

**Final Report**  
**Workshop on Frontier Research Directions in**  
**Civil and Environmental Engineering**

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Civil, Mechanical and Manufacturing Innovation Division (CMMI)  
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**NSF Workshop on  
Frontier Research Directions in  
Civil and Environmental Engineering**

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## Preface

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On June 4<sup>th</sup> and 5<sup>th</sup>, 2007, The National Science Foundation held a Workshop in Washington D.C. to discuss the needs of the Civil and Environmental Engineering and to consider future research directions where Civil and Environmental Engineering must play a significant role. The Workshop was centered on four broad, interdisciplinary, and interrelated themes. Specifically these themes were: *Renewal, Management and Protection of Complex Systems*; *Sustainability*; *Global Impacts*; and, *Energy*. To facilitate discussions, leaders in respective fields were asked to present keynote addresses related to these broad themes, white papers were prepared by attendees and disseminated before the workshop, and breakout sessions were held to consider the role of Civil and Environmental Engineers in research within these areas. While the focus of these discussions was centered on research, other issues including education, partnerships, and U.S. competitiveness were common themes in all discussions.

## Executive Summary

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Civil and environmental engineering plays a critical role in addressing the needs of civilization: improving quality of life, promoting economic growth, and protecting people from threats of natural and human origin. Today, the professionals engaged in civil and environmental engineering are essential for supporting the global economy, securing the health and security of diverse communities, and enhancing environmental quality worldwide. Construction alone constitutes 5% of the Gross National Product of the United States. The United States infrastructure is valued at over \$13 trillion, with a substantial portion of these assets under the stewardship of civil and environmental engineering professions. Never in history has the demand for civil and environmental engineers been greater.

The 21<sup>st</sup> Century needs innovation and leadership from the engineering community. Among the most pressing concerns is human population growth, changing demographics, unprecedented urbanization, increasing per capita resource consumption, national security, climate change, economic globalization, and stresses from intense poverty. We are faced with important questions for which there are no clear answers. For example, changes in our sources of energy are inevitable, but what will they be and when will we be forced to change? As atmospheric greenhouse gases increase, how warm will the planet become? As massive coastal development continues, what will be the impact of sea level rise? As mega-cities arise, how do we create the infrastructure needed for the attendant large, dense populations? Finding answers to questions such as these, and providing solutions for a wide range of urgent societal needs are the responsibility of all engineers. They are especially relevant and compelling for the civil and environmental engineering professions, who are charged with advancing the technological and people-serving frontiers of the human habitat.

The 21<sup>st</sup> century will be a period of global economic expansion coupled with sustainable development. Through science and engineering, we will probe and understand the genomic structure of life, manipulate materials at the level of atoms, develop health technologies that greatly extend life spans, create information systems of unprecedented scale, and connect cultures through comprehensive social and technical networks. Civil and environmental engineering must play a pivotal role in these developments. Advancement aimed at meeting the needs of people will be influenced dramatically through research and graduate education. Today we are at a tipping point. Investment in research within civil and environmental engineering has not been seen as a national priority. As a result, exciting opportunities for students are not plentiful, human capital is limiting growth, and corporations are forced to off shore engineering services. Yet, there is a demand for engineers that exceeds supply and the civil and environmental engineering professions have never been faced with such a broad array of societal challenges that demand solutions. Addressing the challenges facing our profession will require leadership, innovation, and investment.

The limiting factor for corporate growth in civil and environmental engineering today is human capital<sup>1</sup>. Demand can be met only by relying heavily on the ability to hire engineers educated outside the United States. Moreover, there are serious impediments to forging the disciplinary links needed in the next generation(s) of U.S. civil and environmental engineers. The globalization of supply chains, the capacity of information technology, and the low cost of labor

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<sup>1</sup> Workshop address by Ralph Peterson, CEO of CH2MHill, is attached as Appendix 2.

elsewhere have the potential to make U.S. research and education of civil and environmental engineers “irrelevant”. Can we afford to let this happen? Do we wish to relinquish our leadership in this field and hope that others are committed to addressing the challenges facing society? Can we develop a bold vision for sustained leadership committed to new programs that develop and encompass fertile research areas, attract great minds, and transform results to meet the needs of people? To this end, the following points were considered throughout the workshop discussions:

- areas in which civil and environmental engineering have had a leading role in research associated with the complex challenges of the future;
- other disciplines needed as partners to accelerate the pace of research and educate students in new contexts;
- relevance of topics identified as frontier research and leadership of programs to transform results to meet societal needs.

Strong support for increased civil and environmental engineering research in each of the Workshop’s four theme areas (*Renewal, Management and Protection of Complex Systems; Sustainability; Global Impacts; and, Energy*) was expressed consistently throughout discussions. In fact, there was a sense that, as a community, we must promote meaningful, large-scale efforts in these areas. Certainly efforts are ongoing at most of the institutions represented, but in aggregate we have not established the cohesion and leadership needed for great advances in the near term. For this reason, a sense of urgency exists. The issues are real, and the societal needs are enormous. *There was a strong consensus that our research efforts must be high impact, interdisciplinary, and socially relevant.* For example, research that is focused on hazard mitigation in civil and environmental engineering is an example of our ability to establish programs with these characteristics. Numerous ideas for new directions in Civil and Environmental Research were discussed at the workshop. Examples of future research areas were developed through the preparation of white papers<sup>2</sup> from many of the workshop attendees. While not considered a comprehensive vision for the future of Civil and Environmental Engineering research, these white papers present compelling ideas, in a range of societal needs, which demonstrate the potential impact of transformative research involving civil and environmental engineers

*Also garnering strong support among attendees was the need for the fusion of civil and environmental research with other disciplines -- in particular social and natural sciences.* Many examples of areas for collaboration were articulated in white papers and during discussions at the workshop:

- the integration of market approaches with technology to manage environmental systems
- advances in nanomaterials for sensing the built and natural environments
- massive integration models for responsive infrastructure systems analysis and management
- using integrated decision support systems, geographical information systems, and health information to understand and address global infectious disease.

It is through applications in Civil and Environmental Engineering that discoveries in science and technology can rapidly improve the human condition. Research programs must be inclusive, so that interdisciplinary research, discovery, and solutions result in applications that improve the lives of all people.

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<sup>2</sup> White papers prepared by workshop attendees are provided in Appendix 2.

Considerable discussion took place regarding the current status of graduate programs and our ability to educate scholars in these new areas. The inability to “find people in these areas” during employment searches that are global in nature was a recurrent concern voiced by industrial as well as academic participants. The civil and environmental engineers of tomorrow will encounter complexity derived from social, cultural, and political contexts not envisioned today. They will need to be capable of producing more on a per capita basis than engineers in other countries where labor costs can be significantly less, and they will need to integrate discoveries into applications at an ever increasing rate. In previous decades, national funding agencies have recognized the need to create new (sub)disciplines through large-scale, innovative, and interdisciplinary graduate research programs. Students from these programs often populate academia and influence education profoundly. It is our hope that such an endeavor is considered strongly. *The most important outcome from research in these new areas will be the education of students with expertise focused on the pressing needs of tomorrow.* From these new research areas, new educational programs will evolve and impact the practice of civil and environmental engineering.

The themes of complex systems, energy, sustainability, and global impacts are not problems in isolation, but comprise cross-cutting issues where research can and should be focused. In doing so, themes would be addressed in the context of societal needs that can be articulated, understood, and valued. Our future societal needs demand broad research approaches, where discoveries are translated to solutions and where research is directed towards needed outcomes. *This requires civil and environmental engineers to emerge from the silos of sub-disciplines and become leaders in multidisciplinary research areas that integrate the physical and life sciences with the social sciences.* A commitment to a shared sense of social responsibility is urgently needed.

Three broad topics for future discussion and focusing of research expertise are:

*1. Energy, carbon cycle management, and climate change*

Civil and environmental engineers have important roles to play in the development of renewable and efficient energy systems. In a recent widely publicized report<sup>3</sup>, the author argues that “preliminary calculations adopting the approach to valuation taken in this Review suggest that the social cost of carbon today, if we remain on a BAU trajectory, is of the order of \$85 per tonne of CO<sub>2</sub>” (from Executive Summary, page xvi; BAU stands for business-as-usual). In other words, the business of reducing greenhouse-gas emissions corresponds to a very significant societal benefit (\$85 for each ton of CO<sub>2</sub> with the total annual emissions of greenhouse gases in 2000 was estimated<sup>4</sup> to be 42 GtCO<sub>2</sub>-e (Gigatons of CO<sub>2</sub> equivalent), of which 77% were CO<sub>2</sub>, 14% methane, 8% nitrous oxide and 1% so-called F-gases).

Major sources of greenhouse-gas emissions in 2000<sup>5</sup> include

- Power (24% of total): Driven from the generation of power and heat, mostly used in domestic and commercial buildings, and by industry.

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<sup>3</sup> Nicholas Stern, *The Economics of Climate Change: The Stern Review*, Cambridge University Press, January 2007

<sup>4</sup> World Resources Institute, 2006

<sup>5</sup> World Resources Institute, 2006

- Land Use (18%): Driven almost entirely from deforestation
- Transport (14%): Three quarters driven from road transport, 1/8<sup>th</sup> from aviation and the rest from rail and shipping.
- Industry (14%): 10% driven from combustion of fossil fuels in manufacturing and construction, 3% from industrial processes such as production of cement and chemicals.
- Agriculture (14%): Essentially non-CO<sub>2</sub> emissions coming from fertilizer use, livestock, and rice management
- Buildings (8%): Driven by direct combustion of fossil fuels and biomass in commercial and residential building mostly for heating and cooking.

We can not continue in a “business-as-usual” mode. *Radical, innovative, and transformational changes* in technology, processes, and policy implementation of many of the activities linked to the Civil and Environmental profession (e.g. transportation, construction, and infrastructure) will be necessary to make a significant impact. Given the many activities associated with our profession, we do have *unique opportunities to be leaders in impacting and contributing to greenhouse-gas reduction/trading*.

A *significant investment in research and development* is needed in the areas of Renewal, Management and Protection of Complex Systems; Sustainability; Global Impacts; and Energy at the most fundamental level for civil and environmental engineers and their colleagues in science and engineering. The following initial broad categories are indicative of major needs:

- Green power/renewable energy: Fundamental research is needed in order to design, develop, and build the various new distribution infrastructures that would be needed in order to bring these new energy sources to market. The burning of fossil fuels—coal, oil, and natural gas—is the largest contributor to greenhouse gas emissions worldwide. Alternative "green" energy sources such as wind, solar, geothermal, and biomass are widely available but are still a small fraction of energy supply.
- Sustainable transportation: Development of technically and environmentally sound solutions to the problems of urban transit.
- Construction materials: Developing new materials, and transforming/adapting current cement-based materials into more energy-efficient and environmentally friendly materials.
- Carbon capture and storage: Innovative research in the science and engineering of carbon capture and storage projects is needed to ensure highest environmental, health and social standards.

## *2. Multi-scale, systems based, hydrologic cycle management*

Meeting global water demand, improving water supply, and the maintenance of aquatic ecosystems has been a major effort of civil and environmental engineering for some time. Due to changes in global population, massive urbanization, and climate change important concerns exist as we look to the future. In the area of water, the compelling problems cut across disciplinary boundaries, geographical scales, and institutional dimensions. Key challenges include: dealing with scarcity, climate change, and degraded supplies; managing needs for the benefit of humans while protecting and restoring fragile ecosystems; and improving supply and sanitation in developing countries.

In a recent report from the National Research Council<sup>6</sup>, it was concluded that “The policies that guided water resources research and development in the twentieth century generally focused on water quantity, were uncoupled from water quality, and too often resulted in programs that focused on short-term and narrowly defined problems”. The hydrologic cycle is a complex system, and we rely on engineered systems for water quality and quantity. It is widely believed that we will become even more reliant on water technologies, including new approaches that require significant research, in the decade ahead. Examples of questions that require resolution include: how do we safely recycle wastewater; how can we better prevent pollution of water resources, including non-point sources; how can sensor technology improve our decision support systems to manage water resources; and, how do we prepare for changes in hydrology due to climate change? Central to all of these, and other questions, are the need to develop systems-based solutions to meet the ever-increasing water demands of the United States.

In developing countries, concerns regarding water include the need to address the links between water supply, poor sanitation, and health. Lack of access to clean water, adequate sanitation, and basic hygiene is blocking efforts to improve global health and development. Across the world, an estimated 1.1 billion people lack access to even a minimal amount of clean water, and 2.6 billion persons live without basic sanitation and hygiene facilities. In addition, fresh water has been depleted in many areas. Providing access to safe water and adequate sanitation is a component of several of the eight UN Millennium Development Goals (MDGs). Safe water is particularly central to the goals of reducing child mortality and achieving environmental sustainability, but is also a major factor in eradicating extreme poverty and hunger, addressing gender inequality, and improving maternal health. Achieving the goals set by the United Nations will require that water and sanitation services must reach 300,000 people each day need through 2015. Significant research is needed ranging from design and operation of decentralized water treatment facilities, minimizing the contamination of water resources through new sanitation facilities, to implementing technological advances in light of cultural barriers between people.

It is important to note that water and international security concerns are predicted to increase in the years ahead. This is most evident in the Middle East today. Suffice it to say, improvements in science, technology, and decision support systems have the potential to greatly improve the security of the United States and other countries.

### *3. Mega-cities and livability*

The rapidly growing world population is becoming concentrated in urban areas as a result of many economic, social, and political factors. The past 50 years has seen the emergence of mega-cities, generally defined as populations greater than 10 million. Many mega-cities are located on coastal regions that exposed to natural hazards and will be impacted by climate change. For example in the U.S., six of the ten largest cities are located in coastal regions or exposed to natural hazards related with coastal regions. Mega-cities are complex systems and the operation, growth, and renewal of these systems is essential to providing a healthy, safe, and vibrant place to live and work for its residents.

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<sup>6</sup> Envisioning the Agenda for Water Resources in the Twenty-First Century, National Academy Press, Washington, D.C.

Civil and environmental engineers have always been at the forefront of engineering our cities, but with the increasing complexities of systems that support mega-cities, dramatically new research avenues need to be pursued to deal with the unprecedented pressures of population growth and density, energy and environmental impacts, and protection from natural and man-made hazards. The characteristics of urban environments need to be recognized when developing new approaches for addressing these problems. The functioning of a city is complex with many interactions between people and social systems, infrastructure systems, business and industry, and the environment. In many cases, the interactions and interdependencies are poorly understood. The complexity has many positive attributes in that it is adaptable and self-organizing, but sometimes in *ad hoc* ways. On the other hand, urban systems may not be able to respond effectively to perturbations, such as the loss of a major transportation link or a natural disaster. The role of people, as individual decision-makers and collectively, has a major role in the adaptability, but also the fragility, of urban systems. These are amplified by the consequences of organizational failures. The livability of cities comprises enduring infrastructure and esthetics and social frameworks, and thus demands more creative use of our knowledge and greater sensitivity to the social contract.

Mega-cities have been designed and built and their evolution has been based on technologies from the mid-twentieth century. The opportunities that have arisen from advances in new materials, information technology, including communications and distributed control systems, renewable energy resources, and energy efficiency must be utilized to improve the robustness, safety, and livability of cities. Civil and environmental engineers are well-placed to lead inquiry into fundamental research questions, such as: how do complex urban systems function and the sub-systems interoperate, particularly when perturbed; what are the interactions between the built and natural environment, and how can they be designed and managed for optimal performance; how can functional, livable, and sustainable space at high densities be created above-ground and below ground recognizing constraints on energy, transportation, and water; what new interoperable infrastructure systems can lead to effective organization and function of mega-cities; and improve the safety and resiliency of cities when major disruptions of systems occur.

Civil and environmental engineers must collaborate with many other disciplines in science, engineering, and the social sciences. Technology alone will not create cities of the future. Engineers will need to be cognizant of the social, economic, and political factors that drive the growth and well being of cities, and create appropriate technological solutions that do not introduce their own set of problems.

### *Looking Toward the Future*

The purpose of this Workshop was to engage leaders in the Civil and Environmental Engineering community in a discussion of future research directions. Themes that emerged were multifaceted. First, there was broad consensus that the challenges facing our profession and society require vibrant research programs that engage Civil and Environmental Engineers in interdisciplinary programs that promote discovery and solutions. Second, it appears that an opportunity exists to create new sub disciplines through crosscutting research programs in fields (e.g. energy, sustainability, complex systems, among others) that will educate the next generation of leaders that are unique among their peers globally, and who will be on the forefront of research for decades to come. Third, there is a sense of urgency to initiate research programs in areas discussed earlier in this document and in the White Papers that follow. Human capital is needed

today and innovation is needed for our competitiveness. Last, we as a community will need to embrace change, emerge from our traditional organizational structures, and commit to focus our efforts on the emerging challenges of the 21st century.

A challenge that we must address initially centers on the ability to engage NSF in the support of research program areas in broad themes. This will require working across directorates and developing coordination on proposal requests, management, and peer review. If this is not addressed, it will be very difficult to make significant progress in the formulation of interdisciplinary teams. A secondary challenge is the engagement of a larger community of researchers in discussions regarding research directions and assets needed from outside of our current research domains. Addressing both of these concerns can be done in parallel, and activities should begin immediately.

As a first step, we anticipate workshops on the three themes with representation from the seven NSF directorates and broad participation from other agencies and non-governmental organizations. The goal would be to expand our vision and imagination, and set the framework for transformative collaborations leading to workable solutions. To engage our community, this report will be shared and disseminated in electronic form to universities around the United States. It is our hope that this report will initiate dialogue and debate regarding how best we can become leaders in interdisciplinary research directed at broad societal challenges that require the involvement of Civil and Environmental Engineers.

Appendix 1  
List of Participants

First Name	Last Name	Title	Institution
Linda M.	Abriola	Dean of Engineering	Tufts University
Adnan	Akay	Director of the Civil and Mechanical Systems	National Science Foundation
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Gregory	Baecher	Professor	University of Maryland
P N	Balaguru	Program Director, ENG/CMMI	National Science Foundation
Kathy	Banks	Professor and Head	Purdue University
Andrea	Be	Administrative Manager	Georgia Institute of Technology
Giovanna	Biscontin	Assistant Professor	Texas A&M University
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Efi	Foufoula-Georgiou	Professor	University of Minnesota
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Chris	Hendrickson	Professor and Department Head	Carnegie Mellon University
Janet	Hering	Director and Professor	Swiss Federal Institute of Aquatic Science & Technology
Martin	Hight	Senior Manager, Government Relations	American Society of Civil Engineers
Sandra	Houston	Professor	Arizona State University
Joseph B.	Hughes	Professor and Chair	Georgia Institute of Technology
James M.	Hughes, MD	Director	Emory University
Mary Ellen	Hynes, PE	Director of Research, Infrastructure and Geophysical Division	Dept. of Homeland Security Science and Technology Directorate
Patrick	Jaillet	Professor and Head	MIT
Paul	Jennings	Provost	California Institute of Technology
James O.	Jirsa	Professor	University of Texas at Austin
James H.	Johnson, Jr.	Dean of Engineering, Arch. & Comp. Science	Howard University
Michael	Kavanaugh	Vice President	Malcolm Pirnie Inc.
Alan J.	Krause	President	MWH International, Inc.
Nancy	Love	Professor	Virginia Tech
Richard G.	Luthy	Professor	Stanford University
Gil	Masters	Professor	Stanford University

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Darell	Nepil	Director of Human Resources	CH2M HILL
Thomas D.	O'Rourke	Professor	Cornell University
Joy	Pauschke	ERC Program Director	National Science Foundation
Ralph	Peterson	Chief Executive Officer	CH2M HILL
Alexander	Puzrin	Professor	Swiss Federal Institute of Technology
Lutgarde	Raskin	Professor	University of Michigan
Dorothy A.	Reed	Professor	University of Washington
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Susan H.	Skemp	Executive Vice President, CEFI	American Society of Civil Engineers
Patrick D.	Sullivan	Environmental Engineer	Air Force Research Laboratory

Appendix 2

White Papers