that a diverse workforce is able to apply new tools and technologies to new applications of geoengineering.

Primarily, the committee's findings and recommendations are directed to the National Science Foundation (NSF) but suggestions for other agencies, education, and practice are made as well. Support for the findings and recommendations are documented in Chapters 2-5.

To summarize, the committee developed a vision for the future of the field of geotechnology as follows: Geotechnology will respond to the societal needs for engineering on and below the surface of Earth and with earthen materials using innovative and sophisticated science and technology, contributing to sustainable practice and participating in the interdisciplinary nature of the civil and environmental engineering problems facing society.

6.1 KNOWLEDGE GAPS AND NEW TOOLS

Finding

The committee finds that significant knowledge gaps continue to challenge the practice of geoengineering, especially the ability to characterize the subsurface; account for time effects; understand biogeochemical processes in soils and rocks; stabilize soils and rocks; use enhanced computing, information, and communication technologies; and understand geomaterials in extreme environments (see Chapter 2 for the full list of knowledge gaps). The committee is concerned that resources for investigator-initiated research at NSF are diminishing and believes that the balance between investigator-initiated research and directed research is unbalanced toward directed research.

Geoengineering is burdened by a lack of adequate characterization of the geomedia and paucity of necessary information, which contributes to some extent to unavoidable uncertainty in design. We are still unable to translate our fundamental understanding of the physics and chemistry of soils and rocks and the microscale behavior of particulate systems in ways that enable us to quantify the engineering properties and behavior needed for engineering analysis of materials at the macroscale. Given these problems, paradigms for dealing with the resulting uncertainty are poorly understood and even more poorly practiced. There is a need for (1) improved characterization technology; (2) improved quantification of the uncertainties associated with characterization; and (3) improved methods for assessing the potential impacts of these uncertainties on engineering decisions requiring engineering judgment (i.e., on risk analysis for engineering decision making).

Recommendation

- NSF should continue to direct funding of the fundamental knowledge gaps and needs in geoengineering.
- NSF should restore the balance between investigator-initiated research and directed research, and should allocate resources to increase the success rate for unsolicited proposals in geoengineering (and civil and mechanical systems) to a level commensurate with other programs in the engineering directorate.

Finding

The committee sees tremendous opportunities for advancing geoengineering through interaction with other disciplines, especially in the areas of biotechnology, nanotechnology, microelectromechanical systems (MEMS) and microsensors, geosensing, information technology, cyberinfrastructure, and multispatial and multitemporal geographical data modeling, analysis, and visualization. Pilot projects in vertical integration of research between multiple disciplines—perhaps including industry, multiple government agencies, and multiple universities—should be explored as alternatives to more traditional interdisciplinary proposals.

New technology—already available or under development—promises exciting new possibilities for geoengineering. Some applications of these new technologies that the committee found of particular interest use (1) microbes to stabilize or remediate soils; (2) nanotechnology to modify the behavior of clay; (3) nanosensors and MEMS to characterize and monitor the behavior of geomaterials and geosystems; (4) remote sensing and noninvasive ground-based sensing techniques; and (5) next-generation geologic data models to bridge sensing, computation, and real-time simulation of behavior for adaptive management purposes and geophysics for urban infrastructure detection. Some of these new technologies likely will have major impacts on geoengineering, such as revolutionizing the way geosystems are characterized, modified, and monitored. However, many of the applications of these new technologies have yet to be identified. In taking advantage of these new technologies, most geoengineering researchers would benefit from additional background in such areas as electronics, biology, chemistry, material science, information technology, and the geosciences. Rapid progress in applying these new technologies will require revised educational programs, novel research schemes, as well as updated and re-equipped laboratory facilities.

Recommendation

NSF should create opportunities to explore emerging technologies and associated opportunities in three types of activities. The first is designed to train researchers in new technologies through directed seed funds for interdisciplinary initiatives, such as continuing education of faculty (off-campus intensive courses), theme-specific sabbaticals, exploratory research initiatives, and focused workshops. The second is to provide funding for new equipment for the adaptation and development of emerging technologies for geoengineering applications.

The NSF Geomechanics and Geohazards Program should emphasize application of biotechnology, nanotechnology, MEMS, and information technology to geoengineering in its annual Small Business Innovation Research (SBIR) Program solicitation.

6.2 GEOENGINEERING FOR EARTH SYSTEMS

Finding

There are no isolated activities in this rapidly changing world. A decision in one place has repercussions in other places, sometimes with dramatic and unanticipated consequences. The influence of countless decisions at all scales is having a marked impact on the environment. In order to respond effectively to issues caused by human interactions with Earth systems, the committee sees a need for a broadened geoengineering discipline. Sustainable development provides a new paradigm for geoengineering practice, in which the tools, techniques, and scientific advances of multiple disciplines are brought to bear on ever more complex problems.

Geoengineering has made significant progress since 1989 in addressing societal needs. However, there has been a change in perspective from national to global and a realization that social, economic, and environmental dimensions must be included to develop robust solutions to fulfill these needs. Increased attention to anthropogenic effects on our environment and to sustainable development are important manifestations of this change in perspective.

Recommendation

NSF should create an interdisciplinary initiative on Earth Systems Engineering (ESE), including GES. The problems of GES occur on all scales from the nano- and microscale behavior of geomaterials, to the place-specific mesoscale investigations and the scale of the globe that responds to climate change.

A GES initiative should include any research problem that (1) involves geotechnology, and (2) has Earth systems implications or exists in an Earth systems context. In this regard, Earth systems have components that depend on each other (i.e., the outcome of one part of the problem affects the process in another part of the problem). There are feedback loops and perhaps dynamical interactions. The parts of the system come from the biosphere (all life on the Earth), geosphere (the rocks, soil water and atmosphere of the Earth), and anthrosphere (political, economic, and social systems), as well as individual components within these "spheres". This initiative should include the development of geo-systems models and support for adaptive management, data collection, management, interpretation, analysis, and visualization.

Finding

Multiple government agencies, including the Department of the Interior, Department of Energy, National Aeronautics and Space Administration, Department of Agriculture, Department of Transportation, Department of Defense, and Department of Homeland Security, have interests in Earth systems problems. These agencies would be well served by advances in geoengineering that could help to address the complex problems, knowledge gaps, and needs they face.

Recommendation

NSF program directors should coordinate GES research and development efforts with other agencies by developing a GES roundtable, sharing and jointly archiving information, and leveraging through cofunded projects.

The committee recommends that a workshop be organized to wrestle with the issue of engaging geoengineers in public policy initiatives on GES and sustainable development. The National Science Foundation is the ideal sponsor of such a workshop, and the United States Universities Council on Geotechnical Education and Research must be urged to be an active participant along with the American Society of Civil Engineers, the American Rock Mechanics Association, and other professional societies. The societies must be represented by their leading practicing-engineer members, rather than by executive administrators of the societies. Unconventional thinking related directly to issues of research and practice and engagement in public policy will be required before the details of how it should be administered are developed.

6.3 INTERDISCIPLINARY RESEARCH AND EDUCATION

Finding

Research and educational institutions are normally organized by discipline. The above findings and recommendations can be realized only if the institutions involved recognize the challenge and find new ways to accommodate research, education, and practice. For truly interdisciplinary solutions, cooperation must be invited, encouraged, and rewarded. Structures must exist in universities as well as funding agencies to facilitate collaboration.

Recommendations

The committee recommends that the NSF

- Encourage cross-disciplinary collaboration and collaboration between researchers and industry practitioners and among tool developers and potential tool users in its proposal preparation guidelines; include such collaboration as an explicit proposal evaluation criterion in its proposal preparation guidelines; and include cross-disciplinary collaboration as an explicit proposal evaluation criterion. Geoengineering proposal review panels should include researchers from related (cross-disciplinary) fields and from other federal research entities to the extent possible.
- Encourage communication among researchers through principal investigator workshops where principal investigators describe their current NSF-funded work. NSF should also require timely dissemination and sharing of experimental data and analytical models using the protocols and data dictionaries being developed for the Network for Earthquake Engineering Simulation (NEES)

project. Proposals should provide specific information on dissemination of this information, and "Results of Prior Research" should document dissemination of data from previous NSF-funded work.

- Conduct a critical evaluation of existing collaboratories and develop criteria for evaluation of collaboratory proposals, including consideration of the relative merit of funding a collaboratory versus funding individual and small-group research.

Finding

A more diverse workforce in terms of educational background, technical expertise, and application domains, as well as more traditional measures of diversity, is required to bring a broad range of cultural understanding, skills, knowledge, and practice to bear on complex geoengineering problems. In parallel with a new perspective on interdisciplinary research and the transfer and adaptation of knowledge between disciplines, a new perspective on science and engineering education is required so that the new workforce is truly ready to do the research and practice.

The diversity of the geoengineering workforce has improved in the last 30 years but more improvement is still needed. The long-term vitality of the geoengineering field depends on the entry of diverse, creative talent to the field.

Recommendation

NSF should make use of the data it has collected during its efforts to improve the educational foundation for a diverse student population and study new measures that could be taken to improve diversity in geoengineering. This effort should also include exploring, evaluating, and expanding programs that cultivate interaction between principally undergraduate institutions and research institutions.

Finding

The structure of universities can facilitate interdisciplinary research but is still lacking in its support of interdisciplinary engineering education.

Recommendation

NSF should create an interdisciplinary undergraduate education program to support education appropriate to GES and adaptation and transfer of knowledge to geoengineering from such disciplines as nanotechnology, biotechnology, and infotechnology.

NSF should leverage research funding to engage design and consulting engineers in geoengineering research and development activities. Proposal evaluation criteria could include credit for matching funds and in-kind services from industry, or some portion of available research funds could be dedicated to projects with matching industry support.

In concluding its work, the committee was pleased to learn of the recently completed National Academy of Engineering report *Engineering Research and America's Future: Meeting the Challenges of a Global Economy*. The main recommendations in that report are for increased investments at the federal and state levels, especially for fundamental research; upgrading and expanding laboratories, equipment, information technologies, and other infrastructure needs of universities; cultivating greater U.S. student interest in, and aptitude for, careers in engineering and in engineering research in particular; development and implementation of innovative curricula; and revision of current immigration procedures to make it easier to attract top scientific and engineering talent from around the world. Each of these recommendations should be adapted specifically to help meet the challenges of geoengineering in the twenty-first century.

6.4 CONCLUSION

The report provides a vision for geological and geotechnical engineering in the new millennium and suggests societal needs that the discipline can help to address. It explores ways that geoengineering should change to achieve this vision. There is real potential for breakthroughs and there are exciting opportunities for geoengineers if they become involved in biotechnology, nanotechnology and advances information technology. New solutions to persistent traditional problems can be obtained with these new nontraditional technologies. Beyond solving old problems in new ways, geoengineers have the potential to engage outside of traditional roles in the larger-scale problems of Earth systems that challenge the future of life on Earth. Geoengineering is the field of engineering most closely aligned with issues of sustainability, and this field should take a leadership role in the primary challenge of our time. This vision requires our educational, research, and industrial institutions to embrace the art of interdisciplinary work. What we recommend here is well captured by Albert Einstein: “We can’t solve problems by using the same kind of thinking we used when we created them.” We recommend new thinking to use emerging engineering science to solve the compelling societal needs we face. This venture will constitute a revitalization of geoengineering and thus represent the possibility for a great new age for geoengineering.

References

AASHTO (American Association of State Highway and Transportation Officials). 2003. Revisions to the Guide Specifications for Design and Construction of Segmental Concrete Bridges. 2nd ed. Washington, D.C.: AASHTO.

ABET (Accreditation Board for Engineering and Technology). 2000. Accreditation Policy and Procedure Manual. Baltimore, Md.: ABET, Inc.

Aki, K., and P. G. Richards. 2002. Quantitative Seismology: Theory and Methods. 2nd ed. New York: University Science Books.

Anderson, S. A., R. Surdahl, and B. Young. 2004. InSAR Evaluation of Landslides and Alternative Transportation Routes. In Proceedings of Geo-Trans 2000: Geotechnical Engineering for Transportation Projects. ASCE Special Geotechnical Publication 126, eds. M. K. Yegian and E. Kavazanjian Jr., pp. 2038-2047. Reston, Va: American Society of Civil Engineers/GEO Institute.

ASCE (American Society of Civil Engineers). 1998. 1998 Report Card for America's Infrastructure. Available at http://www.asce.org/reportcard/index.cfm?reaction= full&page=1. Accessed August 31, 2005.

ASCE. 2003. How to Work Effectively with Consulting Engineers: Getting the Best Project at the Right Price. Reston, Va.: American Society of Civil Engineers.

ASCE. 2004a. Policy Statement 418: The Role of the Engineer in Sustainable Development. Available at http://www.asce.org/pressroom/news/policy_details.cfm?hdlid=60. Accessed September 2, 2005.

ASCE. 2004b. Civil Engineering Body of Knowledge for the 21st Century: Preparing the Civil Engineer for the Future. Prepared by the Body of Knowledge Committee of the Committee on Academic Prerequisites for Professional Practice. Reston, Va.: American Society of Civil Engineers.

ASCE. 2005. Report Card for America's Infrastructure. Available at http://www.asce.org/reportcard/2005/index.cfm. Accessed July 27, 2005.

Atkins, D. E., K. K. Droegemeier, S. I. Feldman, H. Garcia-Molina, M. L. Klein, D. G. Messerschmitt, P. Messina, J. P. Ostrikera, and M. H. Wright. 2003. Revolutionizing Science and Engineering Through Cyberinfrastructure. Report of the National Science Foundation Blue-Ribbon Advisory Panel on Cyberinfrastructure. Washington, D.C.: National Science Foundation.

Baecher, G. B., and J. T. Christian. 2003. Reliability and Statistics in Geotechnical Engineering. New York: John Wiley and Sons.

Bradbury, J. 2004. Animals Everywhere. Hart's E&P net. Available at http://www.eandpnet.com/ep/previous/0204/0204marine_tech.htm. Accessed August 30, 2005.

Bugliarello, G. 1999. Megacities and the developing world. The Bridge 29(4):19-25.

Bugliarello, G. 2000. Rethinking Urbanization. National Academy of Engineering Annual Meeting. Engineering and Environmental Challenges: Technical Symposium on Earth Systems Engineering, pp. 73-90. Washington, D.C.: National Academies Press.

Bugliarello, G. 2003. Large Urban Concentrations: A New Phenomenon. In Earth Science in the City: A Reader, eds. G. Heiken, R. Fakundiny, and J. Sutter, pp. 5-20. Washington, D.C.: American Geophysical Union. Available at http://www.poly.edu/administration/articles/urban_concentration1.cfm. Accessed September 7, 2005.

Caldeira, K., A. K. Jain, and M. Huffert. 2003. Climate sensitivity, uncertainty, and the need for energy without CO2 Emissions. Science (March):2052-2054.

Casagrande, A. 1965. Role of the Calculated Risk in Earthwork and Foundation Engineering. Proceedings of the American Society of Civil Engineers 91(SM4):1-40.

CAWMSET (Congressional Commission on the Advancement of Women and Minorities in Science, Engineering, and Technology Development). 2000. Land of Plenty: Diversity as America's Competitive Edge in Science, Engineering and Technology. Available at http://www.nsf.gov/pubs/2000/cawmset0409/cawmset_0409.pdf. Accessed July 21, 2005.

CCSP (U.S. Climate Change Science Program). 2003. Strategic Plan for the U.S. Climate Change Science Program. Prepared in compliance with Section 515 of the Treasury and General Government Appropriations Act for FY 2001. Available at http://www.climatescience.gov. Accessed on April 1, 2004.

Chapelle, F. H. 2001. Ground-water microbiology and geochemistry. 2nd ed., p. 477. New York: John Wiley and Sons.

Cohen, J. E. 2003. Human Population: The next half century. Science 302:1172-1175.

Collins, P., A. S. Ng, and R. Ramanujam. 1998. Superfund Success Superfast. Civil Engineering 68(12):42-45. Reston, Va.: American Society of Civil Engineers.

Cook, B., and J. King. 2004. Low Income Adults in Profile: Improving Lives Through Higher Education. Washington, D.C.: American Council on Education, Center for Policy Analysis.

Diamond, J. 2004. Collapse: How Societies Choose to Fail or Succeed. New York: Viking Adult.

DOE (Department of Energy). 2003a. Basic Research Needs for the Hydrogen Economy: Report of the Basic Energy Sciences Workshop on Hydrogen Production, Storage, and Use. Available at http://www.sc.doe.gov/bes/hydrogen.pdf. Accessed on September 1, 2005.

DOE. 2003b. Remarks by Energy Secretary Spencer Abraham on Global Climate Change at the American Academy in Berlin, September 17, 2003. Available at http://www.fe.doe.gov/news/speeches/03/03_sec_berlin_091703.html. Accessed on April 1, 2004.

Drexler, E. K. 1986. Engines of Creation—The Coming Era of Nanotechnology. Available at http://www.foresight.org/EOC/index.html#TOC. Accessed on April 1, 2004.

Earth Simulator. 2002. Available at http://www.es.jamstec.go.jp. Accessed April 5, 2004.

Ehrlich, H. L. 1996. Geomicrobiology. 3rd ed. New York: Marcel Dekker.

Ehrlich, H. L. 1999. Microbes as geologic agents: Their role in mineral formation. Geomicrobiology (16):135-153.

EIA (Energy Information Administration). 2004. Monthly Energy Review: March 2004. Washington, D.C.: U.S. Department of Energy. Available at http://tonto.eia.doe.gov/FTPROOT/multifuel/mer/00350403.pdf. Accessed September 6, 2005.

Elwenspoek, M., and R. Wiegerink. 2001. Mechanical Microsensors (Microtechnology and MEMS). Berlin: Springer Verlag.

EPA (Environmental Protection Agency). Superfund Cleanup Figures 1980-2000. Available at http://www.epa.gov/oerrpage/superfund/action/20years/index.htm. Accessed on September 29, 2005.

ERC (Engineering Research Centers). 2005. Virtual Lab Develops Grid-based Portal for Simulating the Effects of a Major Earthquake on an Urban Region. Available at http://www.erc-assoc.org/showcase/accomplishments/earthquake/peer-04-2-spur.htm. Accessed on September 29, 2005.

Ethridge, D. M., L. P. Steele, R. L. Langenfelds, and R. J. Francey. 2001. IGBP PAGES/World Data Center for Paleoclimatology, Data Contribution Series No. 2001-083. Boulder, Colo.: NOAA/NCDC Paleoclimatology Program.

Foster, I., and C. Kesselman. 1999. The Grid: Blueprint for a New Computing Infrastructure, pp. xxiv, 677. San Francisco: Morgan Kaufmann.

Gleick, P. H. 2003. Global Freshwater Resources: Soft-Path Solutions for the 21st Century. Science 302:1524-1528.

Goodings, D. J., and S. A. Ketcham. 2001. Research vs practice in transportation geotechnics: Can we bridge the chasm? ASCE Journal of Professional Issues in Engineering Education and Practice 127(1):26-31.

Harper, L. 2003. CenterLine still on track after 9-2 vote. Daily Pilot, July 22, 2003.

Harte, J., T. Blackburn, and A. Ostling. 2001. Self-similarity and the relationship between abundance and range size. American Naturalist 157:374-386.

Hattori, T. 1973. Microbial Life in the Soil. New York: Marcel Dekker.

Hilton, B., and A. Elioff. 2004. California High-Speed Train: A Statewide Geo-Seismic Evaluation Using GIS. Proceedings of Geo-Trans 2000. In Proceedings of Geo-Trans 2000: Geotechnical Engineering for Transportation Projects. ASCE Special Geotechnical Publication 126, eds. M. K. Yegian and E. Kavazanjian Jr. pp. 903-914. Reston, Va.: American Society of Civil Engineers/GEO Institute.

IISD (International Institute for Sustainable Development). 2002a. Seven Questions to Sustainability: How to Assess the Contribution of Mining and Minerals Activities. Available at http://www.iisd.org/publications/pub.aspx?id=456. Accessed September 8, 2005.

IISD. 2002b. Towards Change: Final Synthesis Report of MMSD North American. Available at http://www.iisd.org/publications/pub.aspx?id=494. Accessed September 8, 2005.

IPCC (Intergovernmental Panel on Climate Change). 2001. Climate Change 2001: The Scientific Basis, eds. J. T. Houghton, Y. Ding, M. Nogua, D. Griggs, P. Vander Linded, K. Maskell. Cambridge, UK: Cambridge University Press.

Jones, E. D., and K. A. Jones. 1987. Treating expansive soils. Civil Engineering 57(8):62-65.

Jones, P. D., K. R. Briffa, T. P. Barnett and S. F. B. Tett. 1998. High-resolution palaeoclimatic records for the last millennium: Interpretation, integration and comparison with General Circulation Model control run temperatures. The Holocene 8:455-471.

Kane, W. F., G. R. Holzhausen, and E. Constable. 2004. Coastal Bluff Monitoring: Alarm System for Railways. In Proceedings of Geo-Trans 2000: Geotechnical Engineering for Transportation Projects. ASCE Special Geotechnical Publication 126, eds. M. K. Yegian and E. Kavazanjian Jr., pp. 2067-2074. Reston, Va.: American Society of Civil Engineers/GEO Institute.

Kavazanjian, E., Jr. 2001. Design and Performance of Evapotranspirative Cover Systems For Arid Region Landfills. In Proceedings, 36th Annual Western States Engineering Geology and Geotechnical Engineering Symposium, 28-30 March 2001, University of Nevada, Las Vegas, Nevada, pp. 11-26.

Keeling, C. D., and T. P. Whorf. 2002. Atmospheric CO_2 Records from Sites in the SIO (Scripps Institution of Oceanography) Air Sampling Network. In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn.

Kovacs, G. T. A. 1998. Micromachined Transducers Sourcebook. Boston: McGraw-Hill.

Liu, S. C., and M. Tomizuka. 2003. Strategic Research for Sensors and Smart Structure Technology. In Proceedings of the First International Conference on Structural Health Monitoring and Intelligent Infrastructure, Tokyo, Japan, November 2003, eds. Z. S. Wu and M. Abe, pp. 113-118. Exton, Pa.: AA Balkema.

Long, J. C. S., and R. Ewing. 2004. Yucca Mountain: Earth-science issues at a geologic repository for high-level nuclear waste. Annual Review of Earth and Planetary Sciences 32:363–401.

Madou, M. J. 2002. Fundamentals of microfabrication: The science of miniaturization. 2nd ed. Boca Raton, Fla.: CRC Press.

Messina, P. 1999. The Accelerated Strategic Computing Initiative. In Impact of Advances in Computing and Communications Technologies on Chemical Science and Technology: Report of a Workshop, pp. 8-19. Washington, D.C.: National Academy Press. Available at http://www.nap.edu/catalog/9591.html. Accessed on April 6, 2004.

Mitchell, J. F. B., D. J. Karoly, G. V. Hegerl, F. W. Zwiers, M. R. Allen, and J. Marengo. 2001. Detection of Climate Change and Attribution of Causes. In Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, eds. J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson, pp. 695-738. Cambridge, UK: University Press.

Mitchell, J. K., and J. C. Santamarina. 2005. Biological considerations in geotechnical engineering. ASCE Journal of Geotechnical and Geoenvironmental Engineering 131(10):1222-1233.

NACEPT (National Advisory Council for Environmental Policy and Technology). 2004. Final Report. Superfund Subcommittee of National Advisory Council for Environmental Policy and Technology. April 12, 2004. Available at http://www.epa.gov/swerrims/docs/naceptdocs/NACEPTsuperfund-Final-Report.pdf. Accessed August 30, 2005.

NAE (National Academy of Engineering). 2002. Engineering and Environmental Challenges: Technical Symposium on Earth Systems Engineering, pp. 67-72. Washington, D.C.: National Academy Press.

NAE. 2004. The Engineer of 2020: Visions of Engineering in the New Century. Washington, D.C.: National Academies Press.

NAE. 2005. Engineering Research and America's Future: Meeting the Challenges of a Global Economy. Washington, D.C.: National Academies Press.

NCPWI (National Council on Public Works Improvements). 1988. Fragile Foundations: A Report on America's Public Works. Washington, D.C.: U.S. Government Printing Office.

Nelson, D. J. 2002. Diversity in academia: A look at gender and race/ethnicity in science and engineering departments. The FASEB Journal 16(4):A524.

Network for Earthquake Engineering Simulation website. Available at http://www.nees.org. Accessed on July 21, 2005.

NRC (National Research Council). 1974. Expansion Joints in Buildings: Technical Report No. 65. Washington, D.C.: National Academy Press.

NRC. 1987. Directions in Engineering Research. Washington, D.C.: National Academy Press.

NRC. 1989. Geotechnology: Its Impact on Economic Growth, the Environment, and National Security. Washington, D.C.: National Academy Press.

NRC. 1993. National Collaboratories: Applying Information Technology for Scientific Research, p. xi. Washington, D.C.: National Academy Press.

NRC. 1999. Our Common Journey: A Transition Toward Sustainability. Washington, D.C.: National Academy Press.

NRC. 2000. Seeing Into the Earth—Noninvasive Characterization of the Shallow Subsurface for Environmental Engineering Application. Washington, D.C.: National Academy Press.

NRC. 2001a. Basic Research Opportunities in Earth Science. Washington, D.C.: National Academy Press.

NRC. 2001b. Evolutionary and Revolutionary Technologies for Mining. Washington, D.C.: National Academy Press.

NRC. 2001c. Issues for Science and Engineering Researchers in the Digital Age. Washington, D.C.: National Academy Press.

NRC. 2002a. Abrupt Climate Change: Inevitable Surprises. Washington, D.C.: National Academies Press.

NRC. 2002b. Coal Waste Impoundments: Risks, Responses, and Alternatives. Washington, D.C.: National Academies Press.

NRC. 2002c. Evolutionary and Revolutionary Technologies for Mining. Washington, D.C.: National Academies Press.

NRC. 2003a. Completing the Big Dig: Managing the Final Stages of Boston's Central Artery/Tunnel Project. Washington, D.C.: National Academies Press.

NRC. 2003b. Novel Approaches to Carbon Management: Separation, Capture, Sequestration, and Conversion to Useful Products—Workshop Report. Washington, D.C.: National Academies Press.

NRC. 2003c. One Step at a Time: The Staged Development of Geologic Repositories for High-Level Radioactive Waste. Washington, D.C.: National Academies Press.

NRC. 2003d. Science and the Greater Everglades Ecosystem Restoration: An Assessment of the Critical Ecosystem Studies Initiative. Washington, D.C.: National Academies Press.

NRC. 2003e. The Carbon Dioxide Dilemma: Promising Technologies and Policies. Washington, D.C.: National Academies Press.

NRC. 2004a. Charting the Future of Methane Hydrate Research in the United States. Washington, D.C.: National Academies Press.

NRC. 2004b. The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs. Washington, D.C.: National Academies Press.

NRC. 2004c. The Engineer 2020. Washington, D.C.: National Academies Press.

NRC. 2004d. Partnerships for Reducing Landslide Risk: Assessment of the National Landslide Hazards Mitigation Strategy. Washington, D.C.: National Academies Press.

NSF (National Science Foundation). 2005. NSF Investments and Strategic Goals. Available at http://www.nsf.gov/about/budget/fy2005/. Accessed January 18, 2006.

Oden, J. T., T. Belytschko, I. Babuska, and T. J. R. Hughes. 2003. Research directions in computational mechanics. Computer Methods in Applied Mechanics and Engineering 192:913-922.

Office of the Press Secretary. National Nanotechnology Initiative: Leading to the Next Industrial Revolution. Press Release, January 21, 2000. Available at http://clinton4.nara.gov/WH/New/html/20000121_4.html. Accessed September 1, 2005.

O'Rourke, T. D., and A. J. McGinn. 2003. Performance of Deep Mixing Methods at Fort Point Channel. Prepared for Bechtel/Parsons Brinckerhoff, Massachusetts Highway Department, and Federal Highway Administration, Cornell University, Ithaca, New York.

Patel, B. Molecular Science and Bioinformatics (slide). Available at http://trishul.sci.gu.edu.au/courses/ss13bmm/introduction_MAM.pdf. Accessed January 18, 2006.

Paul, E. A., and F. E. Clark. 1996. Soil Microbiology and Biochemistry. New York: Academic Press.

Peck, R. B. 1969. Advantages and limitations of the observational method in applied soil mechanics. Geotechnique 19(2):171-187.

Petersen, K. E. 1982. Silicon as a mechanical material. Proceedings of the IEEE 70(5):420-457.

Peterson, T. C., and R. S. Vose. 1997. An overview of the global historical climatology network temperature data base. Bulletin of the American Meteorological Society 78:2837-2849.

Petley, D. N. 1996. The mechanics and landforms of deep-seated landslides. In Advances in Hillslope Processes, eds. S. Brooks and M. Anderson, pp. 823-835. Chichester, UK: John Wiley and Sons.

Pister, K. S. J. 2003. Smart dust-hardware limits to wireless sensor networks. International Conference on Distributed Computing Systems 00(1):2. Los Alamitos, Calif.: IEEE Computer Society Press.

Ristic, L., ed. 1994. Sensor Technology and Devices. Boston: Artech House.

Rosinski, A., K. L. Knudson, J. Wu, R. B. Seed, and C. R. Real. 2004. Development of Regional Liquefaction-induced Deformation Hazard Maps. In Proceedings of Geo-Trans 2000: Geotechnical Engineering for Transportation Projects. ASCE Special Geotechnical Publication 126, eds. M. K. Yegian and E. Kavazanjian Jr., pp. 797-806. Reston, Va.: American Society of Civil Engineers/GEO Institute.

Santamarina, J. C., Klein, K. and Fam, M. 2001. Soils and Waves. Chichester, UK: John Wiley and Sons.

Santer, B. D., M. F. Wehner, T. M. L. Wigley, R. Sausen, G. A. Meehl, K. E. Taylor, C. Ammann, J. Arblaster, W. M. Washington, J. S. Boyle, and W. Brüggemann. 2003. Contributions of anthropogenic and natural forcing to recent tropopause height changes. Science 301:479-483.

Santer, B. D., T. M. L. Wigley, A. J. Simmons, P. W. Kållberg, G. A. Kelly, S. M. Uppala, C. Ammann, J. S. Boyle, W. Brüggemann, C. Doutriaux, M. Fiorino, C. Mears, G. A. Meehl, R. Sausen, K. E. Taylor, W. M. Washington, M. F. Wehner, and F. J. Wentz. 2004. Identification of anthropogenic climate change using a second-generation reanalysis. Journal of Geophysical Research 109(D21).

SCEC (Southern California Earthquake Center). 2001. A Comparison of the February 28, 2001, Nisqually, Washington, and January 17, 1994, Northridge, California, Earthquakes. Available at http://www.scec.org/instanet/01news/feature010313.html. Accessed April 1, 2004.

Senturia, S. D. 2001. Microsystem Design. Boston: Kluwer Academic.

Serafini, D. C., and G. L. Fiegel 2004. Estimating Slope Movement with Time Domain Reflectometry (TDR). In Proceedings of Geo-Trans 2000: Geotechnical Engineering for Transportation Projects. ASCE Special Geotechnical Publication 126, eds. M. K. Yegian and E. Kavazanjian Jr., pp. 2084-2092. Reston, Va.: American Society of Civil Engineers/GEO Institute.

Shirley, K. 2003. Is 'micro' the next big thing? AAPG Explorer, p. 14.

Short, N. M., and J. Bolton. 2004. The Remote Sensing Tutorial. Available at http://rst.gsfc.nasa.gov/Front/overview.html. Accessed August 30, 2005.

Smalley, R. Our Energy Challenge. Public Lecture, Low Library, Columbia University, New York, N.Y.; September 23, 2003. Available at http://smalley.rice.edu/emplibrary/columbia20030923.pdf. Accessed on July 21, 2005.

Snow, C.P. 1959. The Two Cultures. New York: Cambridge University Press.

Tatlow, M. A., and S. M. Buckley. 2003. NASA helps ADWR monitor land subsidence. Southwest Hydrologist 2(3):6, 27.

Telford, W. M., L. P. Geldhart, and R. E. Shefiff. 1990. Applied Geophysics. New York: Cambridge University Press.

The Remarkable Ocean World—The Gaia Hypothesis. Available at http://www.oceansonline.com/gaiaho.htm. Accessed on September 7, 2005.

UN (United Nations). 2000. The Millennium Development Goals and the United Nations Role Fact Sheet. United Nations Department of Public Information. Available at http://www.un.org/millenniumgoals/MDGs-FACTSHEET1.pdf. Accessed July 26, 2005.

USGS. 1995. Fact Sheet FS-61-95. Available at http://water.usgs.gov/wid/html/HRDS.html. Accessed August 30, 2005.

USGS. 2003. Magnitude 6.6 – Southeastern Iran: Preliminary Earthquake Report. Available at http://www.earthquake.usgs.gov/recenteqsww/Quakes/uscvad.htm. Accessed on September 7, 2005.

Utah Department of Transportation. 2003. Proceedings of the I-15 National Testbed Symposium: Highway Bridge and Geotechnical Innovations, Salt Lake City, Utah, September 17-18, 2003.

Wang, Z. L., Y. Liu, and Z. Zhang, eds. 2002. Handbook of Nanophase and Nanostructured Materials, Vol. III: Materials Systems and Applications. Boston: Kluwer Academic/Plenum.

Ward, S. H. 1990. Resistivity and Induced Polarization Methods. In Geotechnical and Environmental Geophysics, vol. 1, ed. S. H. Ward, pp. 147-190. Tulsa, Okla.: Society of Exploration Geophysicists.

Whitman, W. B., D. C. Coleman, and W. J. Wiebe. 1998. Prokaroytes: The Unseen Majority. Proceedings of the National Academy of Sciences U.S.A. 95:6578-6583.

Wulf, W. A. 2001. The Academy of Sciences—Then and Now. Keynote address, Bryn Mawr College National Symposium, Bryn Mawr, Penn., October 26-27, 2001. Available at http://www.brynmawr.edu/womeninscience/keynoteaddress.html. Accessed January 18, 2006.

Yilmaz, O. 1987. Seismic Data Processing, p. 526. Tulsa, Okla.: Society of Exploration Geophysicists.

Zhang, J. Z., Z. L. Wang, J. Liu, S. W. Chen, and G. Y. Liu. 2002. Self-assembled Nanostructures. New York: Kluwer Academic.

APPENDIX A

Biographical Sketches of Committee Members and Staff

Jane C. S. Long, *Chair,* is the associate director of energy and the environment at the Lawrence Livermore National Laboratory. She served as dean at Mackay School of Mines, University of Nevada, Reno, from 1979 until 2003, and while there initiated the Mining Life-Cycle Center and the Great Basin Center for Geothermal Research. Previously, Dr. Long was on the staff of the Lawrence Berkeley National Laboratory for 20 years. She is an expert in rock mechanics and fracture hydrology and has worked on several U.S. and international underground repository research projects. Her research investigates fluid flow in fractures, with applications in nuclear waste storage, geothermal reservoirs, petroleum reservoirs, and contaminant transport. She was the chair for the National Research Council study "Rock Fractures and Fluid Flow: Contemporary Understanding and Applications" and is a member of the Board on Radioactive Waste Management. Dr. Long received a Sc.B. in engineering from Brown University and an M.S. in geotechnical engineering and a Ph.D. in materials science and mineral engineering from the University of California, Berkeley. She is a member of the American Geological Institute Foundation Board and an associate of the National Academy of Sciences.

Bernard Amadei is a professor of civil engineering at the University of Colorado, Boulder. At the University of Colorado, he is leading a new paradigm shift in engineering education and practice called Earth Systems Engineering, which emphasizes the interaction between engineering structures and natural systems. Dr. Amadei was a member of the U.S. National Committee for Rock Mechanics (National Research

Council) and chair of the American Society of Civil Engineering Rock Mechanics Committee. He was one of the cofounders of the American Rock Mechanics Association. He also is the founding president of Engineers Without Borders USA, a nonprofit organization dedicated to helping developing communities with their engineering needs for water, sanitation, and energy systems. He has coauthored two books and approximately 150 technical papers, and has also provided consulting services to various engineering companies and organizations around the world. Dr. Amadei holds an M.S. in civil engineering from the University of Toronto and a Ph.D. in civil engineering from the University of California, Berkeley.

Jean-Pierre Bardet is a professor in the Department of Civil Engineering at the University of Southern California, Los Angeles. He has worked for the university for the past two decades, and his research areas include computational geomechanics, granular mechanics, geotechnical engineering, geotechnical earthquake engineering, post-earthquake field reconnaissance, and geoinformation systems. Dr. Bardet is the author of over 100 technical publications and is on the editorial board of several technical journals. He holds a Ph.D. from the California Institute of Technology. In 2002 he was awarded the Gilbreth lecture from the National Academy of Engineering.

John T. Christian is currently a consulting engineer in Boston and Newton, Massachusetts. Dr. Christian spent much of his career at the Massachusetts Institute of Technology and at Stone and Webster Engineering Corporation. Dr. Christian is a former chair of the American Society of Civil Engineering (ASCE) Geotechnical Engineering Division and of the U.S. National Society of the International Society of Soil Mechanics and Foundation Engineering. An honorary member of ASCE and of the Boston Society of Civil Engineers Section, ASCE, Dr. Christian has been the recipient of several distinguished honors and awards, including the 2003 Terzaghi lecture. He has published over 90 papers and three books in the geotechnical and earthquake engineering fields. In 1999, he was elected to the National Academy of Engineering. In 2003, he chaired the National Research Council (NRC) study "Completing the 'Big Dig': Managing the Final Stages of Boston's Central Artery/Tunnel Project." He is currently a member of the NRC's Committee on Geological and Geotechnical Engineering. Dr. Christian holds a B.S., an M.S., and a Ph.D. in civil engineering from the Massachusetts Institute of Technology.

Steven D. Glaser is a professor at the University of California, Berkeley, faculty geological scientist at Lawrence Berkeley National Laboratory, and a research associate at the Intel Laboratory at Berkeley. Involvement in civil engineering began at age 17, when he began working as a union construction laborer in the Washington, D.C., area. While earning his degree in philosophy at Clark University, Worcester, Massachusetts, he became an apprentice operation engineer. He worked as a driller for eight years in the D.C. area and in Iraq. This experience with geotechnical engineering led to enrollment in the civil engineering program at the University of Texas in 1981.

Deborah J. Goodings is a geotechnical engineering professor in the Department of Civil Engineering, and codirector of the Engineering and Public Policy Program at the University of Maryland, College Park. Dr. Goodings worked with Tippetts Abbett McCarthy Stratton Engineers and Architects for two years, focusing on the huge Tarbela Dam Project, before she joined the faculty at the University of Maryland in 1981. Her reseach interests include engineering and public policy, international development engineering, cold regions geotechnique, extreme heat geotechique, geoenvironmental engineering, cratering by sinkholes and by explosives, and ground improvement. Dr. Goodings serves as a member of the National Science and Engineering Research Council (Canada) Civil Engineering Grant Selection Committee, and as the chair of the Group AF Soil Mechanics Section of the Transportation Research Board. Dr. Goodings is a fellow of ASCE; a recipient of the Fred Burggraf Award from the NRC's Transportation Research Board; a corecipient of the Department of the Army Outstanding Civilian Service Medal; and a recipient of the Distinguished Service Award of the U.S. Universities Council on Geotechnical Education and Research. She received her B.A.Sc. in civil engineering from the University of Toronto and her Ph.D. in Geotechnical Engineering from Cambridge University. She is a registered professional engineer.

Edward Kavazanjian Jr. is associate professor of civil and environmental engineering at Arizona State University (ASU) in Tempe, Arizona. Prior to moving to ASU in 2004, Dr. Kavazanjian spent 20 years in engineering practice. He is recognized for his work on analysis and design of waste containment systems and on geotechnical aspects of earthquake engineering. He has served as engineer in charge of major infrastructure development projects involving up to $8.5 million in engineering services and $150 million in construction and as principal or co-principal investigator on geotechnical engineering research projects sponsored by the Department of Transportation, the National Science Foundation, the U.S. Geological Survey, and the U.S. Army Corps of Engineers. He currently serves on the Board of Governors of the Geo-Institute of the American Society of Civil Engineers and as the chair of the Geoseismic Concerns subcommittee of the Transportation Research Board Committee on Seismic Design of Bridges. Dr. Kavazanjian holds an S.M. in geotechnical engineering, an S.B. in civil engineering from Massachusetts Institute of Technology, and a Ph.D. in geotechnical engineering from the University of California, Berkeley.

David W. Major is a principal of GeoSyntec Consultants, Inc. and obtained his M.S. and Ph.D. degrees from the University of Waterloo where he studied the biodegradation of chlorinated and aromatic compounds in groundwater. For the past 18 years, he has worked with clients, researchers, and regulators to develop practical biological and chemical solutions to remediate contaminated sites. Dr. Major has served on national committees, including the steering committee of the U.S. Environmental Protection Agency (EPA) Remediation Technologies

Development Forum Consortium on Bioremediation of Chlorinated Solvents and the EPA Science Advisory Board to review the efficacy of dense nonaqueous phase liquids treatment technologies, and presented to the National Research Council during its review of the state of the science of monitored natural attenuation and associated protocols. Dr. Major has made 25 national and international presentations and written over 40 relevant publications.

James K. Mitchell is a University Distinguished Professor Emeritus of the Department of Civil and Environmental Engineering at Virginia Polytechnic Institute and State University. Prior to joining Virginia Tech in 1994, he spent 35 years on the civil engineering faculty of the University of California, Berkeley, where he served as chair of the department from 1979 to 1984. He received his Sc.D. in civil engineering from the Massachusetts Institute of Technology. Dr. Mitchell's research interests are in geotechnical engineering, with emphasis on soil properties and behavior, ground improvement, environmental geotechnics, and in situ testing. Much of his recent work has focused on the application of knowledge in these areas to problems in environmental geotechnics and mitigation of seismic risk to earth structures. He is a widely-known and well-respected leader who has received many awards for notable research achievements and for international contributions to engineering practice and education. He has served on several NRC boards and committees including the Geotechnical Board (chair), Committee for Noninvasive Characterization of the Shallow Subsurface for Environmenatal and Engineering Applications, Committee on Subsurface Contamination at Department of Energy Complex Sites: Research Needs and Opportunities (vice chair), Committee for Review of the Hanford Site's Environmental Remediation Science and Technology Plan, Panel on Review Procedures for Water Resources Project Planning (chair), and Committee on Organizing to Manage Construction and Infrastructure in the 21st Century Bureau of Reclamation (chair). He is a member of both the National Academy of Sciences and the National Academy of Engineering.

Mary M. Poulton is the head of the Department of Mining and Geological Engineering at the University of Arizona. She joined the faculty at the University in 1990. Previously she worked as a mining engineer for Pittsburgh and Midway Coal Mining Company and as a hydraulic engineering technician for the U.S. Army Corps of Engineers. Her main research interests include neural networks, geosensing, mineral and petroleum exploration, reservoir characterization, and groundwater management. Her other activities include serving as the chair of the Mining and Geothermal Committee of the Society for Exploration Geophysicists, vice-president of the Symposium on the Application of Geophysics to Engineering and Environmental Problems for the Engineering and Environmental Engineering Society (2002-2003), vice-president of the Near Surface Geophysics Section of Society of Exploration Geophysicists (2000-2001), and as technical session chair for the Symposium on the Application of Geophysics to Environmental and Engineering Problems 2002 in Las Vegas. She is a member of the National Research Council's Committee on Geological and Geotechnical Engineering. She is cofounder and vice-president of the water management firm, NOAH LLC. She holds a Ph.D. and an M.S. in geological engineering from the University of Arizona.

J. Carlos Santamarina is the Goizueta Professor at the School of Civil and Environmental Engineering at the Georgia Institute for Technology. His research focuses on the fundamental study of soils and subsurface processes. These studies have involved the development and use of particle-level testing methodologies, high-resolution process monitoring systems (including combined elastic and electromagnetic waves), and inverse problems. This conceptual and experimental framework has allowed the study of problems in civil engineering systems (dynamic soil response, foundations), mining (clay minerals, crushed rock), and resource recovery (petroleum and methane hydrates). Current research emphasizes engineered particulate systems. Two coauthored books summarize salient concepts and research results. He is a corresponding member of the Argentinean National Academy of Science and National Academy

Engineering. He holds a Ph.D. from Purdue University, an M.S. from the University of Maryland, and a B.Sc. from Universidad de Cordoba.

STAFF

Anthony R. de Souza is currently director of the Board on Earth Sciences and Resources at the National Research Council in Washington, D.C. Previously, he was executive director of the National Geography Standards Project, secretary general of the 27th International Geographical Union Congress, editor of National Geographic Research & Exploration, and editor of the *Journal of Geography*. He has held positions as a professor and as a visiting teacher and scholar at the George Washington University, University of Wisconsin-Eau Claire, University of Minnesota, University of California, Berkeley, and University of Dar es Salaam in Tanzania. He has served as a member of NRC committees. He holds B.A. (honors) and Ph.D. degrees from the University of Reading in England and has received numerous honors and awards, including the Medalla al Benito Juarez in 1992 and the Gilbert Grosvenor honors award from the Association of American Geographers in 1996. His research interests include the processes and mechanisms of economic development and human-environment relationships. He has published several books and more than 100 articles, reports, and reviews.

APPENDIX B

Workshop Agenda and Participants

NATIONAL RESEARCH COUNCIL OF
THE NATIONAL ACADEMIES

Division on Earth and Life Studies
Board on Earth Sciences and Resources

500 Fifth Street, N.W.
Washington, DC 20001
Phone: 202 334 2744
Fax: 202 334 1377
www.nationalacademies.org

COMMITTEE ON GEOLOGICAL AND GEOTECHNICAL ENGINEERING IN THE NEW MILLENNIUM: OPPORTUNITIES FOR RESEARCH AND TECHNOLOGICAL INNOVATION

WORKSHOP AGENDA

February 4–5, 2004
Beckman Center
Irvine, California

WEDNESDAY, FEBRUARY 4, 2004

Open Session

8:00 am Opening Remarks (Auditorium)
Welcome, Jane Long, *Chair*
Societal Imperatives for Geoengineering, Jane Long, *Chair*
Knowledge Gaps/Needs, Jim Mitchell, *Member*

8:15 am **Plenary Session: Key Issues** (Auditorium)

8:15 am Infrastructure Issues, Bill Wallace, *Wallace Futures Group, LLC*

8:45 am Sustainability and Sustainable Development, Dirk van Zyl, *University of Nevada, Reno*

9:25 am **Interdisciplinary Research and Education** (Auditorium)

9:30 am Emerging Issues in Interdisciplinary Research and Education, Debbie A. Niemeier, *University of California, Davis*

9:50 am Connections Between Academic Programs, Research, and Industry, George Bugliarello, *Polytechnic University (by video)*

10:10 am Switch to Breakout Rooms

10:30 am—
12:00 pm Breakout Sessions with Plenary Speakers on Key Issues and Interdisciplinary Research and Education

1:00 pm **Systems Approach to Geotechnology/Societal Issues Connected to Geotechnology** (Auditorium)

1:00 pm Development of GIS - Spatial Modelling Databases and Technology, Bill Miller, *Environmental Systems Research Institute*

1:20 pm Geoengineering for the Developing World, Don Roberts, *Consulting Engineer*

1:40 pm **Nanotechnology** (Auditorium)

1:40 pm Physics/Fundamentals of Nanotechnology, Thomas Kenny, *Stanford University*

2:00 pm Innovative Examples of Applications of Nanotechnology, Zhong Lin Wang, *Georgia Institute of Technology*

2:20 pm Switch to Breakout Rooms

2:20 pm—
5:00 pm Breakout Sessions with Plenary Speakers on Systems Approach to Geotechnology, Societal Issues Connected to Geotechnology, and Nanotechnology

THURSDAY, FEBRUARY 5, 2004

Open Session

8:00 am **Information Technology and Computation** (Auditorium)

8:00 am Large Data Streams in Real-time, Tom Farr, *Jet Propulsion Laboratory*

8:20 am Cyberinfrastructure, Dave Messerschmitt, *University of California, Berkeley*

8:40 am **Characterization Tools and Visualization** (Auditorium)

8:40 am Medical Imaging, Perry Sprawls, *Emory University School of Medicine*

9:00 am Geosensing, David Lumley, *4th Wave Imaging*

9:20 am Switch to Breakout Rooms

9:40 am —
12:00 pm Breakout Session with Plenary Speakers on Information Technology and Computation and Characterization Tools and Visualization

1:00 pm **Biogeochemistry** (Auditorium)

1:00 pm Bridging the Gaps Between Bio and Civil Engineering, Joseph Hughes, *Georgia Institute of Technology*

1:20 pm Using Molecular Biological Processes in Geoengineering, Donald Lush, *Stantech Engineering*

1:40 pm **MEMS and Sensors** (Auditorium)

1:40 pm Mechanical Properties/Commercial Availability of Tools, Andrei M. Shkel, *University of California at Irvine*

2:00 pm Chemical and Biological Sensors, Stephen Casalnuovo, *Sandia National Laboratories*

2:20 pm Switch to Breakout Rooms

2:40—
5:00 pm Breakout Sessions with Plenary Speakers on Biogeochemistry and MEMS and Sensors

5:00 pm—
6:00 pm **Strategy Session** (Auditorium)

5:00 p.m. Open session to discuss strategies for moving forward in research and education, Deborah Goodings, Member

6:00 pm Final Remarks and Adjourn, Jane Long, Chair

OTHER WORKSHOP PARTICIPANTS

Akram Alshawabkeh, Northeastern University
Jean Benoît, University of New Hampshire
Craig H. Benson, University of Wisconsin-Madison
David Bloomquist, University of Florida
Jean-Louis Briaud, Texas A&M University
Patricia J. Culligan, Columbia University
Thomas W. Doe, Golder Associates
Richard J. Finno, Northwestern University
Richard J. Fragaszy, National Science Foundation
Dante Fratta, Louisiana State University
J. David Frost, Georgia Institute of Technology
George G. Goble, George G. Goble Consulting Engineer LLC
Bojan Guzina, University of Minnesota
Karen S. Henry, U.S. Army Cold Regions Research and Engineering Laboratory
Francois E. Heuze, Lawrence Livermore National Laboratory
Sandra Houston, Arizona State University
Roman Hryciw, University of Michigan
Boris Jeremic, University of California
Barbara Luke, University of Nevada, Las Vegas
W. Allen Marr, Geocomp Corporation
Muralee Muraleetharan, University of Oklahoma
Juan M. Pestana, National Science Foundation

Ellen Rathje, University of Texas
Rodrigo Salgado, Purdue University
Nicholas Sitar, University of California, Berkeley
Chris Swan, Tufts University
Masayoshi Tomizuka, National Science Foundation
Jorge G. Zornberg, University of Texas at Austin

APPENDIX C

Acronyms

ABET	Accreditation Board for Engineering and Technology
ACTA	Alameda Corridor Transportation Authority
ASCE	American Society of Civil Engineers
ASCI	Accelerated Strategic Computing Initiative
ASFE	Association of Soil and Foundation Engineers
CAD	computer-aided design
CAT	computer-aided tomography
CA/T	Central Artery/Tunnel
CFCs	chlorofluorocarbons
CMOS	complementary metal oxide semiconductor
DOD	Department of Defense
DOE	Department of Energy
DOI	Department of the Interior
EERI	Earthquake Engineering Research Institute
EPA	Environmental Protection Agency
ESE	Earth Systems Engineering
EWB	Engineers Without Borders
FY	fiscal year
GES	Geoengineering for Earth Systems
GIS	geographic information systems
IC	integrated circuit
IIED	International Institute for Environment and Development
InSAR	Interferometric synthetic aperture radar
LIDAR	light detection and ranging
MEMS	microelectromechanical systems

MRI	magnetic resonance imaging
NAE	National Academy of Engineering
NASA	National Aeronautics and Space Administration
NEES	Network for Earthquake Engineering Simulation
NEHRP	National Earthquake Hazard Reduction Program
NGES	National Geotechnical Experimentation Sites
NIMBY	not in my back yard
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NSF	National Science Foundation
PCBs	polychlorinated biphenyls
PET	positron emission tomography
RF	radio frequency
SAR	synthetic aperture radar
SBIR	Small Business Innovation Research
SIS	Slope Information System
SPUR	Seismic Performance for Urban Regions
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
WBCSD	World Business Council for Sustainable Development