PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

Report of the First Joint Planning Meeting for the Second Phase of NEES/E-Defense Collaborative Research on Earthquake Engineering

Held at the U.S. National Science Foundation
Arlington, Virginia
January 12–13, 2009

Convened by the NEES Consortium, Inc.
and
Hyogo Earthquake Engineering Research Center
National Research Institute for Earth Science and Disaster Prevention

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PEER Report 2009/101
Pacific Earthquake Engineering Research Center
College of Engineering
University of California, Berkeley

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PREFACE

Following an agreement between the Japan Ministry of Education, Culture, Sports, Science and Technology (MEXT) and the U.S. National Science Foundation (NSF), the First Planning Meeting for NEES/E-Defense Collaboration on Earthquake Engineering Research was held in 2004. This meeting laid the groundwork for a five-year joint research program related to improving understanding and reducing the seismic vulnerability of bridges and steel buildings. To formalize the collaboration, two Memorandums of Understanding (MOUs) were executed, one between the NEES Consortium Inc. (NEES Inc.) and the National Research Institute for Earth Science and Disaster Prevention (NIED) of Japan in July 2005, and one between NSF and MEXT in September 2005. These MOUs cover collaborative activities through 2010.

Based on the success of the NEES/E-Defense Collaborative Research Program, and the potential positive impact of continued collaboration, a Planning Meeting was convened during January 12–13, 2009, to consider a possible second phase. The First Planning Meeting for the Second Phase of the NEES/E-Defense was held at NSF in Arlington, Virginia, in the U.S. The meeting, organized by NSF and NEES Inc. of the U.S. and MEXT and NIED of Japan, was attended by leading researchers from both countries as well as representatives from NSF, MEXT, and other government agencies. Overall, ten participants from Japan and twenty-six participants from the U.S. attended the meeting.

This report contains a summary of the meeting, along with the recommendations and resolutions reached by the participants. The appendices contain the list of participants, the meeting agenda and schedule, the reports of break-out sessions where participants discussed in detail various scientific and engineering challenges that should be addressed during future NEES/E-Defense collaboration, and white papers on various topics prepared by the participants prior to the meeting.

Joint Technical Coordinating Committee

Prof. Stephen Mahin, UC Berkeley

Dr. Steven McCabe, NEES Inc.

Prof. John Wallace, UCLA

Dr. Minoru Hakamagi,
Executive Director, NIED

Prof. Masayoshi Nakashima,
Kyoto University

Dr. Yoshimitsu Okada,
President, NIED

ACKNOWLEDGMENTS

The Joint Technical Coordinating Committee for the NEES/E-Defense Collaborative Research Program in Earthquake Engineering would like to thank the meeting participants for making the meeting a success by generously sharing of their time, experience, and ideas. The participants agree that the cordial and harmonious atmosphere at the meeting, and the candid and thoroughgoing discussions signal an outstanding future for NEES/E-Defense Collaboration.

The meeting was held at the National Science Foundation in Arlington, Virginia. The participants would like to express their gratitude to NSF for opening its facilities to them for this purpose. The support of NSF program managers, especially that of Dr. Joy Pauschke, and NSF staff contributed greatly to the success of the meeting.

The willingness of the Japanese delegation to participate in the meeting under their own funding is greatly appreciated.

The meeting was hosted by the NEES Consortium, Inc. who also made local arrangements and provided travel support for the U.S. participants. This financial support was made possible by Cooperative Agreement No. CMMI-0402490 and subsequent amendments and supplements from the U.S. National Science Foundation and the NEES Consortium Inc.

The findings, recommendations, and conclusions contained in this report are the consensus of the meeting participants and do not necessarily reflect the opinions of any one individual or the policy or views of the National Science Foundation, the National Earthquake Hazards Reduction Program, the NEES Consortium Inc., or other organizations in the U.S., nor of the Ministry of Education, Culture, Sports, Science and Technology, National Research Institute for Earth Science and Disaster Prevention, or the Hyogo Earthquake Engineering Research Center, in Japan.

CONTENTS

SUMMARY AND RESOLUTIONS OF THE FIRST JOINT PLANNING MEETING FOR SECOND PHASE OF NEES/E-DEFENSE COLLABORATIVE RESEARCH ON EARTHQUAKE ENGINEERING

BACKGROUND

The U.S.-Japan Joint High Level Committee (JHLC) on Science and Technology emphasized, in the Joint Communiqué of the Ninth Meeting, that the two countries should cooperate on multiple aspects of earthquake-related research. During the first Japan-U.S. Workshop on Science and Technology for a Secure and Safe Society (held in February 2004), the Japan Ministry of Education, Culture, Sports, Science and Technology (MEXT) and the U.S. National Science Foundation (NSF) agreed to discuss opportunities for cooperative activities related to earthquake research, citing NEES/E-Defense collaboration as a specific example of such cooperation.

To realize the cooperation, the First Planning Meeting for NEES/E-Defense Collaboration was held in 2004, and the basic scheme for a five-year joint research was established. Two thrust areas, i.e., steel buildings and bridges, were given highest priority for the joint research. To formalize the collaboration, two Memorandums of Understanding (MOUs) were executed, one between NEES Consortium Inc. (NEES Inc.) and the National Research Institute for Earth Science and Disaster Prevention (NIED) of Japan in July 2005, and between NSF and MEXT in September 2005. These MOUs cover collaborative activities through 2010.

SUMMARY OF PHASE I

The past four years of the First Phase of the NEES/E-Defense Collaborative Research Program on Earthquake Engineering have been successful. Five planning meetings (from the Second to the Sixth Planning Meeting) were convened in the U.S. and Japan during the past three years. Several important collaborative NEES/E-Defense research projects have been undertaken. Extensive exchange of data is occurring between counterpart researchers. Successful NEES/E-Defense sessions were organized and held at two ASCE Structural Congresses and the Fourteenth World Conference on Earthquake Engineering (14WCEE). Other joint project meetings and presentations at important professional gatherings in Japan, the U.S., and elsewhere are being planned to help plan the remaining research and disseminate its overall findings.

PLANNING MEETING FOR PHASE II

Based on the success of the current phase of the NEES/E-Defense Collaborative Research Program, and the potential positive impact of continued collaboration, a Planning Meeting was convened January 12–13, 2009, to consider a possible second phase. The First Planning Meeting for the Second Phase of the NEES/E-Defense was held at NSF in Arlington, Virginia, in the U.S. The meeting, organized by NSF and NEES Inc. of the U.S. and MEXT and NIED of Japan, was attended by leading researchers from both countries as well as by representatives from NSF, MEXT, and other government agencies. Overall, ten participants from Japan and twenty six participants from the U.S attended the meeting. The meeting was hosted by NEES Inc. The list of participants and the meeting agenda are provided in Appendix I and Appendix II, respectively.

ISSUES DISCUSSED

The meeting was organized to summarize the efforts and experiences during the past four years, to present an overview of the current environment of earthquake engineering, to identify the critical scientific challenges and research needs in earthquake engineering, and to seek a framework for the best collaboration between NEES and E-Defense. The final reports from the break-out sessions are presented in Appendix III. A series of white papers on a variety of topics is presented in Appendix IV.

The following topics were discussed in the plenary and breakout sessions.

Global Issues

A number of general issues related to the global need for large-scale testing and the mutual benefits of U.S.-Japan collaboration were discussed at the meeting.

Benefits of Large-Scale Testing. Scientific challenges in earthquake engineering that necessitate large-scale testing using E-Defense and NEES facilities were discussed. The ability of integrated computational/experimental investigations of large-scale foundation/structure systems to overcome limitations associated with experiments performed with small- and medium-scale models of components and systems, as well as of current numerical simulations, were highlighted in these discussions.

NEES/E-Defense Collaboration. Various frameworks for conducting a possible second phase of the NEES/E-Defense program were discussed. Among various alternatives, research based on broader meta-themes was found to be most effective. The issues may include validating model-based numerical simulation procedures, developing improved or new forms of construction that improve post-earthquake functionality (e.g., disaster-resilient communities), and devising design concepts to resist unusually large events, among others. Several options for enhancing collaboration were considered, including the introduction of "testbed" structures and jointly funded capstone experiments.

Meta-Themes

Three societal systems-level challenges, or meta-themes, were discussed as a means of focusing future research collaboration on high-priority needs of the U.S. and Japan, and for identifying the overarching scientific and engineering research challenges to be overcome and for suggesting specific research activities. The meta-themes examined were

Disaster-Resilient Communities. Disaster resiliency as a topic is virtually identical to seismic design issues raised by the Japanese participants at earlier meetings related to business interruption costs, or the "time is money" focus of modern society. This topic is also included in the draft NEHRP Strategic Plan in the U.S. It was recognized that the word "resiliency" should be defined more clearly; that is, is it simply making structures stronger? What are the scientific and engineering challenges? What are the expected outcomes, or can we integrate this topic with related topics of sustainability? Some have advocated considering disaster resiliency or seismic performance as a component of sustainability. Any meta-themes would likely involve parallel emphases on buildings, bridges, and other lifelines.

Preparing for the "Big One" (A Reference Magnitude 9 Event). Characteristics of great earthquakes and associated scientific and engineering challenges were discussed. Should such an event happen in urban areas, the consequences could be catastrophic. The ground shaking is unusually intense, has a long duration (measured in minutes), and when occurring near faults, may have unusually large and long-duration pulses that can adversely affect a range of structures in ways not seen previously. Failure modes not seen in lower-magnitude events may dominate behavior, e.g., large lateral displacements, ratcheting-type geometric nonlinearities, low-cycle fatigue, and others.

Low-Probability and High-Consequence Events. Protecting society from high-consequence but very low-probability events was discussed. Many new engineering problems that cannot be solved with the current earthquake engineering knowledge are present. They include the lack of information on regional seismic activities (inland areas of Japan, the central portions of the U.S.), lesser motivation and preparedness by the governmental authorities and general public, a larger difference between the normal and extreme seismic forces, and others. Different approaches are needed for both new construction and the retrofit of existing structures.

Additional information on these meta-themes can be found in Appendices III and IV.

Specific Scientific Challenges

To make timely and effective progress on the meta-themes considered, a number of critical scientific and engineering challenges need to be addressed. These were discussed in plenary as well as break-out sessions that focused on

Buildings. Special challenges related to building structures that are intended to be resilient, that use special materials, incorporate new technologies, or resist unprecedented large earthquakes were discussed. Topics included seismic isolation, supplemental damping devices, other response modification devices and systems, rocking foundations or uplifting modes of behavior, self-centering technologies, new materials, soil-structure interaction, among others.

Nonstructural Elements. Special challenges and opportunities associated with nonstructural components and systems to achieve resiliency or withstand an M9 event were discussed. Conventional design approaches are intended to avoid collapse of structures, but damage to nonstructural components and systems may be costly to repair and may seriously limit the use of a structure following a major earthquake.

Socio-Economic Issues. In the context of earthquake resiliency, discussion focused on engineering and economic information that is urgently needed to improve estimates of performance, repair cost, downtime, inspection requirements, and so on.

Transportation Systems. Topics were discussed related to improving bridge designs to minimize the need for post-earthquake damage repair and to maximize post-earthquake traffic flow, for example, seismic isolation, supplemental damping devices, other response modification devices and systems, rocking foundations, self-centering technologies, new materials, and soil-structure interaction.

Lifelines, Including Geotechnical Issues. Special challenges were discussed related to lifelines such as buried structures (subways, tunnels, etc.), water and wastewater systems, levees, power generation and distribution systems, and telecommunications systems, etc., that are intended to be resilient or resist unprecedented large earthquakes with limited disruption of services to the public. The topics discussed include soil-structure interaction, rocking/uplifting foundations, methods of soil improvement, among others.

Computational Simulation. Discussions focused on experiments needed to help address fundamental problems in developing and verifying high-fidelity modeling of engineered structures and in conducting high-performance (peta-scale) computations.

Monitoring and Damage Assessment. For the types of meta-themes mentioned above, rapid assessment of the condition of a structure following an earthquake would be highly desirable. Large-scale tests using NEES and E-Defense facilities provide an excellent opportunity to implement and evaluate such technology.

OVERALL OBSERVATIONS

All participants in the meeting unanimously agreed upon the productive history of collaboration on earthquake engineering between the United States and Japan for the past several decades and upon the successful implementation of the NEES/E-Defense collaboration for the past four years.

The participants also all learned that our contemporary societies, particularly those in urban areas, have become more vulnerable against earthquake disasters than fifteen years ago when we experienced the 1994 Northridge and 1995 Kobe earthquakes, and that the United States and Japan share the following recognition—society today is characterized by “continuing quest for quality of life,” “huge information flow,” “time is money,” and “complex interaction and inter-dependency of various constituents,” but that our buildings and urban infrastructures have not been accommodated or renewed to comply with society’s changing expectations and needs. Various challenges, including scientific, technological, economic, and societal ones, lie before the achievement of this goal, and the NEES/E-Defense collaboration is no doubt the best mechanism to work together toward this effort.

Based on the experiences of NEES/E-Defense for the past four years, it was agreed upon that the mechanism most appropriate for solid, focused, yet versatile collaboration is to set up “meta-themes” under which more specific and individual projects will be carried out in a complementary manner among various research groups in the two countries. It is also recognized that any meta-theme would most likely involve parallel emphases on a variety of components that form urban areas including buildings, bridges, and other lifelines, and that require strong ties between experimentation and computation.

RESOLUTIONS

Based on the presentations, discussions, and deliberations, the participants of the Planning Meeting for the second phase of NEES/E-Defense Collaboration formulated and unanimously adopted the following specific resolutions.

Resilient City as a Common Meta-Theme

The three meta-themes discussed in the meeting, i.e., “Disaster-resilient Communities,” “Preparing for the Big One,” and “Low-Probability, High-Consequence Events” are linked in many ways. The fundamentals of the first meta-theme are damage reduction and quick recovery. These require development of new materials and technologies that would enhance the performance of various components that form the urban area. Methods to detect damage quickly and systems that can be repaired (or re-built) with minimal interruption of life and business are also important topics to consider. In the second meta-theme, development of new materials and technologies are the key to the prevention of a downward spiral of deterioration. The third meta-theme has much in common with the preceding two in light of the specific scientific challenges to be pursued. Thus, it was agreed that the Resilient City provided a mutually important goal upon which members of the U.S. and Japanese earthquake engineering communities could work and that U.S.-Japan collaboration would accelerate realization of this goal and leverage the resources available in both countries.

Second Phase of NEES/E-Defense Collaboration Needed to Speed Realization of the Resilient City

Because of the importance of the Resilient City meta-theme to both the U.S. and Japan, and the smooth and effective collaboration already established between NEES and E-Defense, the participants agree that a second phase of the NEES/E-Defense Collaborative Research Program in Earthquake Engineering is needed. They also endorse pursuing the Resilient City meta-theme as the focus of the second phase. It is strongly believed that NEES/E-Defense collaboration by the U.S. and Japan provides the strongest mechanism to accelerate the pace of discovery and development in engineering needed to realize the goals of the earthquake disaster-resilient city.

Type of Collaboration

The Resilient City meta-theme requires an integrated effort of various disciplines (including architecture, economics, geotechnical and structural engineering, and so on) and consideration of various types of engineered structures that make up a contemporary city (including buildings, and transportation and other lifeline systems). A strong tie between experimentation and computation is indispensable in these studies. For the implementation of this collaboration, it is recommended that joint testbed structures be introduced and that jointly funded capstone experiments be conducted. Such synergistic exercises serve as an important tool for integrating research findings accumulated from a variety of more specific subprojects, explored by multiple small groups in both the United States and Japan, as well as for providing a final verification of the approaches, details, and technologies developed. It is recommended that engineering and other professionals are involved in the planning and interpretation of the research efforts to speed implementation and arrive at practical and cost-effective solutions. .

Scientific Challenges and Specific Research Needs

In the scope of the meta-theme of Resilient City, scientific challenges and specific research needs as well as the benefit acquired through the NEES/E-Defense collaboration, are shown below with respect to the focus area. The details of respective focuses are summarized in Appendix III.

Buildings. The Resilient City, with undertones of low damage, quick recovery, and sensible rebuilding, needs new building materials, technologies, and systems that efficiently control damage, as well as smart structures that can "tell you where it hurts." These high-performance structures perform well whatever (within reason) they are subjected to, and sustain damage that can be quickly found and repaired. Attention should be focused on methods to improve the resilience of existing structures. Several concepts provide particularly attractive avenues to pursue through NEES/E-Defense collaborative research: Structures with clearly defined and replaceable fuses; self-centering systems (unbonded post-tensioned cast-in-place walls, seismic isolation (including use in high-rise structures), rocking/uplifting systems (including structure-foundation-soil interaction effects), new and innovative structural systems, etc.); structures with improved nonstructural systems, including unibody systems that utilize nonstructural components as part of the lateral load-resisting system; new high-performance materials that are less susceptible to damage; and super-resilient structures. Large-scale NEES and E-Defense tests of complete structural systems are important to provide essential "proof of concept" demonstrations as well as the quantitative data needed to calibrate design and analysis methods.

Nonstructural Elements. Damage to nonstructural components and contents contribute significantly to the safety of engineered structures during and following earthquakes and the cost and duration needed for repairs. Many nonstructural components are complex, often extending throughout a structure and interacting with other nonstructural systems (electricity, communications, etc.). The behavior of these systems is not adequately understood, and plentiful opportunities exist to develop improved nonstructural components that are more resistant to damage, or structural systems that substantially reduce damage to nonstructural components and systems. E-Defense and NEES tests provide many opportunities to improve our understanding of and ability to control the factors that govern the seismic performance of nonstructural elements and systems.

Transportation Systems. Transportation systems are vital to the health, prosperity, and security of modern society. Recent earthquakes have shown that these systems can be vulnerable to earthquake damage with unacceptable socio-economic consequences. Damage-free bridges with minimal loss of functionality and repair time should be explored, with cost effectiveness in mind, to facilitate post-earthquake emergency response and the rapid recovery of the affected region. Specific research needs include the development of damage-free smart bridges using innovative materials, devices, and configurations, the development of bridge configurations that enable faster repair, and the development of damage-free foundations subjected to large ground movement.

Lifelines, Including Geotechnical Issues. The focus of the research should be on buried lifelines and other underground structures. Damage to such buried structures during large earthquakes has serious implications for the life of a city, as it may interrupt essential transportation, power and water supply functions, as well as trigger destructive fires following the earthquake. There are large and complex underground structures whose seismic performance and interaction with surrounding soils are not yet well understood. Engineering and scientific challenges are mainly in the areas of soil-structure interaction (SSI) and geotechnical research. Specific research needs where E-Defense/NEES collaboration would be most helpful were identified as follows: (i) response of subway stations, tunnels, and buried pipes; (ii) strategies to improve performance of underground structures; (iii) prevention of flotation of underwater tunnels; (iv) development and evaluation of ground improvement and remediation strategies; (v) increased knowledge of permanent ground deformation hazard and its effects, especially in challenging and heterogeneous soil profiles; and (vi) soil-structure interaction studies of both underground and above-ground structures considering the whole structure-foundation-soil system. Tests at E-Defense should be generally planned as part of research programs including appropriate centrifuge and smaller shake table tests, as well as a computational effort; in some cases coordination with testing at large static facilities, like that at Cornell University, should also be considered.

Computational Simulation. Numerical simulation of the full range of behavior of 3D structure-foundation-soil systems up through collapse is a basic tool needed to evaluate the seismic resistance and safety for a resilient city. Specific research areas include improvement of models of materials and components, particularly for nonductile and deteriorating modes of behavior; development of algorithms and software systems that conform to modern computer architectures; simulation of collapse of 3D structural systems; and representation of the uncertainty in behavior. A true integration between experimentation and simulation modeling is needed to realize robust, high-fidelity numerical simulation capabilities. Hybrid tests and large-scale shaking table tests are essential to carry out coordinated structure-foundation-soil interaction tests at a range of scales to improve the current simulation models and algorithms that use massively parallel computation.

Monitoring and Condition Assessment. Structural health monitoring systems can provide vital information on the state of a structure (a) before an earthquake, leading to repair and strengthening, (b) during the emergency response period, providing information on critically damaged or collapsed structures, and (c) during the recovery period, providing information on the type and degree of damage of a large number of structures and thereby reducing the recovery time. NEES and E-Defense tests provide important opportunities for conducting parallel structural health monitoring and prognosis projects that develop and implement structural health monitoring systems, and that validate and calibrate damage diagnosis and prognosis algorithms. All these activities are needed to increase the resiliency of the earthquake-affected region.

Future Discussion and Establishment of Implementation Mechanism

The participants found that this meeting was an excellent starting point for jointly discussing critical societal level issues (meta-themes) that earthquake engineering should act upon to protect the welfare of contemporary society, and for the contributions that NEES/E-Defense collaboration can make toward this end. Every effort has to be made, and any opportunity utilized, to continue and enhance the discussion between the two countries on this topic, and to put in place an implementation mechanism for the type of NEES/E-Defense collaboration discussed.

Several opportunities exist in the near-term to continue these discussions. These include a full-scale test at E-Defense in early March 2009 on a steel structure equipped with various passive dampers; the 2009 NEES annual meeting in Hawaii in mid-June 2009; and another full-scale test at E-Defense in August 2009 on a NEES rocking frame.

The participants also agreed that the Joint Technical Coordinating Committee (JTCC) of NEES/E-Defense collaboration should be reorganized so that the committee can take a more active role to the planning of the collaboration in addition to its implementation. This is a subject for resolution as quickly as possible.

CLOSURE

The participants believe that the Planning Meeting for the second phase of the NEES/E-Defense Collaborative Research Program on Earthquake Engineering was highly successful, and that NSF and MEXT should be congratulated for providing the earthquake engineering community with cutting-edge tools that will substantially accelerate progress toward the important goals of earthquake loss reduction. The attendees agree that the cordial and harmonious atmosphere at the meeting, and the candid and thoroughgoing discussions signal an outstanding future for NEES/E-Defense collaboration. The participants encourage the appropriate funding agencies in the U.S. and Japan to provide funds needed to realize the benefits of the second phase of

NEES/E-Defense collaboration. The participants also appreciate and heartily thank NSF for its efforts in hosting this successful meeting.

APPENDIX I: LIST OF PARTICIPANTS

Participants from Japan:

JTCC/E-Defense

Dr. Minoru Hakamagi, Executive Director of NIED**

Prof. Masayoshi Nakashima, Kyoto University/Steel; Director, Hyogo Earthquake Engineering Research Center

Dr. Yoshimitsu Okada, President, NIED

Dr. Takahito Inoue, Head of Planning Section of E-Defense

Government Agencies:

Dr. Kohei Miyagawa, Deputy Head of Disaster Mitigation Section of MEXT

Earthquake Engineering Research Community

Prof. Muneo Hori, University of Tokyo, Simulation

Prof. Toshimi Kabeyasawa, University of Tokyo, Building/RC

Prof. Kazuhiko Kawashima, Tokyo Institute of Technology, Bridge/RC

Prof. Akira Nishitani, Waseda University, Structural Control/Monitoring

Prof. Ikuo Towhata, University of Tokyo, Geotech/Soil

Prof. Kohji Tokimatsu, Tokyo Institute of Technology, Geotech/Soil

Participants from the United States:

JTCC/NEES Consortium, Inc.

Prof. John Wallace, University of California, Los Angeles, Structural engineering; President, NEES Consortium, Inc.

Dr. Stephen McCabe, Executive Director, NEES Consortium, Inc.

Prof. Stephen Mahin, University of California, Berkeley, Structural engineering/protective systems

Tiffany Lawhorn, Executive Assistant, NEES Consortium, Inc.

NEHRP and Government Agencies:

Dr. Joy Pauschke, Dr. Rick Fragaszy, Dr. George A. Hazelrigg (Acting Division Director), Dr. MP Singh and Dr. Dennis Wenger, Program Managers, NSF

Dr. Jack Hayes, Director, National Earthquake Hazards Reduction Program (NEHRP)

Jay Harris and H.S. Lew, NIST

Mike Mahoney and Ken Wong, FEMA

Dr. Phil Yen, FHWA

Earthquake Engineering Research Community

Prof. Ross Boulanger, University of California, Davis, Geotech

Prof. Ian Buckle, University of Nevada, Reno, Bridges/Protective systems

Prof. Gregory Deierlein, Stanford University, Structural Engineering

Prof. Ricardo Dobry, RPI, Geotech

Prof. Gregory Fenves, University of Texas, Austin, Computational simulation
Prof. Maria Garlock, Princeton University, Self-centering systems/fire
Prof. Jerry Hajjar, University of Illinois, Urbana-Champaign, Composite systems and computational simulation
Prof. Anne Kiremidjian, Stanford University, Health monitoring/condition assessment/sensor technology)
Prof. Michael Kreger, Purdue, Structural Engineering; NEESops proposal team representative
Prof. Roberto Leon, Georgia Institute of Technology, Atlanta, Structural engineering; NEESops proposer
Prof. Manos Maragakis, University of Nevada, Reno, Nonstructural components
Prof. Jack Moehle, University of California, Berkeley, Structural engineering
Prof. Andrei Reinhorn, University of Buffalo, Structural engineering
Prof. Bill Spencer, University of Illinois, Urbana-Champaign, Health monitoring/control; NEESops proposer

** Not able to attend

APPENDIX II: MEETING AGENDA AND SCHEDULE

DAY 1: Monday, January 12, 2009

Time	Topics	Presenters	Chairs
9:00 – 9:15	**Welcoming Remarks** (NEES, NIED/E-Defense, NSF, MEXT, NEHRP)	McCabe (NEES) Okada (NIED) Pauschke (NSF) Miyagawa (MEXT) Hayes (NEHRP)	Mahin, Nakashima
9:15 – 10:00	**Introductions**		Wallace, Nakashima
	Purpose and agenda for meeting	Mahin	
	History of U.S.-Japan Cooperation, including NEES/E-Defense Collaborative Research program	Mahin	
	Japanese R&D plan on disaster reduction	Okada	
	National Earthquake Hazards Reduction Program *… a research and implementation partnership*	Hayes	
10:00 –10:45	**Vision for Next Phase of NEES/E-Defense Collaboration**		Buckle, Kabeyasawa
	“White paper” plenary presentations on Global issues		
	Why are full-scale experiments of large systems needed?	Nakashima, Deierlein	
	Organizational structure for NEES/E-Defense collaboration	Mahin, Nakashima	
10:45 – 11:00	**Break**		
11:00 – 12:20	**Plenary Discussion on Global Issues**	All	Buckle, Kabeyasawa
	“White Paper” Presentations on Possible Meta-Themes		
	Earthquake Disaster Resiliency	Reinhorn, Nakashima, Garlock ,Hori, Moehle	
	Preparing for the big one (a reference M 9 event)	Mahin, Tokimatsu	
	Design high-consequence but low-probability events	Hajjar, Kawashima	
12:20 – 13:00	**Plenary Session Discussion on Meta-Themes**	All	
13:00 -14:00	**Lunch**		
14:00 – 15:45	**Break-out sessions on Meta-Themes** Resiliency Big one Low Probability		Moehle, Nakashima Mahin, Tokimatsu Hajjar, Kawashima
15:45 – 16:00	**Break**		
16:00 – 17:00	**Plenary session** (summarizing prior break-out sessions, and getting comments from all)	All	Deierlein, Tohata
18:30	**Dinner**		

Appendix II:—*Continued*

DAY 2: Tuesday, January 13, 2009

Time	Topics	Presenters	Chairs
8:45 – 10:00	**Plenary Discussion on Engineering Challenges-1**		
	"White Paper" Presentations on Specific Engineering Challenges 1		Boulanger, Nishitani
	Buildings, including foundations	Kabeyasawa, Moehle	
	Nonstructural and socio-economic issues	Maragakis, Deierlein, Nakashima	
	Bridges and transportation systems, including foundations	Buckle, Kawashima	
10:00 – 10:15	**Break**		
10:15 – 11:15	**Break-out sessions on *Engineering Challenges1***		
	Buildings		Moehle, Kabeyasawa
	Nonstructural		Maragakis, Inoue
	Bridges		Buckle, Kawashima
11:15– 11:45	**Plenary Session on *Engineering Challenges – 1*** (to present break-out session findings)	All	Garlock, Hori
11:45 – 12:45	**Lunch**		
12:45– 14:00	**Plenary Discussion on Engineering Challenges- 2**		Hajjar, Tokimatsu
	"White Paper" Presentations on Specific Engineering Challenges 2		
	Lifelines (underground structures)	Tohata, Boulanger, Dobry Tokimatsu	
	Computational simulation	Fenves, Hori	
	Health monitoring, damage assessment, new technologies	Nishitani, Kiremidjian	
14:00 – 15:00	**Break-out sessions on *Engineering Challenges 2***		
	Lifelines		Boulanger, Tohata
	Analysis		Fenves, Hori
	Monitoring		Kiremidjian, NIshitani
15:00 – 15:30	**Plenary Session on *Engineering Challenges - 2*** (to present break-out session findings)	All	Hajjar, Tokimatsu
15:30 – 15:45	**Break**		
15:45 – 16:15	**Plenary Session on Recommendations and Resolutions**	All	Mahin, Nakashima
	Specific recommendations on NEES/E-Defense and White Paper topics	All	
	Recommendation for follow-up meeting and potential invitees	All	
16:15 - 16:30	**Closing Session**		

APPENDIX III: BREAK-OUT SESSION FINAL REPORTS

META-THEME: THE RESILIENT CITY

Members: M. Nakashima (co-chair), J. Moehle (co-chair), R. Boulanger, I. Buckle, G. Fenves, M. Garlock, T. Kabeyasawa, A. Kiremidjian, M. Maragakis, A. Nishitani, and A. Reinhorn

Background

The concept of the Resilient City envisions a city in a highly seismic region that has made a comprehensive plan for hazard mitigation, emergency preparedness, and rebuilding, with a target schedule for when certain key city functions are restored. The objective of the plan is to ensure that the city can recover from expected earthquakes in an efficient manner that enables people to remain in the city and receive needed services in a timely manner.

Essential components of the plan include the ability to

- **Contain the effects** of earthquakes through mitigation;
- **Carry out recovery** activities in ways that minimize social disruption; and
- **Rebuild** in ways that mitigate the effects of future earthquakes.

The comprehensive plan for the Resilient City might include a target schedule in which emergency response facilities are **immediately functional;** household units are inspected and most are safe for inhabitants to shelter in place **within one day;** 90% of the water, power, and waste water systems are operational **within 3 days;** 90% of transportation systems, schools, and businesses are open and serving the local workforce **within 30 days;** etc.

The research question pertinent to NEES and E-Defense is What technologies can earthquake engineering research develop and demonstrate to support the resilience goals of the Resilient City?

Scientific Challenges

Several scientific challenges arise, including

- Identification of seismic shaking hazards and the distribution of those hazards across an urban region, to better understand the spatial distribution of seismic demands that will affect performance citywide;
- Development of new materials that are more damage resistant;
- Development of new, high-performance systems for new and existing buildings and lifelines systems;
- Remote sensing and rapid data assimilation for health monitoring and damage assessment; and
- Computer modeling and simulation capabilities for components of the Resilient City, as well as massive-scale simulation of regional response to earthquake effects.

Specific Research Needs

- Damage detection using remote sensing. The objective would be to be able to identify damage in facilities given various degrees of knowledge of the details (materials, construction quality, structural system, etc.) that may be available for the range of facilities in the Resilient City.
- Development of structural systems/materials that are less impacted by earthquake effects and that are more easily repaired;
- Development of improved modeling and simulation through a coordinated program of experimental and numerical simulation;
- Development of appropriate definitions and metrics to quantify resilience; and
- Incorporated consideration of aftershocks and fire following earthquake.

Benefits of NEES / E-Defense Collaboration

- Broad research theme to promote broad thinking from the community, but with a focus that is important socially and technically;

- Studies are needed at the materials, components, subsystem, and complete structural system levels using NEES and E-Defense facilities. Of particular importance will be to demonstrate system behavior at large scale using relatively complete 3D models.
- E-Defense structures can serve as blind test structures for improving analysis/simulation and for testing damage detection methods.

META-THEME: PREPARING FOR THE BIG ONE

Members: Kohji Tokimatsu (co-chair), Stephen Mahin (co-chair), Ricardo Dobry, Jay Harris, Muneo Hori, Takahiro Inoue, Roberto Leon, and John Wallace

Background

Great earthquakes occur in the U.S. and Japan at regular intervals and pose a tremendous life-safety and economic threat to urban areas that experience such motions. Preparations for such large events focuses on achieving

- Resilient or life safe structures when subjected to a magnitude 8+ event, or
- Adequate safety under earthquakes significantly larger than considered in design (characteristics may depend on location).

Scientific Challenges

Several interrelated challenges need to be addressed in a multidisciplinary fashion:

1. Characterization of ground motions
   a. Long duration of strong shaking, including aftershocks
   b. Unusually high displacements, velocities, and accelerations
   c. Unusual ground motion features, such as rupture-related pulses, directivity effects, and surface waves
   d. Large region affected by intense earthquake shaking
2. Collapse prediction, including improved capabilities for numerical simulation to assist in understanding and mitigating the effects of
   a. Low-cycle fatigue
   b. Geometric nonlinearities
3. Focused studies of special structures that may be particularly vulnerable to large-magnitude earthquakes, including structures having long fundamental periods, such as
   a. Tall buildings
   b. Large tanks
   c. Long-span bridges, etc.
   d. Nuclear and other power-generation facilities

4. Development and validation of new systems, materials, and technologies to reduce structural vulnerability to great events
5. Development of understanding of the vulnerability of buildings following earthquakes to fire, and effective methods for suppressing the spread of fire. Fire initiation and spread is expected to be more likely following large events.
6. Development of improved strategies to control the motion of structures during intense shaking.
   a. Develop and assess the effectiveness of new systems and technology
   b. Improve performance of nonstructural elements and systems
   c. Better understand human response to seismic motions and develop effective methods for reducing adverse effects of human perception
7. Evaluation of the integrity of gravity-load-only resisting systems during great earthquakes, and improvement as needed to achieve a desired confidence in structural safety.

Specific Research Needs

Need collaborative and coordinated efforts by multi-disciplinary teams to

1. Improve characterization of primary and aftershock ground motions for great earthquakes;
2. Improve understanding of behavior, including deterioration and failure, of materials, components and subassemblages of structures, foundation systems, and soils and buried lifelines when subjected to intense, long-duration 3D motions;
3. Improve understanding of response and sensitivity of response various structural systems to ground motion characteristics representative of great earthquakes (pulses, long-duration shaking, surface wave effects, etc.);
4. Improve understanding of response and sensitivity of response of soft soil to many cycles of strong shaking during great earthquakes and effects on structures and lifelines.

Benefit of NEES/E-Defense Collaboration

1. Development and validation of material failure characteristics (deterioration and failure models) possible
2. Subassemblages of structures, nonstructural elements, lifelines, foundations, etc. (deterioration and failure models) can be tested.
3. System response studies for various ground motion histories representative of great earthquakes (rupture-related pulses, long-duration, surface waves, etc.), including
    a. Collapse-related studies,
    b. 3D shaking,
    c. Soil deposits and buried structures,
    d. Tall buildings,
    e. Innovative systems to improve behavior, and
    f. Accuracy of numerical models under long duration shaking.
4. Use of data for “un-invalidating” numerical simulation models and procedures.

META-THEME: MITIGATING CATASTROPHES FROM LOW-PROBABILITY, HIGH-CONSEQUENCE EVENTS

Participants: K. Kawashima (co-chair), J. Hajjar (co-chair), G. Deierlein, M. Kreger, H. S. Lew, B. Spencer, and I. Towhata

Background

1. Low-Probability, High-Consequence Seismic Events
    a. U.S.: *East of the Rockies*: *New Madrid; Charleston, SC; Northeast U.S.*
        i. Adoption of seismic provisions is not uniform across the country. Many localities east of the Rocky Mountains have little history of adopting seismic design codes or practices, even after national specifications have strengthened seismic requirements in these regions;
        ii. Construction practices remain fundamentally different in zones of low-probability, high-consequence events as compared to high seismic zones;
        iii. If one state adopts seismic provisions and a neighboring state does not, regional cost-benefit assessment becomes more complicated.
    b. Japan: *Inland Earthquake*
        i. While inland earthquakes have long recurrence intervals (for example, there had not been a major seismic event in Kobe, Japan, for over 400 years prior to the 1995 event), seismic engineering and construction practices are often comparable across the country.
2. Common ground:
    a. Some regions of each country have better seismicity and soil data than other parts of each country.
    b. Regions with long recurrence intervals have strong differences between the public and engineering perception of the threat.

Science-based Engineering Challenges

1. *Geotechnical Information* is lacking in the U.S. and Japan. Need
   a. Micro-zonation maps including site-specific ground motions, liquefaction potential, and slope stability;
   b. Improved resolution of borings; and
   c. New technologies for accurate prediction of liquefaction on a widespread basis.
2. *Engineering Detailing*
   a. In the U.S.: In regions of low-probability, high-consequence events:
      i. Building officials often do not know how to assess high seismic systems;
      ii. Fabricators and contractors often do not know how to detail high seismic systems;
      iii. Inspectors often are not trained in West Coast inspection practices;
      iv. Engineers often are reluctant to adopt West Coast seismic systems.
   b. In the U.S. and Japan:
      i. Developing lower-cost, limited-ductility systems may be especially valuable for low-probability, high-consequence events;
      ii. Developing fuses that absorb appropriate amounts of damage at different levels of seismic magnitude may offer specific opportunities in these regions.
3. *Performance-Based Engineering*

   Low-probability events skew performance-based engineering targets and decision support priorities to focus on most critical facilities.

Specific Research Needs

1. Characterization of previously unknown high-magnitude, near-fault, long-duration ground motions for low-probability earthquakes. Neither country has had an 8.0 earthquake on its mainland in recent history.
2. Increasing the resolution of soil information in these regions that have little history of dense geotechnical readings, including general soil conditions and liquefaction.
3. Characterization of previously unknown high-magnitude, near-fault ground motions for low-probability earthquakes.
4. Developing procedures for designing for potential surface rupture at known faults, especially for transportation and lifeline systems. For example, transportation and

lifeline systems are becoming increasingly complicated in three-dimensions, thus complicating the understanding of low-probability, high-consequence events.

5. Understanding the performance and improving the collapse resistance of limited-ductility systems:
   a. Performance-based design targets may need to be restructured for these regions;
   b. Retrofit priorities and decision-support engines may need to be recalibrated for corresponding appropriate performance targets.
6. Development of new engineering strategies appropriate for affected regions.

Benefits of NEES/E-Defense Collaborative Research

How best to achieve synergy on these topics?

1. Common high-priority issues between the U.S. and Japan include
   a. Some regions in each country are relatively unprepared as compared to other regions.
   b. Approaches are needed for better characterizing seismic hazard in regions that historically have not received significant attention.
2. Disparate issues between the U.S. and Japan:
   a. U.S. has regions with much less historical seismic preparation than in Japan.
   b. U.S. has regions with dramatically different construction practices than in high seismic regions.

Target Topics for NEES-E-Defense Planning:

1. Lower-cost, limited ductility systems, fuse systems, or systems that target appropriate performance objectives (new construction and retrofit) may enable new prefabricated technology development in these regions.
2. Possible specific opportunities of creating new industries related to industrialized, prefabricated solutions in these regions.

Coordination:

1. Japan can offer geotechnical engineering solutions on effect of soils for very strong, low-probability ground motions; these strong motions may liquefy soils that historically have not been.

2. Japan can offer structural engineering solutions on resistance to very strong, low-probability ground motions.
3. U.S. can take the lead on low-ductility systems that may offer significant benefits to both countries.
4. Both countries have interest in fuse-based systems.
5. U.S. can offer component testing on appropriate structural systems.
6. Japan can offer large-scale testing of appropriate structural systems.
7. Japan can offer testing of appropriate large-scale, complex lifeline systems.
8. U.S. can offer testing of appropriate large-scale centrifuge testing of complex lifeline systems.

SPECIAL ENGINEERING CHALLENGES: BUILDINGS

Members: Kabeyasawa (co-chair), J. Moehle (co-chair), R. Dobry, M. Garlock, J. Hajjar, M. Hori, M. Kreger, R. Leon, A. Nishitani, A. Reinhorn, K. Tokimatsu

Background

Three main meta-themes were considered as part of the Phase 2 NEES/E-Defense Research Planning Meeting. Each meta-theme poses a slightly different focus for future research needs related to buildings, though there are many overlapping aspects.

- The **Resilient City**, with undertones of low damage, quick recovery, and sensible rebuilding, needs new building materials, technologies, and systems that efficiently control damage, as well as smart structures that can "tell you where it hurts."
- **Preparing for the Big One** incorporates concepts of the Resilient City—how to avoid the downward spiral to a New Orleans Hurricane Katrina scenario. It also suggests the need for new structural materials, technologies, and systems that control the rate of deterioration of the lateral force-displacement relationship when displacements exceed the maximum values heretofore contemplated.
- **Mitigating Disasters from Low-Probability, High-Consequence Events** likewise envelops the preceding two concepts in many ways. Interpreted from the perspective of a massive earthquake on the San Andreas fault in Southern California or a mega-earthquake off the coast of Japan, this theme links well with the preceding two. Interpreted from the perspective of a large earthquake in the central United States, or a large, low-probability inland earthquake in Japan, the implications for buildings research are wholly different because of the differences in construction types and social perspectives between traditionally "seismic" and "low-seismic" regions.

Scientific Challenges

The societal focused meta-themes considered suggest a need for structures that are

- Robust and able to maintain their structural integrity for ground shaking that is very large compared to recent earthquakes experienced in the U.S. and Japan or larger than considered in normal design.

- Resilient and able either to sustain damage that is easy to detect and repair, or able to withstand major earthquake shaking without need for extensive post-earthquake repair.

To accomplish these enhanced performance goals, considerable research will be needed to develop and validate cost-effective systems that utilize new materials, details, technologies or configurations, or behave in a fashion fundamentally different from current structural systems.

Inherent in the development and design of such high-performance or next-generation structures is the ability to conduct high-fidelity computational simulations of the full range of seismic response, and to monitor the behavior of the structure during an earthquake to confirm immediately its safety, suitability for continued occupancy, and the nature of any needed repairs.

Specific Research Needs

Specific examples of high-priority research needs are provided below, with emphasis on topics that require physical experimentation or that suggest the need for physical experimentation to validate a concept.

High-Performance Buildings

These structures perform well whatever (within reason) they are subjected to, and sustain damage that can be quickly found and repaired. High-performance structures that are economical are especially sought so they can be more widely used. Consideration should be given, perhaps as a priority, to existing structures. Concepts considered should be innovative, but it would be desirable to include engineering practitioners in the research to ensure practical and cost-effective solutions. Large-scale tests of complete structural systems are important to provide essential "proof of concept" demonstrations as well as quantitative data. Some specific ideas include

- **Structures with clearly defined and replaceable fuses.** If the fuse is clearly identified beforehand, it can be quickly inspected and replaced if necessary, reducing costs and speeding the recovery process. The fuse might be designed using a performance-based approach (perhaps more suitable for a highly seismic region) or it might be some inherent or prescriptive fuse that does not require detailed calculation (perhaps more suitable for a less seismically active region). Designs should take advantage of inherent yield mechanisms considered in the design of many structures.

- **Self-centering structures.** These structures are inherently resilient because of the self-centering nature. Some examples have been explored already, but their applicability seems restricted and their reliability has not been fully demonstrated; therefore, they are not widely used. The concept needs to be generalized to use more common construction technologies, and these need to be validated through component tests and complete structural system shaking table tests. Examples include unbonded post-tensioned cast-in-place walls, seismic isolation (including use in high-rise structures), rocking/uplifting systems (including structure-foundation-soil interaction effects), and new and innovative structural systems, etc.
- **Buildings with improved nonstructural systems.** Examples abound, but this could include development of new systems for contents, interior nonstructural components, cladding, vertical MEP systems, etc. It may be possible to develop new structural systems, like those discussed above, which help protect contents and nonstructural elements and systems.
- **Unibody construction.** "Unibody" residential construction could make effective use of all the partitions to resist seismic loads (e.g., think about how the auto industry moved from fenders on frame systems to welded unibody systems). Can the idea be scaled up to larger buildings?
- **Homeowner solutions.** If a goal is for residents to be able to shelter in place following an earthquake, what simple, cost-effective, versatile systems can be developed to enable this to become an achievable goal for homeowners?
- **Super-resilient buildings.** Rather than attempt to raise the performance of large populations of buildings, focus could be placed on selective hardening of a smaller number of buildings. This concept would promote a more freethinking approach to achieving resilient communities less encumbered by the staggering economics of toughening large urban regions. Such superhard facilities would not only improve the resilience of a city, but would provide a margin for earthquake shaking exceeding the maximum considered shaking levels. Both new and retrofit approaches could be considered.
- **New high-performance materials.** Many examples exist or can be engineered. A well-known example is tensile-strain-hardening fiber reinforced concrete, high-strength materials, low-yield-strength steels as local fuses, new damage (fracture or fatigue)

resistant materials or details, etc. Greater use should be made of new or recycled materials that contribute to global sustainability. To ensure effective use of these materials in a range of structural components and systems needs experimental validation.

Structural Health Monitoring

The Resilient City is one that can rapidly assess the condition of its building stock (or individual buildings) after an earthquake. Rapid access to actual response data and means to visualize those data are essential for making a reasonably rapid post (mega-) event assessment of functionality, level of damage, and time and cost of repairs. The system must be flexible enough to accommodate various sensors, data rates, etc., and to utilize sensors and networking systems that are inexpensive, ubiquitous, and robust.

- Research is needed involving multidisciplinary teams of researchers with interests in complex experiments (SFSI, complete systems), health monitoring (use of novel sensors, data communication, management and visualization), and computational simulation. The teams could focus on smaller-scale (NEES), quasi-static and shake table tests of systems that include both lateral and gravity systems, including diaphragms and possible foundation/soil systems. Development work could be done on smaller-scale test structures (quasi-static, dynamic) and in the field (ambient- and forced-vibration), with a final test of maybe two systems using E-Defense facilities.

Benefit of NEES/E-Defense Collaboration

The U.S. and Japan share many of the same problems related to the seismic performance of buildings. Collaboration of U.S. and Japanese researchers and engineers via NEES and E-Defense will accelerate realization of high-priority goals of mutual interests. Many technologies have been around for decades, but their implementation are impeded in many cases by onerous acceptance criteria (e.g., consider seismic isolation in the U.S.). While improved acceptance methods for new systems and materials are needed, large-scale complete system tests and performance-based computational simulations that assess and validate these systems and their associated design methods will facilitate and promote implementation. This will greatly help in addressing the high-priority challenges associated with the meta-themes considered at this meeting.

SPECIAL ENGINEERING CHALLENGES: HIGHLY RESILIENT HIGHWAY SYSTEMS

Members: Kazuhiko Kawashima (co-chair), Ian Buckle (co-chair), Ross Boulanger, and I. Towhata

Background

Transportation systems are vital to the health, prosperity, and security of modern society. Recent earthquakes have shown that these systems can be vulnerable to earthquake damage, with unacceptable socio-economic consequences. Restoration of service is critically important to emergency response and the rapid recovery of the region. Due to an aggressive research program in both Japan and the U.S. in recent years, most highway systems today are resilient to some degree, but few, if any, are highly resilient. Highly resilient systems are necessary if the objective of minimal regional impact of a moderate-to-large earthquake is to be achieved.

Scientific Challenges

Increase resiliency of highway networks principally by increasing the resiliency of individual bridges. This can be done by developing damage-free bridges with minimal loss of functionality and repair time. But the challenge is to do so in a cost-effective manner.

The degree of resilience may vary between urban, suburban and rural bridges, and earthquake size (small, moderate, or large), but the objective is to be able to assure that with ground motions up to a certain size, a bridge will remain functional.

Specific Research Needs

Develop smart bridges, including a new generation of isolation devices, self-centering substructures (including rocking), innovative configurations, and materials (ductile cross-frames in steel bridges, SMA in plastic hinge zones, etc.). Another objective is to control pounding, which can cause significant damage in superstructures.

Develop new bridge configurations that are faster to repair using, e.g., technologies currently under development for accelerated bridge construction.

Develop damage-free foundations subject to large ground movement (remediation possible but structural fixes may be preferable: e.g. (1) develop foundations with minimal resistance to lateral flow and the strength to resist this flow elastically; and/or (2) include tolerance for movement in superstructures (sacrificial shear keys and large seat widths).

Benefit of NEES/E-Defense Collaboration

- Shared expertise … “two heads are better than one.”
- Shared cost and resources have potential to accelerate progress.
- For example: collaborative studies of single, full-scale, self-centering columns could be conducted at E-Defense and compared with system performance on, e.g., half-scale bridge model with self-centering columns at NEES.

SPECIAL ENGINEERING CHALLENGES: LIFELINES

Members: K. Tokimatsu (co-chair), I. Towhata (co-chair), R. Boulanger (co-chair), R. Dobry(co-chair), I. Buckle, J. Harris, K. Kawashima, M. Kreger, S. Mahin, S. McCabe, K. Miyagawa, Y. Okada

Background

Due to its importance to the seismic resiliency of cities, the session focused on buried lifelines and other underground structures. Damage or failure of such buried structures during large earthquakes has serious implications for the life of a city, as it may interrupt essential transportation, power and water supply functions, as well as trigger destructive fires following the earthquake. Engineering and scientific challenges are mainly in the areas of soil-structure interaction (SSI) and geotechnical research, with many of the challenges being also relevant to other structures such as buildings, bridges, levees, and ports. Therefore, in addition to its main focus on underground systems, the session also considered key geotechnical and SSI research important to other structures.

Tests at E-Defense should generally be planned as part of research programs including appropriate centrifuge and smaller shake table tests as well as a computational efforts; in some cases coordination with testing at large static facilities, like the NEES shared-use lifeline test facility at Cornell University, should also be considered.

The discussion during the session used as a starting point the research topics proposed in the white papers by Dobry and Boulanger (Geotechnical Research for Lifeline and Other Infrastructure Systems), Tokimatsu (Geotechnical Engineering Challenges with Emphasis on Problems in the Tokyo Metropolitan Area), and Towhata (Engineering Challenge: Protection of Lifelines from Earthquake Effects—with Emphasis on Railway Tunnels).

Scientific Challenges

A main scientific challenge arises from the complexity of the seismic response and performance of underground systems with complicated geometric and boundary conditions, as well as poorly understood interfacing between soil and structural materials. This was vividly illustrated during the discussion by considering the complexity of an underground subway station connected to several vertical shafts and horizontal tunnels. In many cases, this complexity is further increased by a complicated geology and associated additional uncertainty in predicting the soil response and input motion characteristics. Besides having a strong pressure-dependent and nonlinear stress-strain response, soft and liquefiable soils may develop significant permanent ground deformation in the free field and near the structure, which by itself may cause structural damage and loss of functionality. Changes in material properties during the seismic shaking of liquefying sands and soft clays add to the complexity and uncertainty of performance predictions; these time effects are expected to become even more significant with the very long shaking durations and numbers of cycles expected during very large-magnitude earthquakes. A number of the challenges related to the evaluation of soil material properties are also present when predicting the free-field response of the ground, typically a necessary first step toward predicting the response of the underground structure, and sometimes these challenges can be solved more easily in the context of free-field studies. Remediation of soils either near the structure, or over a larger area, introduces additional boundaries and challenges, especially with new and innovative soil remediation technologies now being developed. Finally, beyond solving the scientific challenges, additional challenges remain in extending and translating predicted performance into engineering application.

Specific Research Needs Were Identified in the Following Areas

- Seismic behavior of subway stations, tunnels, buried pipes, and other underground structures subjected to extreme seismic events, including effects of crossing through a geologic boundary;
- Evaluation of strategies to improve seismic response of underground structures to shaking and permanent ground deformation, either through structural modifications (like flexible connections) or surrounding soil stiffening or softening (including backfills), with the objective to optimize performance and decrease any needed repair time;
- Evaluation of strategies to preventing flotation of underwater tunnels and large pipes due to liquefaction of the backfill or surrounding natural soil;
- Studies to develop and evaluate ground improvement and remediation strategies for underground and above-ground structures;

- Evaluation of permanent ground deformation hazard and effects on underground structures and foundations, especially in challenging and heterogeneous soil profiles including gravelly soils and soils with plastic fines and organics such as peats. Of special interest are ground deformations associated with very strong and long shaking.
- Soil-structure-interaction studies of both underground and above-ground structures of various degrees of geometric and material behavior complexity, subjected to extreme events, with appropriate modeling of the structural, foundation, and soil parts of the structural system (including realistic modeling of radiation damping in the soil).

Benefits to E-Defense/NEES

- Complementary combination of large soil and SSI tests at E-Defense (3D) with smaller 1g shaking table and 2D centrifuge tests at NEES facilities
- Possibility of studying performance of entire structures and structural systems

FUNDAMENTAL KNOWLEDGE AND ENABLING TECHNOLOGIES: COMPUTATIONAL SIMULATION

Members: Muneo Hori (co-chair), Gregory L. Fenves (co-chair), Ross Boulanger, Gregory Deierlein, Jerry Hajjar, Takahito Inoue, Toshimi Kabeyazawa, Jack Moehle, and Kevin Won

Background

Computational modeling and simulation of structural and geotechnical systems has a rich history in earthquake engineering. From the earliest years of the field, researchers and practitioners developed computer applications to determine the effects of earthquake ground motion on buildings, bridges, and other structure-foundation-soil systems. It is now routine for design engineers to use computer-based analysis of a structure to determine the forces and deformation under earthquake loading, typically assuming linear material behavior and small displacements for equivalent static loads or a response spectrum analysis. Engineers are increasingly using nonlinear static analysis with simple component models, often referred to as pushover analysis, to evaluate deformation capacity, particularly for retrofit design. In geotechnical earthquake engineering, the analysis of site response and foundation systems is generally based on equivalent linear analysis methods, although behavior of piles may be represented in a nonlinear static analysis of a soil-structure system. Although there have been advances, the limitations of the models and analysis methods used in practice do not provide engineers with the information about the expected performance of a system, such as nonstructural damage, structural damage, residual effects, and collapse.

Whereas thirty years ago, earthquake engineering pushed the limits of computing, today the state-of-the-art in earthquake engineering modeling and simulation lags behind the enormous advances in computing capability in computer architecture, software engineering, data fusion, and scientific visualization. Computational science and engineering have transformed other fields that had been reliant exclusively on testing. For example, computational fluid dynamic simulation for aerodynamic design of aircraft replaces much of the wind tunnel testing, and large-displacement analysis for automobile crash design replaces much of the vehicle crash testing. The potential for computational simulation to transform earthquake engineering has not yet been tapped.

Scientific Challenges

Our goal in earthquake engineering research should be to develop the capability to simulate the full range of damage mechanisms of structure-foundation-soil systems all the way to collapse under a wide range of earthquakes, including the uncertainties associated with the design, construction, and health of the structure, in addition to the inherent uncertainty of the hazard. Achieving this goal of simulating scenarios, and ultimately distributions of performance, for individual structures and inventories of structures would provide many benefits in terms of improved performance, higher reliability, and reduced construction costs.

Research Needed

A radical transformation in the way we use computational modeling and simulation in earthquake engineering requires several key ingredients.

- The first is a true integration between experimentation and simulation modeling so that each experiment is designed to improve one or more simulation models, and each model is validated against well-designed experiments.
- Second, a new effort is needed to improve dramatically the fidelity of models for materials and components, particularly for nonductile modes of behavior such as fracture and shear, degradation of strength and stiffness under cyclic loads for structural components, large-strain deformation of soils, and the complex nonlinear behavior of foundation-soil interaction.
- Third, new algorithms and software systems need to be developed to take advantage of modern computer architectures, from the multi-core processors now on laptops to the massively parallel processor computers that are becoming increasingly available for routine computation.
- Fourth, the uncertainty in behavior must be represented throughout the modeling and simulation process so that engineers understand the distribution of performance that may be expected.

Benefit of NEES/E-Defense Collaboration

The extensive experimental research that is now being conducted by E-Defense in Japan and NEES in the U.S. provide valuable data that should be fully utilized to validate computational models. In many cases the models have been found to be inadequate in capturing complex nonlinear behavior, indicating clearly that research in model development is lagging. While it is recognized that the primary goals of these two programs is experimental research, testing should not be an end to itself. The research and practice communities, and our educational enterprise, would benefit by an equally ambitious program for improving computational simulation.

For the purpose of planning future E-Defense/NEES activities, the following "big picture" issues should be considered:

1. The simulation models and methods for cumulative damage in structural components under long-duration ground motion with many cycles are not adequate for assessing damage potential and estimating repair/replacement costs (or other decision variables). Coordinated tests and model simulation methods are needed to obtain the data and improve the models. New simulation methods such as multi-scale procedures, discrete particle methods, and others can be validated with experimental data. It is essential that local behavior be measured (strain, fracture, buckling) in tests for fine-grain model validation.
2. The capability to simulate collapse of 3D structural systems is inadequate. There is an urgent need for a comprehensive program to test different systems to collapse and validate computational models through the entire range of collapse scenarios. Large-scale shaking table tests and hybrid (including multi-site) tests are needed to investigate collapse.
3. The uncertainties in structural behavior need to be assessed through experiments on a number of samples. The data can be used to characterize the distribution of demand and damage, and incorporated into models.
4. The interaction between a structure and its foundation and soil has a large impact on structural and nonstructural performance. Coordinated SFSI interaction tests at a range of scales and methods (shaking table, centrifuge, hybrid, etc.) are needed to improve simulation models for the complete system.

There are many other areas of research necessary for improving computational simulation (e.g., high-fidelity models, robust and scalable algorithms, high-performance computing, visualization of behavioral phenomena, and for simulation steering, data fusion of simulated and experimental data). These are essential for improving the tools for the design of individual structural systems. Second, it is important to make progress in simulating the impacts of an earthquake on an entire urban region. A coordinated research program in experiments and simulation would allow combining the empirical approach for loss estimation, urban resiliency, and urban resumption planning with sound scientific simulation of earthquake scenarios.

FUNDAMENTAL KNOWLEDGE AND ENABLING TECHNOLOGIES: HEALTH MONITORING AND CONDITION ASSESSMENT

Members: A. Nishitani (co-chair), A Kiremidjian (co-chair), M. Garlock, J. Moehle, M. Nakashima, A. Reinhorn, B. Spencer, and J. Wallace

Background

Structural health monitoring systems can provide vital information on the state of a structure (a) before an earthquake leading to repair and strengthening, (b) during the emergency response period providing information on critically damaged or collapsed structures, and (c) during the recovery period with information on the type and degree of damage of a large number of structures thereby reducing the recovery time. All these activities are needed to increase the resiliency of the earthquake-affected region.

Large-scale experiments using E-Defense or NEES facilities can provide a convenient method for quantitatively assessing the practicability of various types of structural health monitoring systems and the reliability of damage and integrity predictions. Easy, safe and accurate damage-detection techniques for structures subjected to earthquakes should be developed to realize the goals of resilient buildings and lifelines.

Scientific and Technological Challenges

- Provide timely, accurate and cost-effective damage diagnosis and prognosis on a variety of structures, particularly critical facilities;
- Many structural systems, and many types and degrees of damage need to be monitored and assessed;
- Damage diagnosis algorithms are in their infancy—largely untested in the laboratory and in the field. Research is needed related to
    - Identification,
    - Localization,
    - Classification, and
    - Quantification
- Prognostic models are virtually non-existent;

- Need robust sensors to detect different types of damage, e.g., cracks in steel/concrete, corrosion in concrete rebar, etc.;
- Need test data for validating/unvalidating structural health monitoring systems, including their operation and ability to diagnosis post-earthquake integrity.

Specific Research Needs

Design NEES/E-Defense structural health monitoring and prognosis projects in parallel with structural and nonstructural testing. Planned tests will provide test-beds for validation and calibration of damage diagnosis and prognosis algorithms, structural health monitoring system functionality, etc. Such monitoring should be included as a fundamental aspect of all tests, if possible.

Benefit of NEES/E-Defense Collaboration

Collaboration of U.S. and Japanese researchers using NEES and E-Defense facilities will accelerate the development of reliable, scalable, and robust structural health monitoring systems by

- Providing valuable data for testing structural health monitoring system performance, damage diagnosis algorithms, and decision support systems;
- Assessing and improving robustness of structural health monitoring systems; and
- Increasing the potential deployment of such systems in the field.

FUNDAMENTAL KNOWLEDGE AND ENABLING TECHNOLOGIES: NONSTRUCTURAL AND SOCIOECONOMIC ISSUES

Members: T. Inoue (co-chair), M. Maragakis (co-chair), G. Deierlein, A. Kiremidjian, M. Nakashima, B. Spencer, and K. Wong

Background

- There is a need for the study of the seismic performance of nonstructural components and systems
- Damage to nonstructural elements contributes significantly to economic losses, loss of function, fire hazard, potential for injury, downtime, etc.
- Resilience is reduced by damage to nonstructural components, in terms of continuing post-earthquake hazards, degree of loss and length of time needed to restore a structure to service.
- There is a need to relate structural and nonstructural damage to losses, downtime, and life-safety risks. Cost-benefit relations need to be established with measurable metrics—at the building level as well as at the community level.
- ATC-58–like frameworks are needed to quantify performance and should be extended and validated.

Scientific Challenges

- Complex and interrelated nonstructural systems found in buildings and other structures
- High variability of actual installations
- Complicated boundary conditions
- Damage-resistant nonstructural components needed
- Building designs capable of protecting nonstructural systems needed
- New materials and configurations should be explored
- Effects of vertical accelerations, especially for isolated buildings, should be investigated.

Research Needs

- Pipes, ceiling, partitions

- Equipment
- Elevators
- Contents
- Anchorage systems
- Interaction of structural/nonstructural systems
- Research needed at system level, not just individual elements
- Medical facilities (emergency rooms)
- Multidisciplinary research approach needed

Benefits of NEES/E-Defense Collaboration

- State-of-the art experimental equipment available to conduct research
- Several NEES/E-Defense and E-Defense projects already focusing on seismic performance of certain nonstructural components and systems
- Payload opportunities are likely to have big impact with minimal cost
- Research is of high priority and should be conducted as soon as possible

APPENDIX IV: BACKGROUND PRESENTATIONS AND PRESENTED WHITE PAPERS

Disaster Management System in Japan and the National R&D Plan Regarding Disaster Reduction

Yoshimitsu OKADA

President

National Research Institute for Earth Science and Disaster Prevention（NIED, Japan）

2009/1/12 NEES/E-Defense Phase2 Planning Meeting(NSF,Verginia)

NIED

Natural disasters in Japan

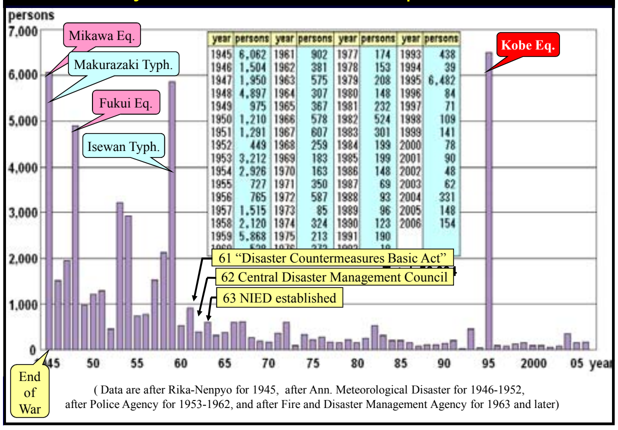
Earthquake (1995 Kobe)

Volcanic Eruption (1986 Izu-Oshima)

Flood (1986 Kokai River)

Landslide (1982 Nagasaki)

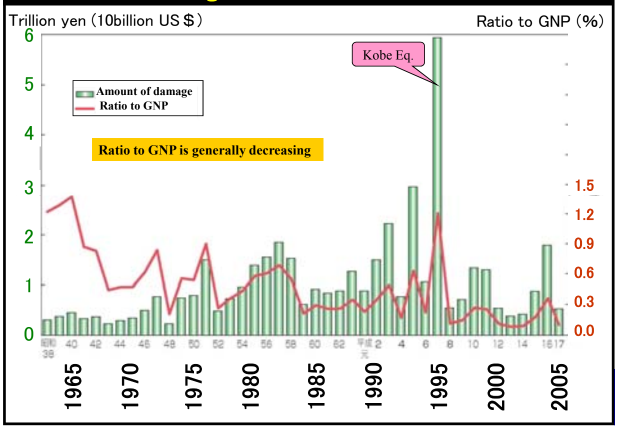
Death by natural disasters in Japan (1945-2006)



year	persons	year	persons	year	persons	year	persons
1945	6,062	1961	902	1977	174	1993	438
1946	1,504	1962	381	1978	153	1994	39
1947	1,950	1963	575	1979	208	1995	6,482
1948	4,897	1964	307	1980	148	1996	84
1949	975	1965	367	1981	232	1997	71
1950	1,210	1966	578	1982	524	1998	109
1951	1,291	1967	607	1983	301	1999	141
1952	449	1968	259	1984	199	2000	78
1953	3,212	1969	183	1985	199	2001	90
1954	2,926	1970	163	1986	148	2002	48
1955	727	1971	350	1987	69	2003	62
1956	765	1972	587	1988	93	2004	331
1957	1,515	1973	85	1989	96	2005	148
1958	2,120	1974	324	1990	123	2006	154
1959	5,868	1975	213	1991	190		

(Data are after Rika-Nenpyo for 1945, after Ann. Meteorological Disaster for 1946-1952, after Police Agency for 1953-1962, and after Fire and Disaster Management Agency for 1963 and later)

Amount of damage and its ratio to GNP (1963-2005)

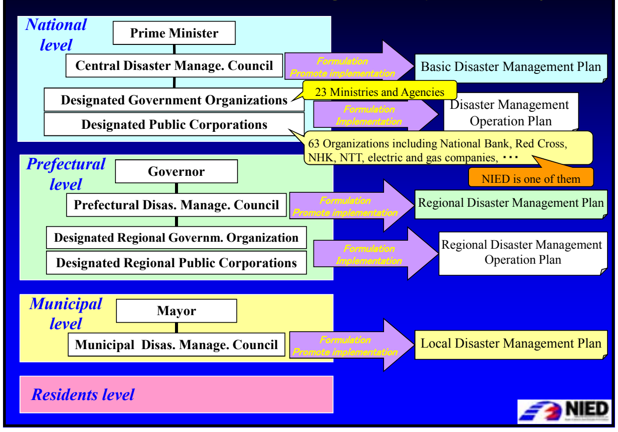


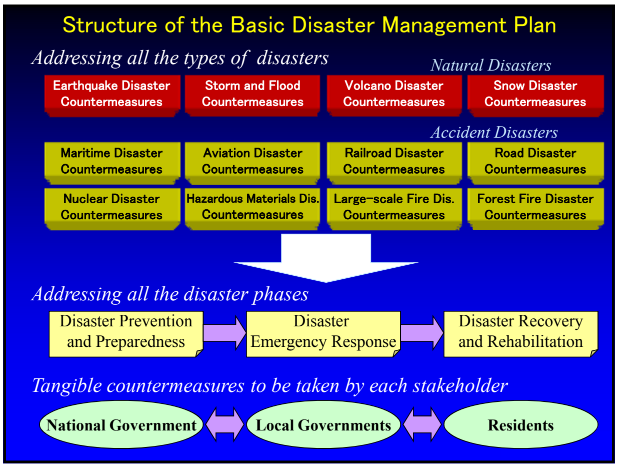
Progress in Disaster Management Laws and Systems

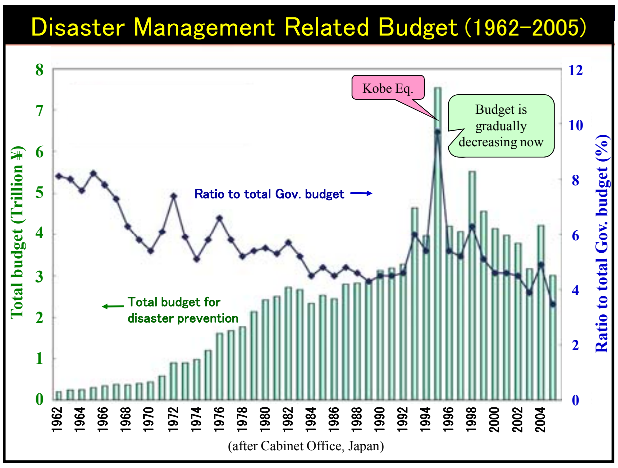
Events	Disaster Management Acts	Disaster Management Plans and Systems
1940		
46・Nankai Earthquake	47・Disaster Relief Act	
48・Fukui Earthquake	49・Flood Control Act	
1950	50・Building Standard Law	
59・Ise-wan Typhoon	60・Soil Conserv. & Flood Control Urgent Meas. Act	
1960	61・Disaster Countermeasures Basic Act	61 ・designate Disaster Reduction Day
61 ・Heavy Snowfalls	62・Act on Special Financial Support to Deal with Extremely Severe Disasters	62 ・establish Central Disaster Management Council
64 ・Niigata Earthquake		63 ・Basic Disaster Management Plan
1970	・Act on Special Meas..for Heavy Snowfall Areas	63 NIED established
73・Mt. Sakurajima Eruption	66・Act on Earthquake Insurance	
76・SSJ's report about the possibility of Tokai Eq.	73・Act on Special Measures for Active Volcanoes	
	78・Act on Special Measures for Large-scale Eqs.	
78・Miyagi-ken-oki Earthq.	80・Act on Spec.Financ.Meas. for Urgent Eq. Counterm. Improve. Projects in Areas for Intensified Meas.	79 ・Tokai Eq. Countermeasures Basic Plan
1980	81・amend Building Standard Law	
1990		
95・Kobe Earthquake	95・Act on Spec.Meas. for Eq. Disaster Countermeas.	95 ・amend Basic Disaster Management Plan
99・Torrential Rains in Hiroshima	・Act on Promot.of the Eq-proof Retrofit of Buildings	・designate Disaster Reduction and Volunteer Day
・JCO Nuclear Accident	96・Act on Spec.Meas. for Preservation of Rights and Profits of the Victims of Specified Disasters	01 ・establish the Cabinet Office
2000	97・Act on Promot. of Disas. Resilience Improvement in Densely Inhabited Areas	03 ・Policy Framework for Tokai Eq.
00・Torrential Rains in the Tokai Region		・Policy Framework for Tonankai and Nankai Eqs.
04・Niigata-ken-Chuetsu Eq.	98・Act on Support for Livelihood Recovery of Disaster Victims	04 ・Tonankai & Nankai Eq. Counterm. Basic Plan
		05 ・Tokai Eq. Disaster Reduction Strategy
05・Typhoons and Torrential Rains	99・Act on Special Measures for Nuclear Disasters	・Tonankai & Nankai Eq. Disas. Reduction Strategy
	00・Act on Promot. of Sediment Disaster Counterm. for Sediment Disaster Prone Areas	・Policy Framework for Tokyo Inland Eqs.
	02・Act on Spec.Meas. for Promotion of Tonankai and	06 ・Policy Framework for Trench-type Eqs. in the Vicinity of the Japan and Chishima Trenches
		・Counterm. Basic Plan for Trench-type Eqs. in the Vicinity of the Japan and Chishima Trenches
		・Tokyo Inland Eq. Disaster Reduction Strategy
		・Basic Framework for promoting a Nationwide Movement for Disaster Reduction

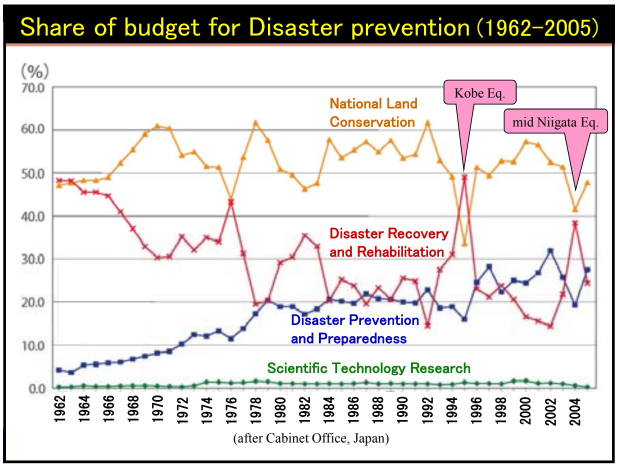
Disaster management system in Japan has been developed and strengthened following the bitter experiences of large-scale disasters and accidents.

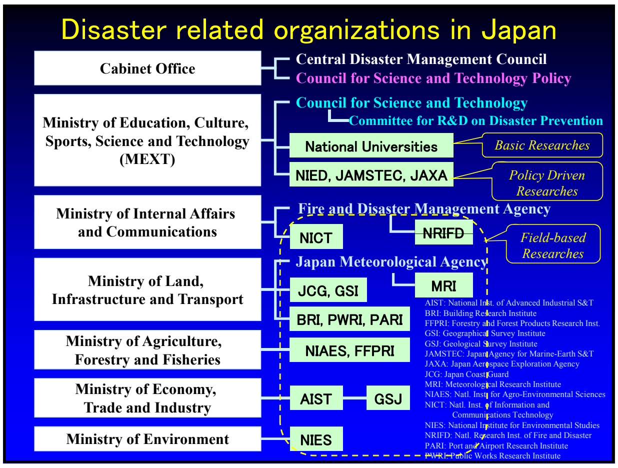
Outline of the Disaster Management System in Japan

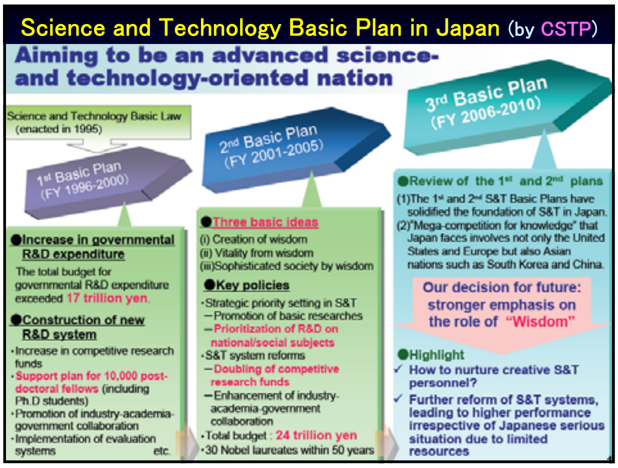


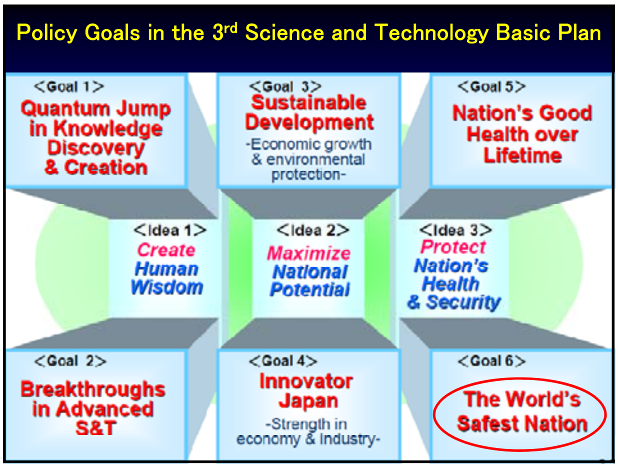

Structure of the Basic Disaster Management Plan
Addressing all the types of disasters
Natural Disasters
Earthquake Disaster Countermeasures
Storm and Flood Countermeasures
Volcano Disaster Countermeasures
Snow Disaster Countermeasures
Accident Disasters
Maritime Disaster Countermeasures
Aviation Disaster Countermeasures
Railroad Disaster Countermeasures
Road Disaster Countermeasures
Nuclear Disaster Countermeasures
Hazardous Materials Dis. Countermeasures
Large-scale Fire Dis. Countermeasures
Forest Fire Disaster Countermeasures
Addressing all the disaster phases
Disaster Prevention and Preparedness
Disaster Emergency Response
Disaster Recovery and Rehabilitation
Tangible countermeasures to be taken by each stakeholder
National Government
Local Governments
Residents

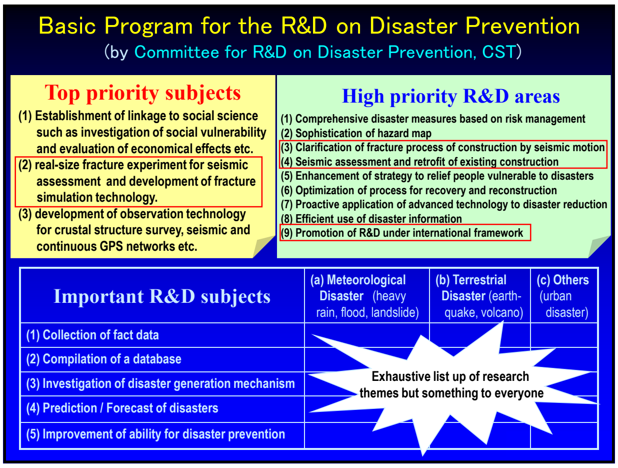

Disaster Management Related Budget (1962-2005)
Total budget (Trillion ¥)
Ratio to total Gov. budget (%)
Kobe Eq.
Budget is gradually decreasing now
Ratio to total Gov. budget
Total budget for disaster prevention
(after Cabinet Office, Japan)

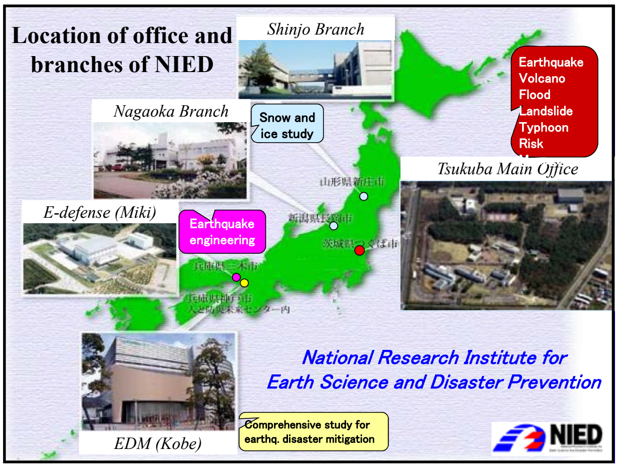

Share of budget for Disaster prevention (1962-2005)
(%)
Kobe Eq.
mid Niigata Eq.
National Land Conservation
Disaster Recovery and Rehabilitation
Disaster Prevention and Preparedness
Scientific Technology Research
(after Cabinet Office, Japan)

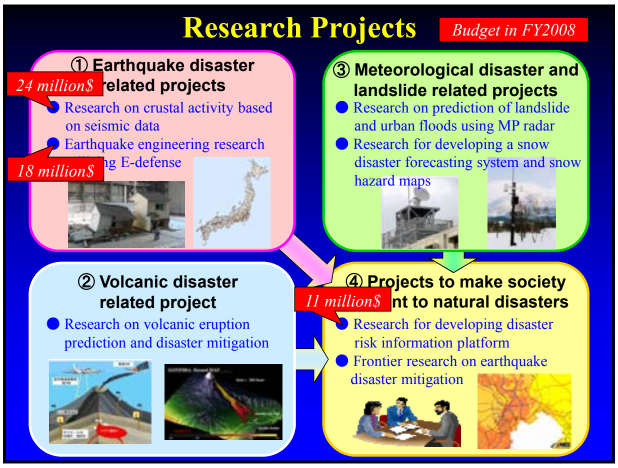

Disaster related organizations in Japan
Cabinet Office
Central Disaster Management Council
Council for Science and Technology Policy
Ministry of Education, Culture, Sports, Science and Technology (MEXT)
Council for Science and Technology
Committee for R&D on Disaster Prevention
National Universities
Basic Researches
NIED, JAMSTEC, JAXA
Policy Driven Researches
Ministry of Internal Affairs and Communications
Fire and Disaster Management Agency
NICT
NRIFD
Field-based Researches
Ministry of Land, Infrastructure and Transport
Japan Meteorological Agency
JCG, GSI
MRI
BRI, PWRI, PARI
Ministry of Agriculture, Forestry and Fisheries
NIAES, FFPRI
Ministry of Economy, Trade and Industry
AIST
GSJ
Ministry of Environment
NIES
AIST: National Inst. of Advanced Industrial S&T
BRI: Building Research Institute
FFPRI: Forestry and Forest Products Research Inst.
GSI: Geographical Survey Institute
GSJ: Geological Survey Institute
JAMSTEC: Japan Agency for Marine-Earth S&T
JAXA: Japan Aerospace Exploration Agency
JCG: Japan Coast Guard
MRI: Meteorological Research Institute
NIAES: Natl. Inst. for Agro-Environmental Sciences
NICT: Natl. Inst. of Information and Communications Technology
NIES: National Institute for Environmental Studies
NRIFD: Natl. Research Inst. of Fire and Disaster
PARI: Port and Airport Research Institute
PWRI: Public Works Research Institute

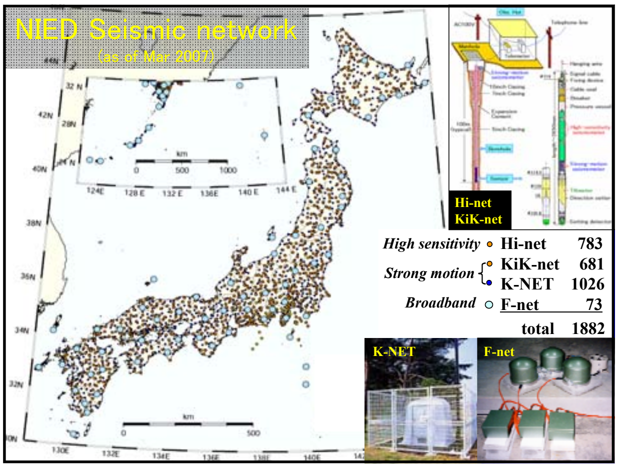

Science and Technology Basic Plan in Japan (by CSTP)
Aiming to be an advanced science- and technology-oriented nation
Science and Technology Basic Law (enacted in 1995)
1st Basic Plan (FY 1996-2000)
2nd Basic Plan (FY 2001-2005)
3rd Basic Plan (FY 2006-2010)
●Increase in governmental R&D expenditure
The total budget for governmental R&D expenditure exceeded 17 trillion yen.
●Construction of new R&D system
・Increase in competitive research funds
・Support plan for 10,000 post-doctoral fellows (including Ph.D students)
・Promotion of industry-academia-government collaboration
・Implementation of evaluation systems etc.
●Three basic ideas
(i) Creation of wisdom
(ii) Vitality from wisdom
(iii)Sophisticated society by wisdom
●Key policies
・Strategic priority setting in S&T
－Promotion of basic researches
－Prioritization of R&D on national/social subjects
・S&T system reforms
－Doubling of competitive research funds
－Enhancement of industry-academia-government collaboration
・Total budget : 24 trillion yen
・30 Nobel laureates within 50 years
●Review of the 1st and 2nd plans
(1)The 1st and 2nd S&T Basic Plans have solidified the foundation of S&T in Japan.
(2)"Mega-competition for knowledge" that Japan faces involves not only the United States and Europe but also Asian nations such as South Korea and China.
Our decision for future: stronger emphasis on the role of "Wisdom"
●Highlight
✓ How to nurture creative S&T personnel?
✓ Further reform of S&T systems, leading to higher performance irrespective of Japanese serious situation due to limited resources

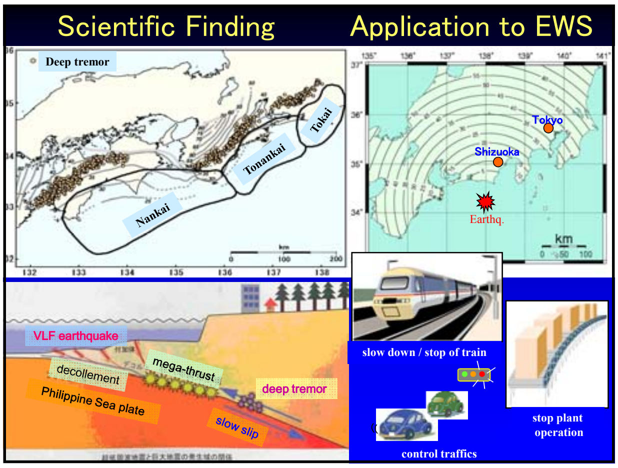

Policy Goals in the 3rd Science and Technology Basic Plan
<Goal 1>
Quantum Jump in Knowledge Discovery & Creation
<Goal 3>
Sustainable Development
-Economic growth & environmental protection-
<Goal 5>
Nation's Good Health over Lifetime
<Idea 1>
Create Human Wisdom
<Idea 2>
Maximize National Potential
<Idea 3>
Protect Nation's Health & Security
<Goal 2>
Breakthroughs in Advanced S&T
<Goal 4>
Innovator Japan
-Strength in economy & Industry-
<Goal 6>
The World's Safest Nation

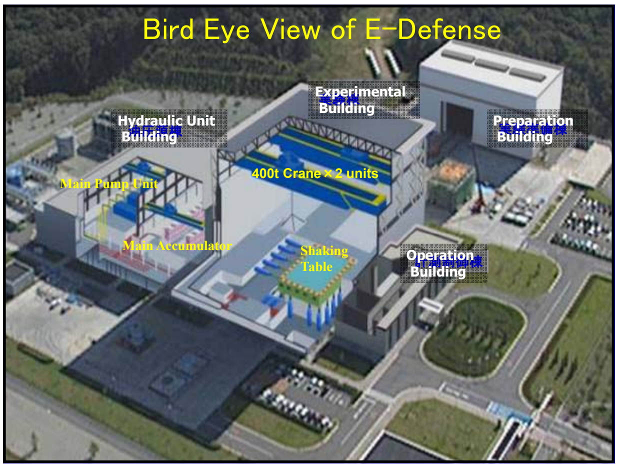

Basic Program for the R&D on Disaster Prevention
(by Committee for R&D on Disaster Prevention, CST)
Top priority subjects
(1) Establishment of linkage to social science such as investigation of social vulnerability and evaluation of economical effects etc.
(2) real-size fracture experiment for seismic assessment and development of fracture simulation technology.
(3) development of observation technology for crustal structure survey, seismic and continuous GPS networks etc.
High priority R&D areas
(1) Comprehensive disaster measures based on risk management
(2) Sophistication of hazard map
(3) Clarification of fracture process of construction by seismic motion
(4) Seismic assessment and retrofit of existing construction
(5) Enhancement of strategy to relief people vulnerable to disasters
(6) Optimization of process for recovery and reconstruction
(7) Proactive application of advanced technology to disaster reduction
(8) Efficient use of disaster information
(9) Promotion of R&D under international framework
Important R&D subjects
(a) Meteorological Disaster (heavy rain, flood, landslide)
(b) Terrestrial Disaster (earth-quake, volcano)
(c) Others (urban disaster)
(1) Collection of fact data
(2) Compilation of a database
(3) Investigation of disaster generation mechanism
(4) Prediction / Forecast of disasters
(5) Improvement of ability for disaster prevention
Exhaustive list up of research themes but something to everyone

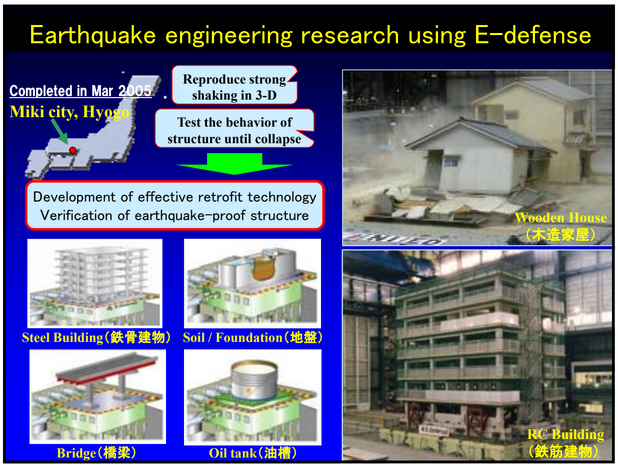

Location of office and branches of NIED
Shinjo Branch
Nagaoka Branch
Snow and ice study
Earthquake
Volcano
Flood
Landslide
Typhoon
Risk
Tsukuba Main Office
E-defense (Miki)
Earthquake engineering
National Research Institute for Earth Science and Disaster Prevention
EDM (Kobe)
Comprehensive study for earthq. disaster mitigation
NIED

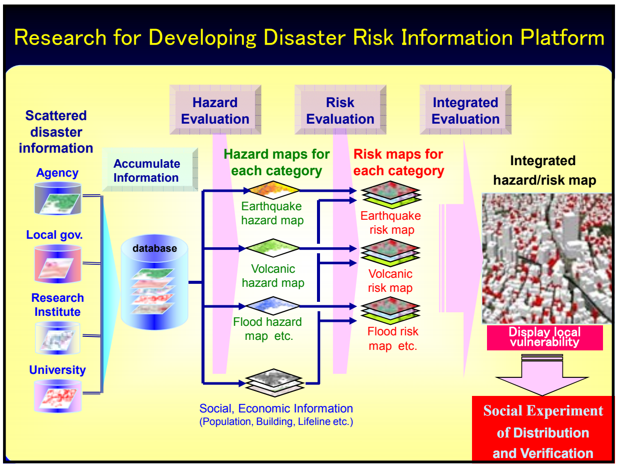

Research Projects
Budget in FY2008
① Earthquake disaster related projects
24 million$
Research on crustal activity based on seismic data
Earthquake engineering research
18 million$
ng E-defense
③ Meteorological disaster and landslide related projects
Research on prediction of landslide and urban floods using MP radar
Research for developing a snow disaster forecasting system and snow hazard maps
② Volcanic disaster related project
Research on volcanic eruption prediction and disaster mitigation
④ Projects to make society
11 million$
nt to natural disasters
Research for developing disaster risk information platform
Frontier research on earthquake disaster mitigation


NIED Seismic network
(as of Mar 2007)
Hi-net
KiK-net
High sensitivity
Strong motion
Broadband
Hi-net 783
KiK-net 681
K-NET 1026
F-net 73
total 1882
K-NET
F-net


Scientific Finding
Application to EWS
Deep tremor
Tokai
Tonankai
Nankai
Tokyo
Shizuoka
Earthq.
VLF earthquake
decollement
mega-thrust
deep tremor
Philippine Sea plate
slow slip
slow down / stop of train
stop plant operation
control traffics


Bird Eye View of E-Defense
Experimental Building
Hydraulic Unit Building
Preparation Building
400t Crane×2 units
Main Pump Unit
Main Accumulator
Shaking Table
Operation Building


Earthquake engineering research using E-defense
Completed in Mar 2005
Miki city, Hyogo
Reproduce strong shaking in 3-D
Test the behavior of structure until collapse
Development of effective retrofit technology
Verification of earthquake-proof structure
Wooden House（木造家屋）
Steel Building（鉄骨建物）
Soil / Foundation（地盤）
Bridge（橋梁）
Oil tank（油槽）
RC Building（鉄筋建物）


Research for Developing Disaster Risk Information Platform
Hazard Evaluation
Risk Evaluation
Integrated Evaluation
Scattered disaster information
Agency
Local gov.
Research Institute
University
Accumulate Information
database
Hazard maps for each category
Earthquake hazard map
Volcanic hazard map
Flood hazard map etc.
Risk maps for each category
Earthquake risk map
Volcanic risk map
Flood risk map etc.
Integrated hazard/risk map
Display local vulnerability
Social, Economic Information
(Population, Building, Lifeline etc.)
Social Experiment of Distribution and Verification

National Earthquake Hazards Reduction Program

… a research and implementation partnership for risk mitigation

Presentation for
Phase 2 Planning Meeting
NEES/E-Defense Collaborative Research Program on Earthquake Engineering
12 January 2009

Jack Hayes – NEHRP Director
www.nehrp.gov

NEES
E-Defense

FEMA · NIST National Institute of Standards and Technology · NSF · USGS science for a changing world

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national earthquake hazards reduction program

National Earthquake Hazards Reduction Program

A Statutory Multi-Agency Partnership

FEMA
NSF
nehrp
NIST National Institute of Standards and Technology
USGS science for a changing world

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Public Law 108-360

Statutory "Program Activities"

- Improve understanding of earthquakes and their effects.
- Develop effective measures for earthquake hazards reduction.
- Promote adoption of earthquake hazards reduction measures.
- Develop, operate, and maintain Advanced National Seismic System; *George E. Brown, Jr.* Network for Earthquake Engineering Simulation; and Global Seismographic Network.

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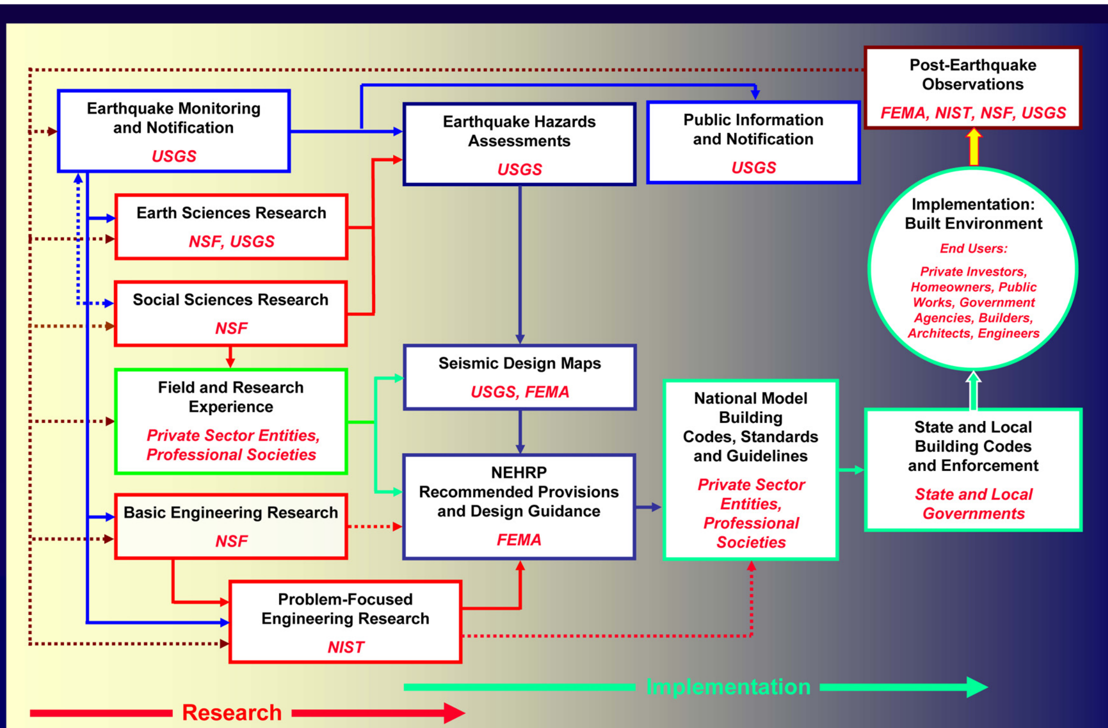

NEHRP Impact on the Built Environment

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Program Budgets

Agency	$M									
	FY 2005		FY 2006		FY 2007		FY 2008		FY 2009	
	Authorized[1]	Enacted[2]	Authorized[1]	Enacted[2]	Authorized[1]	Enacted[2]	Authorized[1]	Enacted[2]	Authorized[1]	Requested[3]
FEMA[4]	21.0	14.7	21.6	9.5	22.3	7.2	23.0	6.1	23.6	8.6
NIST	10.0	0.9	11.0	0.9	12.1	1.7	13.3	1.7	14.6	6.4
NSF[5]	58.0	53.1	59.5	53.8	61.2	54.2	62.9	55.6	64.7	56.4
USGS[6]	77.0	58.4	84.4	54.5	85.9	55.4	87.4	58.1	88.9	53.1
Totals	166.0	127.1	176.5	118.7	181.5	118.5	186.6	121.5	191.8	124.5

Notes:

1. Budgets authorized by Congress in Public Law 108-360.
2. "Enacted" budgets reported by NEHRP agencies for FY 2005 – FY 2008.
3. "Requested" budgets for NEHRP agencies in President's FY 2009 Budget Request in February 2008, except for FEMA.

   FEMA FY 2009 "requested" budget is estimated portion of President's FY 2009 DHS budget request that will be allocated for FEMA NEHRP activities.
4. FEMA FY 2005 enacted budget covered program activities & S&E, but excluded state grants that are administered by FEMA Preparedness Directorate.

   FEMA FY 2006 – FY 2009 enacted/requested budgets cover program activities, but exclude S&E and state grants that are administered by FEMA Preparedness Directorate.
5. NSF budgets include NEES O&M funds: FY 2005 -$17.9M, FY 2006 - $20.3M, FY 2007 - $20.5M, FY 2008 - $22.1M, FY 2009 - $22.9M.
6. USGS authorization includes for ANSS: FY 2005 - $30M, FY 2006 and beyond - $36M per year.

   USGS FY 2005 enacted budget includes funds for tsunami warning from emergency supplemental appropriation ($3.95M for EHP, $4.15M for GSN).

   USGS budgets include funds for GSN: FY 2005 - $7.5M, FY 2006 - $3.9M, FY 2007 - $3.9M, FY 2008 - $4.4M, FY 2009 - $4.0M.

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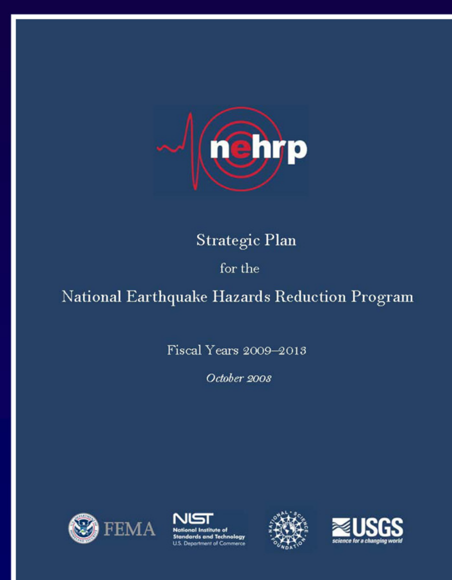
Strategic Plan

Outline

- Executive Summary
- Introduction – Background (History, Prior Accomplishments)
- Vision / Mission / Strategic Planning Principles
- Goals / Objectives / Outcomes
- Strategic Priorities
- Summary
- Appendices



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national earthquake hazards reduction program

NEHRP Strategic Plan

National Vision Statement

The Program is driven by a national vision for the future:

A nation that is earthquake-resilient in public safety, economic strength, and national security.

This vision gives rise to the NEHRP Mission Statement (see next slide).

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NEHRP Strategic Plan

NEHRP Mission Statement

To develop, disseminate, and promote knowledge, tools, and practices for earthquake risk reduction – through coordinated, multi-disciplinary partnerships among the NEHRP agencies and their stakeholders – that improve the nation's earthquake resilience in public safety, economic strength and national security.

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NEHRP Strategic Plan

Strategic Goals

A. Improve understanding of earthquake processes and impacts.

B. Develop cost-effective measures to reduce earthquake impacts on individuals, the built environment, and society-at-large.

C. Improve the earthquake resilience of communities nationwide.

Goals closely parallel three major statutory program activities.

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national earthquake hazards reduction program

NEHRP Strategic Plan

Strategic Planning Principles

… including …

- Program impact through effective development and transfer of knowledge, tools, and practices
- Program revision – not reinvention
- Interagency coordination / cooperation / synergy
  - Includes coordinated budget development
  - Emphasizes that progress towards all Plan goals and objectives presented in this Plan will be made, but not all of the outcomes will be fully realized during the Plan period of 2008 – 2012
- Adoption of nine Strategic Priorities that support Program goals and objectives

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national earthquake hazards reduction program

NEHRP Strategic Plan

Strategic Planning Principles (cont'd)

- Close partnerships with stakeholder communities
- Exploitation of ANSS, GSN, IRIS, NEES
  - Includes emphasis on instrumentation and facility utilization by program
  - Includes recurring support for operating key research and data collection facilities (e.g. ANSS, NEES), providing the necessary foundation for achieving Plan goals and objectives
- Multi-disciplinary approach
- Multi-hazard leveraging awareness
- Linkages with broader federal policies, plans, and priorities (e.g. SDR *Grand Challenges for Disaster Reduction*)
- Increased international cooperation

national earthquake hazards reduction program

NEHRP Strategic Plan

Strategic Plan Structure

- NEHRP goals:
  Broad and long-term with expected impacts that should be realized, in full or in part, during the five year planning period; serve to guide and focus NEHRP planning and activities to accomplish the NEHRP Mission.
- NEHRP objectives:
  Specific achievements towards broad goals, with expected outputs and outcomes, that should be realized, in full or in part, during the five year planning period.

Note:

1. Fulfilling many of the objectives will contribute to more than one goal. Objectives are listed under the goal to which they principally contribute.
2. Statute also requires an Implementation Plan, which will contain more agency-specific data. That plan will be developed following Strategic Plan completion.

national earthquake hazards reduction program

NEHRP Strategic Plan

Goal A: Improve understanding of earthquake processes and impacts

- Objective 1: Advance understanding of earthquake phenomena and generation processes
- Objective 2: Advance understanding of earthquake effects on the built environment
- Objective 3: Advance understanding of social, psychological, and economic factors linked to implementing risk reduction and mitigation strategies in the public and private sectors
- Objective 4: Improve post-earthquake information management

nehrp national earthquake hazards reduction program

NEHRP Strategic Plan

Goal B: Develop cost-effective measures to reduce earthquake impacts on individuals, the built environment, and society at large.

- Objective 5: Assess earthquake hazards for research and practical application
- Objective 6: Develop advanced loss estimation and risk assessment tools
- Objective 7: Develop tools to improve the seismic performance of buildings and other structures
- Objective 8: Develop tools to improve the seismic performance of critical infrastructure

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NEHRP Strategic Plan

Goal C: Improve the earthquake resilience of communities nationwide

- Objective 9: Improve the accuracy, timeliness, and content of earthquake information products
- Objective 10: Develop comprehensive earthquake scenarios and risk assessments
- Objective 11: Support development of seismic standards and building codes and advocate their adoption and enforcement

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NEHRP Strategic Plan

Goal C: Improve the earthquake resilience of communities nationwide (continued)

- Objective 12: Promote the implementation of earthquake-resilient measures in professional practice and in private and public policies
- Objective 13: Increase public awareness of earthquake hazards and risks
- Objective 14: Develop the nation’s human resource base in earthquake safety fields

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NEHRP Strategic Plan

Strategic Priorities

Describes 2006 ICC examination of "gaps" & emphasizes 9 strategic priorities (presented in order of first association with goals and objectives):

- Fully implement Advanced National Seismic System (ANSS)
- Improve techniques for evaluating & rehabilitating existing buildings
- Further develop Performance-Based Seismic Design (PBSD)
- Increase consideration of socio-economic issues related to hazard mitigation implementation

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NEHRP Strategic Plan

Strategic Priorities (continued)

Describes 2006 ICC examination of "gaps" & emphasizes 9 strategic priorities (presented in order of first association with goals and objectives):

- Develop a Post-Earthquake Information Management System (PIMS)
- Develop advanced risk mitigation technologies & practices
- Develop earthquake-resilient lifeline components and systems
- Develop & conduct earthquake scenarios for effective earthquake risk mitigation
- Facilitate improved earthquake mitigation at state & local levels

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Background Information

These slides will not be presented but are included as background material.

national earthquake hazards reduction program

NEHRP Background

- NEHRP was established by the US Congress in the *Earthquake Hazards Reduction Act of 1977-* it has existed since then.
- Through NEHRP, Congress *authorizes* appropriation levels for the four principal agencies.
- Most recent reauthorization (Public Law 108-360, enacted 25 October 2004) covered FY 2005 – FY 2009 at average annual totals (for all 4 agencies) of ~ $180M, an increase of $75M per year from previous levels.
- NEHRP focus is on pre-earthquake mitigation.

national earthquake hazards reduction program

Public Law 108-360

NEHRP Agency Roles

Department of Homeland Security

Federal Emergency Management Agency (FEMA)

- Promote, with NIST, implementation of research results.
- Promote better building practices.
- Operate program of grants & assistance.
- Support implementation of a comprehensive earthquake education and awareness program.
- Assist NIST, other Federal agencies, & private sector groups, in preparing, maintaining, & widely disseminating seismic resistant design guidance.
- Aid in developing performance-based design guidelines.
- Develop, coordinate, & execute National Response Plan when required following an earthquake, & support development of specific State and local plans.

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Public Law 108-360

NEHRP Agency Roles

FEMA, continued

- Develop approaches to combine measures for earthquake hazards reduction with measures for reducing other natural and technological hazards.
- Provide preparedness, response, and mitigation recommendations to communities after an earthquake prediction has been made.
- Enter into cooperative agreements or contracts to establish demonstration projects on earthquake hazard mitigation, to link research & mitigation efforts with emergency management programs, or to prepare educational materials for national distribution.

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NEHRP Agency Roles

National Institute of Standards and Technology (NIST)

Lead Agency

Responsible for program planning & coordination.

- Promote implementation of earthquake hazard reduction measures.
- Support development and promote commercial application of performance-based seismic engineering tools.
- Request assistance of Federal agencies other than the Program agencies, as necessary to assist.
- Work with FEMA, NSF, & USGS, to develop a comprehensive plan for earthquake engineering research to effectively use existing testing facilities and laboratories, upgrade facilities & equipment as needed, & integrate new, innovative testing approaches.

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NEHRP Agency Roles

NIST

- Perform R&D to improve building codes and standards & practices.
- Work closely with national standards and model building code organizations, in conjunction with FEMA, to promote implementation of research results.
- Promote better building practices among architects and engineers.
- Work closely with national standards organizations to develop seismic safety standards and practices for new and existing lifelines.
- Support development & commercial application of cost-effective and affordable performance-based seismic engineering.
- Work with other program agencies to develop comprehensive plan for earthquake engineering research using existing facilities, upgrade facilities as needed, and integrate new testing approaches.

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NEHRP Agency Roles

National Science Foundation (NSF)

- Fund (fundamental) research on earth sciences, earthquake engineering, and human response to earthquakes.

  Note: *Earthscope* is maintained as a related non-NEHRP activity.

- Encourage prompt dissemination of significant findings, sharing of data, samples, physical collections, & other supporting materials, & development of intellectual property.
- Support individual investigators, university research consortia & centers for research in geosciences & in earthquake engineering.
- Work closely with USGS to identify geographic regions of national concern.
- Support research that improves the safety & performance of buildings, structures, & lifeline systems using large-scale experimental and computational facilities of NEES & other institutions.

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NEHRP Agency Roles

NSF, continued

- Emphasize development of economically feasible methods to retrofit existing buildings and protect lifelines.
- Support research that studies political, economic, & social factors that influence implementation of hazard reduction measures.
- Include diverse institutions, including HBCUs and those serving large proportions of (minorities) and other underrepresented populations.
- Work with other program agencies to develop comprehensive plan for earthquake engineering research using existing facilities, upgrade facilities as needed, and integrate new testing approaches.

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NEHRP Agency Roles

U.S. Geological Survey (USGS)

- Conduct research & other activities necessary to characterize and identify earthquake hazards, assess earthquake risks, monitor seismic activity, and improve earthquake predictions.
- Conduct a systematic assessment of seismic risks in each region of the Nation prone to earthquakes, including appropriate establishment and operation of intensive monitoring projects on hazardous faults, seismic microzonation studies in urban & other developed areas with significant earthquake risk, & engineering seismology studies.
- Work with officials of State & local governments to ensure that they are knowledgeable about specific seismic risks in their areas.
- Develop standard procedures for issuing earthquake predictions, including aftershock advisories.

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NEHRP Agency Roles

USGS, continued

- Issue, when necessary, earthquake predictions or other earthquake advisories.
- Operate, using the National Earthquake Information Center (NEIC), a forum for the international exchange of earthquake information.
- Operate a National Seismic System (ANSS).
- Support regional seismic networks that complement the National Seismic Network.

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NEHRP Agency Roles

USGS, continued

- Work with other program agencies to develop comprehensive plan for earthquake engineering research using existing facilities, upgrade facilities as needed, and integrate new testing approaches.
- Work with other Program agencies to coordinate Program activities with similar earthquake hazards reduction efforts in other countries.
- Maintain suitable seismic hazard maps in support of building codes for structures and lifelines, including additional maps needed for performance-based design approaches.

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GLOBAL ISSUE: WHY ARE FULL-SCALE EXPERIMENTS OF LARGE SYSTEMS STILL NEEDED?

Masayoshi Nakashima
Kyoto Univ. and E-Defense

Change from "learning from actual earthquake damage" to "learning from quasi-actual earthquake damage"

Earthquake engineering has a long history of "learning from actual earthquakes and earthquake damages." That is, we first understand problems by actual damage; then develop engineering to patch them. Here are examples in Japan; RC apartment buildings were toppled in the 1964 Niigata earthquake, which awakened liquefaction; many school buildings suffered from column failures in the 1968 Tokachi-oki earthquake, which triggered research on short columns and shear failures; numerous old houses and infrastructural systems collapsed in the 1995 Hyogoken-Nanbu earthquake, which had accelerated seismic retrofit.

This nature of earthquake engineering, i.e., "learning from actual damage," seems to make sense, because civil/building engineering traditionally places much emphasis on "experiences" compared to other engineering disciplines. Furthermore, this attitude may be tolerable when the country is young and in a rapid growing mode. Looking at the reality, we see that Japan is rich, stable, and mature, and in such a country, expectation toward insurance for "quality of life" naturally becomes very high. This means our society becomes less tolerable against inconvenience in life after quakes. This trend shall continue at least for the coming half a century, all the while most probably very large ocean-ridge quakes will hit many large cities in Japan within several ten years. Will we be able to maintain the expected quality of life after such large quakes? The answer is most likely NO.

Then, how shall we save our country and what should we do for the welfare of our offspring? One very practical and practicable approach is the change of our attitude from "learning from actual damage" to "learning from quasi-actual damage." Shall this approach be successful, we would be able to predict our current problems, take action to solve or resolve them, and prepare for the future, all achieved before a real one would hit us.

How are we able to produce quasi-actual damage – "very large-scale (or realistic-scale) tests," "tests using actual ground motions," and "tests on the entire structure (rather than members and elements)" is the solution. Small scale tests, quasi-static tests, and member tests are no doubt very important for the development and refinement our fundamental knowledge. As evidenced by the history, however, those tests were not enough to convince all layers of stakeholders associated with earthquake damage and its mitigation, including the general public and government authorities, for changes.

GLOBAL ISSUE: WHY ARE LARGE-SCALE EXPERIMENTS OF STRUCTURAL COMPONENTS AND SYSTEMS NEEDED?

Gregory G. Deierlein
Stanford University

> "Structural engineering can be characterized as the art of molding materials we do not entirely understand into shapes that we cannot precisely analyze so as to withstand forces we cannot really assess, in such a way that the community at large has no reason to suspect the extent of our ignorance." (Coduto, 2001)

Throughout history, engineers have faced the continual challenge to plan, design and construct buildings and the civil infrastructure with limited resources and incomplete knowledge of structural behavior and loads/hazards. While knowledge about material and structural behavior, analysis methods, and characterization of loads have improved, so too have the challenges of increasingly complex facilities that are necessary for the functioning of modern societies. Large-scale laboratory testing is expensive, but when weighed against the tremendous value and importance of the built environment, the learning from research, enables the design and construction of more efficient and reliable facilities, far outweigh the research costs. This is especially true in earthquake engineering where highly nonlinear behavior is expected under extreme earthquake effects. Modern performance-based engineering methods further leverage the knowledge gained by large scale testing by facilitating the design of innovative structures.

Large-scale testing, like any research methods, should be planned appropriately based on the research objectives. While the pursuit of scientific knowledge and understanding should be an important component of all testing, there may be other worthwhile testing objectives as well. For example, large-scale testing can at times be appropriate to demonstrate proof-of-concept of new innovative systems to accelerate their adoption by the engineering community and other stakeholders. Conversely, large-scale testing may be an effective mechanism to persuade stakeholders (the public, elected representatives, building code officials) of critical risks in existing construction. While these benefits may seem obvious, it is incumbent on the research community to clearly articulate and, to the extent possible, quantify the benefits of large scale testing so as to ensure continued support by research sponsors and institutions.

The tremendous advances in computing and simulation technologies over the past few years have certainly affected the role and need for physical tests. However, as modern performance-based engineering approaches rely on accurate analyses to simulate nonlinear behavior of complex structural systems, the greater reliance on analyses has increased (rather than decrease or minimize) the need for high-quality physical testing. First and foremost, physical testing is essential to understand and characterize behavioral phenomena and failure modes that must be considered in design and analysis. Next, testing of materials and components is necessary for calibration of analysis models and acceptance criteria. Finally, testing of subassemblies and systems provide critical information on indeterminate system response and data to validate computational models. Given the inter-relationship of testing and analysis, the objectives and planning for large-scale tests should be closely coordinated with the needs to improve computational models.

The NEES and E-Defense facilities offer a broad range of capabilities for testing components and systems, ranging from unique apparatus for quasi-static cyclic testing of large structural components (e.g., the NEES-MAST facility) to three-dimensional shake table testing of building assemblies (e.g., the E-Defense) facility. Pseudo-dynamic and hybrid-simulation capabilities allow tests that mimic some features of dynamic shake table testing with quasi-static loading equipment - important alternatives to shake table testing for systems whose size or complexity exceed that which can be tested on shake tables. The following are some specific attributes that influence the testing needs and requirements:

- **Scale and Size Effects:** While there are obvious benefits to testing at reduced scales, many situations and types of phenomena require test of structural components at or close to full scale. For example there are certain minimum sizes below which the material and physical characteristics of reinforced concrete, structural steel members and connections (bolted and welded), masonry and wood cannot be accurately replicated. For example, minimum sizes for reinforced concrete are limited by concrete mixes with 10 to 20 mm (3/8 to 3/4 inch) aggregates, 10 mm diameter (#3 bar) tie reinforcement, and representative reinforcing bar detailing. Beyond the minimum sizes required to represent the basic material and structural behavior, certain phenomena are size dependent and, thus, require testing at sizes as close as possible to full-scale. Shear cracking behavior in reinforced concrete is an example of behavior that is size dependent, the significance of which remains an open research question. Manufactured components, such as seismic isolators and mechanical devices, often warrant full-scale testing to validate response characteristics that are size dependent.
- **Indeterminate System Response:** While testing of members and subassemblies of members can suffice for characterizing many types of structural behavior, certain aspects require testing of large portions of those systems. For example, tests of isolated steel beam-column subassemblies may not represent accurately the constraint and boundary conditions that exist in complete structural systems due to restraint provided by the floor slab and frame continuity. Indeterminate interaction of structural systems and non-structural components (partitions, cladding, stair framing) is another example where system testing is important.
- **Variability:** Structural materials or components that display significant variability in their response (due to inherent randomness or aleatoric uncertainty in the underlying phenomena) present unique challenges due to the need for testing of many replicate specimens to characterize uncertainty. In such cases, it is economically prohibitive to fully characterize the variability solely through large-scale system tests. Instead, a coordinated set of material/component tests to characterize the uncertainty distribution as a pre-requisite to undertaking a large scale test. The same argument can be made for structural systems where variability may be introduced through many options for local detailing within one structural system type.
- **Dynamic Effects:** While researchers commonly apply dynamic analysis to simulate overall system response, it is generally recognized that there are many assumptions in such models that lead to inaccuracies (or in some cases may invalidate) the analysis results. This is particularly the case for (a) indeterminate structural systems that experience nonlinear behavior, (b) systems where viscous damping is significant, and (c) structural systems and components that experience dynamic pulse/impact effects that are difficult to model accurately (e.g., structures that exhibit foundation or base rocking, pounding at expansion joints, etc.).

- **Loading Rate Effects:** Associated but distinct from dynamic effects are the effect of loading rate on structural materials and systems that must be considered in planning tests. Obvious examples are systems with viscous damping devices, whose entire response depends on replicating the realistic loading rates. Less obvious but often significant are loading rate effects that are overlooked or ignored (for practical reasons) in design, e.g., structures whose behavior and governing modes of failure may be affected by modest changes in material behavior (yielding and fracture in steel, cracking and crushing in concrete, etc.) due to loading rate effects.

This paper has attempted to briefly outline the value and issues associated with physical testing of large scale structural components and systems. Clearly, large-scale testing continues to be an essential research component for the reliable design and development of buildings, bridges, and other facilities that allow modern societies to function and flourish. It is important, though, that large-scale testing programs be carefully conceived and planned to be consistent with clearly stated research objectives and to maximize their use and benefit to society.

White Paper on

Organizational Structure for NEES/E-Defense Collaboration

Prepared by Stephen Mahin
University of California, Berkeley

There has been a long and productive history of organized collaborative research between US and Japanese researchers related to earthquake engineering. This research resulted in a better understanding of seismic behavior and the many complex relations among various types of experimental and numerical simulation, and accelerated development of innovative and effective design and analysis procedures for several types of structural systems of common interest in the US and Japan. Funded by the US National Science Foundation and the Japanese Ministry Construction through the Building Research Institute, the **U.S.-Japan Cooperative Earthquake Research Program** started in 1979 following recommendations outlined in the final report of the U.S.-Japan Planning Group for the program (1). The overall objective of that program was to improve seismic safety practices in both countries through cooperative studies to determine the relationship among full-scale tests, small-scale tests, component tests, and related analytical and design implication studies. A series of five-year research projects were carried out focusing on (1) reinforced concrete shear wall buildings, (2) steel braced frame structures, (3) masonry structures, (4) precast structures, and (5) composite and hybrid structures. This program continued though less focused fashion on issues related to Urban Earthquake Disaster Mitigation and Smart Structures.

With the advent of the NSF-funded George E. Brown, Jr. Network for Earthquake Engineering Simulation, and the E-Defense program at the Hyogo Earthquake Engineering Research Center funded by the Ministry of Education, Sports, Culture, Science and Technology (MEXT), the NEES/E-Defense Collaborative Earthquake Engineering Research Program was established in 1994 for a period of 5 years. During this first phase of the collaborative research two principle research thrusts were pursued. The first of these related to Steel Buildings, and the second focused on Bridges.

With the end of the first phase of the NEES/E-Defense program approaching, it is desirable to assess the desirability of extending the scope of the research through a second phase, and identify possible changes in how the collaboration is conducted to help accelerate discovery, solve important scientific challenges and promote innovation and to more fully utilize the unique capabilities of the E-Defense and NEES facilities

Two issues related to modifications in how the NEES/E-Defense collaboration is conducted are addressed below to stimulate discussion. There is no presumption in these discussions that the current collaboration is deficient in any manner, but only whether the impact of the program can be increased.

1. Focus of future research

Currently, the NEES/E-Defense program focuses on steel buildings and bridges. The next phase could thus logically focus on:

- other construction materials (e.g., wood structures),
- new forms of construction (e.g., industrialized or prefabricated structures) or
- innovative materials or components (e.g., high performance concrete, supplemental energy dissipation systems, seismic isolation, etc.).

This was the conclusion reached at the conclusion of the first planning meeting for the NEES/E-Defense Collaborative Earthquake Research Program. Recommendations were advanced for the particular topics noted above and others.

During the current phase of research, the individual projects funded on Bridges or Steel Buildings involve strong collaboration between Japanese and US researchers, but there is weak correlation between the various projects on buildings or bridges. Thus, some have suggested that there is inadequate opportunity for synergism among the projects funded. In earlier projects, such as the US-Japan Coordinated Research Project on Composite and Hybrid Structures, researchers were encouraged to write proposals that were complementary so a complete series of investigations on Hybrid Wall Systems and Steel/Reinforced Concrete Composite frames were carried out encompassing a broad set of components, connections, subassemblages and complete systems and detailed analytical parametric studies using validated numerical models were executed to devise improved design recommendations. This program also had a component termed Research for Innovation, which attracted numerous investigations that introduced many innovative ideas to balance other projects that provided in-depth studies of the major backbone of the systems being investigated.

Question: How can we encourage research proposals that are more complementary so that they more readily build upon one another in a synergistic fashion and were the totality of the structural system being addressed is considered?

Alternatively, the next phase of NEES/E-Defense collaboration could focus on broader meta-themes that relate to societal level issues. For example, it could focus on issues related to:

- realizing the goal of model-based numerical simulation procedures,
- developing improved or new forms of construction that minimize post-earthquake disruption caused by damage to structural and nonstructural elements (e.g., disaster resilient structures or cities),
- devising design concepts to resist unusually large events (say M = 9),
- developing design concepts to protect life safety in extremely rare, high consequence events, or
- obtaining knowledge to implement reliably performance based design for a wide variety of structural forms,
- sustainable development.

These ideas might be considered societal or system level issues, whereas the ones focusing of particular structures, materials, concepts and the tools needed to simulate and design those structures might be considered research directed at fundamental knowledge or enabling technologies. Thus, these are not contradictory approaches, but ones that complement one another.

Question: Should NEES/E-Defense research be focused on societal level meta-themes? If so, which ones? What types of research at the enabling technology and fundamental knowledge levels are needed to realize the broader system level goals?

2. How to best utilize E-Defense and NEES resources

Currently, the Japanese side has conducted several large scale tests based on a consensus of the research needs of the Japanese side, while the US side has carried out tests on the E-Defense shaking table of smaller specimens associated with each NEESR project.

Some have suggested that this model might be modified to encourage a few large US-Japan capstone tests on the E-Defense shaking table jointly designed and funded by US and Japanese researchers. A corollary issue would be whether it is possible to engage more US researchers in the E-Defense research efforts being undertaken by the Japanese side. The Japanese side has amassed a tremendous amount of useful information in their tests and there is concern that this is not being utilized to the extent possible by the US side, since the Japanese efforts extend beyond the scope of projects that are funded on the US side. That is, there are no US counterparts for some of the important Japanese investigations.

If the focus were on one or more major capstone experiments for various meta-themes, individual US NEESR projects would still do tests looking at particular aspects related to the meta-theme, but using NEES facilities. However, they might participate in the planning of a few large capstone tests undertaken jointly on the E-Defense shaking table. Some projects might focus only on the capstone project and not use NEES facilities in the US. Others might focus only on enabling technologies such as developing and validating analytical simulation tools. This is similar to how efforts were undertaken in prior US/Japan cooperative research efforts. Some projects might not involve testing at all, but only focus on the capstone test. For instance, individual NEES investigators could look at various types of resiliency, and some projects could focus on social-economic issues and others could look at computational issues only. A large capstone project, and some coordinating mechanism, would tie them all together. However, this would require a new model for how NEES/E-Defense projects are carried out, but it is similar to previous US/Japan coordinated research programs.

Question: Should a communal capstone test jointly funded by NEES and E-Defense be considered?

It may be possible for Japanese researchers to conduct more research in the US. Some E-

Defense research projects involved testing in the US.

3. Opportunities for Partnering

In recent years, few direct partnerships with other agencies and industries have been undertaken to help fund NEES/E-Defense research. Given the high cost of test specimens, some more formal mechanism for partnering with material or trade associations and with industry would be desirable. Similarly, trade and professional associations and business and industrial partners might be able of co-fund research activities. Other NEHRP agencies could fund research topics of interest to them.

References

1. Recommendations for a US-Japan Cooperative Research Program Utilizing Large-Scale Testing Facilities," Report No. UCB/EERC 79-26, 1979.

GLOBAL ISSUE: ALTERNATIVE ORGANIZATIONAL STRUCTURE FOR NEES/E-DEFENSE COLLABORATION

Masayoshi Nakashima
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Collaboration under Meta-Theme and Establishment of Theme Structures

In view of the activities of the Japan's earthquake engineering community after the 1995 Hyogoken-Nanbu earthquake, many efforts were notable on the identification of critical research needs and organization of comprehensive and collective research projects. Multiple projects were eventually funded by MEXT, the Ministry of Construction, and other agencies. Those collective efforts to launch the projects in which human resources were gathered nationwide, however, seem to have been dormant in the past few years. Research projects being implemented seem to become more and more disorganized, fragmented, and smaller.

Similar seems to be observed for the collaboration between the US and Japan. We have a beautiful history of US-Japan for many decades since the mid 1970s. In early days, the NSF and the Ministry of Construction (Building Research Institute) conducted a series of comprehensive experimental projects using large scale testing facilities. They included RC buildings (Phase I), steel buildings (Phase II), masonry buildings (Phase III), pre-cast buildings (Phase IV), composite structures (Phase V), and smart structures (Phase VI). After the 1995 Hyogoken-Nanbu, a US-Japan joint project co-sponsored by the NSF and MEXT was carried out for five years until 2002. This project is probably the last US-Japan in which many researchers in diverse disciplines gathered under one common umbrella.

Recalling the initiation of NEES/E-Defense, we gathered for a few times before its establishment. One was held at Tsukuba in the fall of 2003, and another was held at Kobe in the spring of 2004, and one more was held at NSF in the summer of 2004, in which we chose the targets of research collaboration, i.e., steel and bridges. Furthermore, we had three more meetings, two on steel and one on bridges, before the spring of 2005 in which the research project on the Japan side began officially.

Yes, the NEES/E-Defense is a visible and explicit collaboration between the US and Japan for the past few years, but I personally see some limitations of research collaboration in the current form. My concerns are: (1) even within the steel or bridges, it is rather difficult to lay out a consistent and (medium-term, say, for five years) plan in that funding to individual researchers, i.e., awards to proposals, is unpredictable; (2) the subjects are limited only to steel and bridges, which are very specific objects of research in light of the inherent nature of diversity attached to earthquake engineering and mitigation. (1) is attributed primarily to the funding mechanism of the NSF, i.e., equal opportunities to all, while the Japan side is primarily responsible for the restriction of (2). At the time of establishing the NEES/E-Defense, E-Defense had already been conducting comprehensive research projects (under the theme name of Dai-Dai-Toku) on the RC, wood, and geotechnical engineering. E-Defense had to avoid a project that would suggest an overlap and had asked us to limit the scope of research to something different from those already under way.

For the possible next phase of the NEES/E-Defense, we may want to reconcile the problems that we have encountered in the current phase and reformulate the method of collaboration. One suggestion is: (a) to set up a meta-theme(s) that are equally important and challenging in both countries and (b) to jointly work on a large-scale theme structure(s) (at E-Defense) in which a variety of components that will have been explored in the individual, more specific research projects (through NEES) are accommodated and their effectiveness are verified and calibrated in a most realistic manner. This way, research endeavors of much more diverse disciplines can be integrated together, and the genuine complementary effort can be achieved between NEES and E-Defense.

DISASTER RESILIENCE FRAMEWORK

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University at Buffalo – the State University of New York

The goal of enhancing the disaster resilience of communities requires integrating improvement of capability to prepare and respond to disasters, based on political-socio-economic decisions based on measurements of resilience, with clearly defined dimensions of resilience, to gauge improvements in resilience.

Community resilience to hazards is defined as the ability of social units, e.g., organizations and communities, to mitigate hazards, contain the effects of hazard-related disasters when they occur, and carry out recovery activities in ways that minimize social disruption and mitigate the effects of future hazards. The objectives of enhancing disaster resilience are to minimize loss of life, injuries, and economic impacts – in short, to minimize any reduction in quality of life due to the effects of these hazards. Resilience can be achieved by enhancing the ability of a community's infrastructure, e.g., lifelines and structures, to perform during and after a hazard, as well as through emergency response and strategies that effectively cope with and contain losses and recovery strategies that enable communities to return to levels of pre-disaster functioning (or other acceptable levels) as rapidly as possible.

As such, the goal of enhancing the disaster resilience of communities requires that standard methods be established to measure states of resilience, define the dimensions of resilience, and thus gauge improvements in resilience. Progress in earthquake engineering research (Bruneau et al., 2003) has shown that the evaluation of resilience to hazards can be expressed in general terms by the concepts illustrated in Figure 1. This approach is based on the notion that a time-varying measure of the quality of the infrastructure (or functionality) of a community can be defined. Specifically, infrastructure functionality can range from 0% to 100%, where 100% means no degradation in service and 0% means no service is available. If the infrastructure is subjected to a hazard at time t_0, it could cause sufficient damage to the infrastructure such that the functionality is immediately reduced during the occurrence of this disturbance (for example from 100% to 50%, as shown in Figure 1). Restoration of the infrastructure is expected to occur over time, as indicated in the figure, until time t_1 when it is completely repaired (indicated by a return to 100% of infrastructure quality). The resilience can be measured as the area below the functionality (quality) of infrastructure

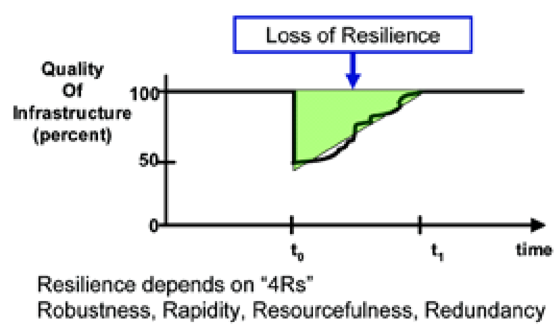

Figure 1. Evaluation of resilience to hazards – conceptual definition.

$$R = \int_{t_{OE}}^{t_{OE}+T_{LC}} Q(t)/T_{LC}\, dt\ ,$$

hence, the loss of resilience with respect to the exposure to a specific hazard (area shown in green in Figure 14), which is the size of the integrated expected degradation in quality (probability of failure) over time (that is, time to recovery). Obviously, resilience must be measured in light of the full set of potential hazards that threaten a community and, therefore, must include joint probabilities of occurrences of various hazards.

The framework and measurement of seismic resilience has formed the foundation to guide MCEER's research for the last ten years. The measure of seismic resilience for both physical and social systems has been further defined by the following properties:

- **Robustness:** strength or the ability of elements, systems, and other units of analysis to withstand a given level of stress or demand without suffering degradation or loss of function;
- **Redundancy:** the extent to which elements, systems, or other units of analysis exist that are substitutable, i.e., capable of satisfying functional requirements in the event of disruption, degradation, or loss of functionality;
- **Resourcefulness:** the capacity to identify problems, establish priorities, and mobilize resources when conditions exist that threaten to disrupt some elements, systems, or other units of analysis. Resourcefulness can be further conceptualized as consisting of the ability to apply material (i.e., monetary, physical, technological, and informational) and human resources to meet established priorities and achieve goals; and
- **Rapidity:** the capacity to meet priorities and achieve goals in a timely manner in order to contain losses and avoid future disruption.

Research Example: Lifelines

With respect to the seismic performance of the power transmission system in Los Angeles, California, robustness is defined in terms of performance indices of different dimensions such as power supply still available (technical), percentage of customers still having power (social) and level of regional gross product (economic) following a severe earthquake event. **Resourcefulness** is induced in the repair and restoration model, where the resources are assumed to be available through Federal and State assistance, utility emergency response contingency funds, mutual aid, etc. **Redundancy** is taking into consideration the inherently redundant design of bus configuration and redundancy of transmission lines connected to nodes of receiving stations. **Rapidity** is obviously highly dependent on all the R's and it demands complex modeling, which is an important future research subject. Indeed, rapidity is the culmination of how well preparedness, situation assessment and emergency response are managed and implemented. MCEER has developed models for performance analysis and repair management for the Los Angeles Department of Power and Water's (LADWP) power transmission system, calibrated with the Northridge earthquake event and used for simulation of risk and restoration curves under a set of scenario earthquakes representing the seismic hazard of Los Angeles and Orange Counties, California. Figure 1 demonstrates the resilience characteristics of the transmission system. Under the regional seismic hazard considered, the figure shows that the annual reliability is 98% that at least 66% of customers will have power following an earthquake.

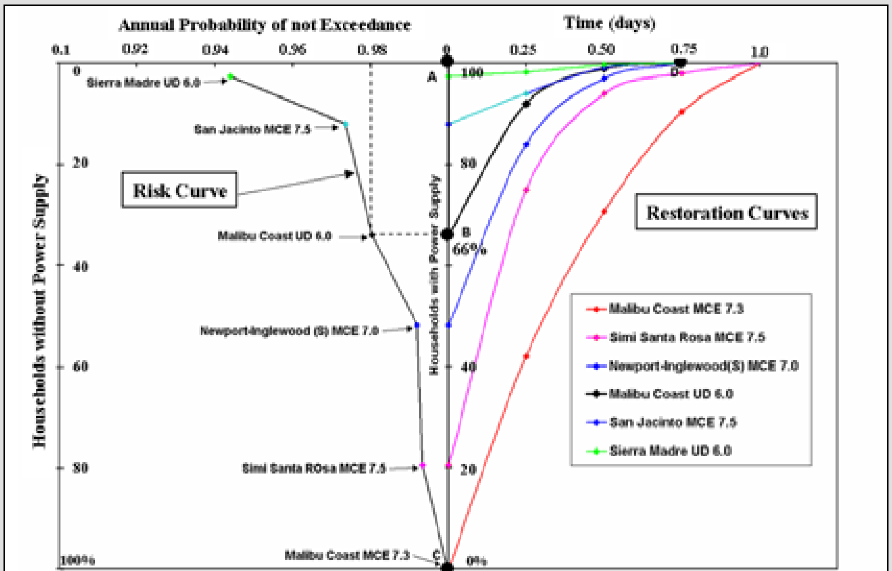

Figure 2. Performance analysis and repair management model for LADWP's power transmission system. (Shinozuka and Chang, 2004)

Resilience to the earthquake hazard has been further conceptualized as encompassing four interrelated dimensions: **technical, organizational, social, and economic** (Bruneau et al, 2003). The *technical* dimension of resilience refers to the ability of physical systems (including components, their interconnections and interactions, and entire systems) to perform to desired levels when subject to earthquake forces. The *organizational* dimension of resilience refers to the capacity of organizations that manage critical facilities and have the responsibility for carrying out key disaster-related functions to make decisions and take actions that contribute to achieving the properties of resilience outlined above – that is, that help to achieve greater robustness, redundancy, resourcefulness, and rapidity. The *social* dimension of resilience consists of measures specifically designed to lessen the extent to which earthquake-stricken communities and governmental jurisdictions suffer negative consequences due to the loss of critical services as a result of earthquakes. Similarly, the *economic* dimension of resilience refers to the capacity to reduce both direct and indirect economic losses resulting from earthquakes.

These four dimensions of community resilience – technical, organizational, social and economic (TOSE) – cannot be adequately measured by any single measure of performance. Instead, different performance measures are required for different systems under analysis. Research activities at MCEER address the quantification and measurement of resilience in all its inter-related dimensions – a task that has never been addressed before by the earthquake engineering research community. This is an extremely complex and difficult task. It requires integrated research tasks aimed at developing, testing, and refining quantitative measures of resilience.

The above framework is flexible and sufficiently general to broadly address disaster resilience in quite a generic manner. Quantification approaches are already being developed that can encompass any type of extreme condition, although it is recognized that specific resilience dimensions will be expressed differently to recognize infrastructure-specific parameters and constraints, as well as disaster-specific conditions. A list of references are provided at the end of this paper to enable the interested reader follow several approaches to quantification though worked examples

Research Example: Health Care Facilities

Mathematical relationships have been developed for quantification of the technical dimension of resilience for critical facilities (e.g., Bruneau, 2005, Filiatrault, 2004 and Cimellaro, 2006). Concurrently, an operational resilience framework has been developed for acute-care facilities (Figure 3). The former provide important necessary input to be able to assess the effective resilience provided by the latter. These can be used as a key step toward attainment of the operational resilience, expanded as the number of patient-days that can be provided as a measure of the treatment capacity of the health care facilities. This could be done for a single institution or for all facilities across a geographical region. The integrated focus on the physical infrastructure and their ability to provide their intended function was found, by the California Office of State Health and Planning, to provide a practical and effective framework to assess the effectiveness of policies in enhancing disaster resilience.

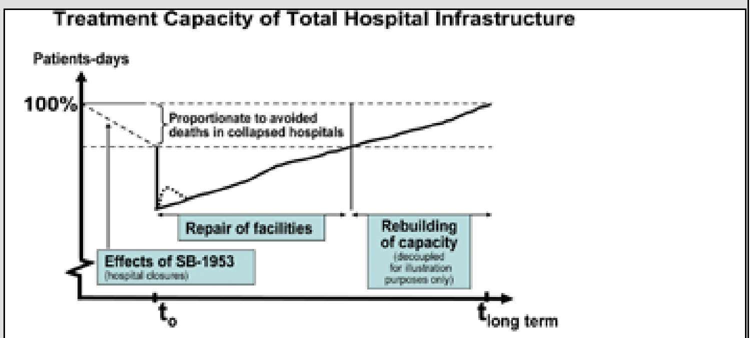

Figure 3. Quantification of seismic resilience of acute care facilities as patients/day treatment capacity of the total available hospital infrastructure. (Bruneau and Reinhorn, 2007)

For an infrastructure system, technical and organizational resilience can be measured as the annual probability that the system can satisfy the robustness and rapidity criteria with respect to earthquake risk (boxes Community and System Resilience Performance Estimation based on Resilience Criteria in Figure 4). This probability can be evaluated, for example, by evaluating the performance of an infrastructure system in a series of scenario earthquakes (the bottom line of boxes in Figure 4 followed by the Estimation or Evaluation of in boxes of Components and Systems). In case of actual earthquakes sensing and monitoring is done before the estimation /evaluation. The expected reduction in performance (reduction in power supply for an electric power system, for example) and expected time to recovery could then be evaluated for each of the earthquake scenarios (box for Resilience Assessment). Identifying those scenarios that meet technical and organization resilience criteria, and aggregating the scenario probabilities of occurrence, would yield an estimate of annual probability indicating overall resilience reliability for the electric power system. If expected resilience is deemed to be below the desired targets, options are to focus on response and recovery preparedness (box for Decision Support)) and/or modify the system to enhance its resilience (box for Advanced System Modifications). Water, hospital, and emergency response and recovery systems can be treated in a similar fashion with suitably defined performance criteria. At the community level, social and economic resilience can be evaluated analogously.

For example, advanced loss estimation models can be applied to estimate the economic consequences of damage and disruption sustained by the power, water, hospital, and emergency response and recovery systems. The extent to which an earthquake causes a reduction in gross regional product (GRP) can be viewed as an indicator of economic robustness or the lack of it, for example, and the time for GRP to recover to without-earthquake levels is an indicator of the rapidity dimension of economic resilience. As indicated above in the discussion on housing and community resilience, measures of social resilience can be evaluated similarly. The numbers of scenarios in which the robustness and rapidity criteria are met, and their associated probabilities of occurrence, then indicate the annual probability that resilience criteria are satisfied at the community level. At both the infrastructure systems and community levels, the annual probability of achieving resilience can be evaluated for cases with and without the application of specific advanced technologies (e.g., new materials, response modification technologies). The difference would directly indicate the potential resilience improvement from applying the advanced technology. While advanced technologies will generally yield improvements in system robustness, some advanced methodologies (e.g., decision-support systems, and/or rapid repairs technologies) could foster resilience by improving restoration rapidity. Other advanced methodologies (e.g., system models and advanced economic models) are needed to quantitatively estimate resilience more accurately, with reduced levels of uncertainty associated with resilience estimates. Because the systems diagram associates research tasks with the quantification or enhancement of systems and community resilience, it can also be used as a management tool for a coordinated research effort.

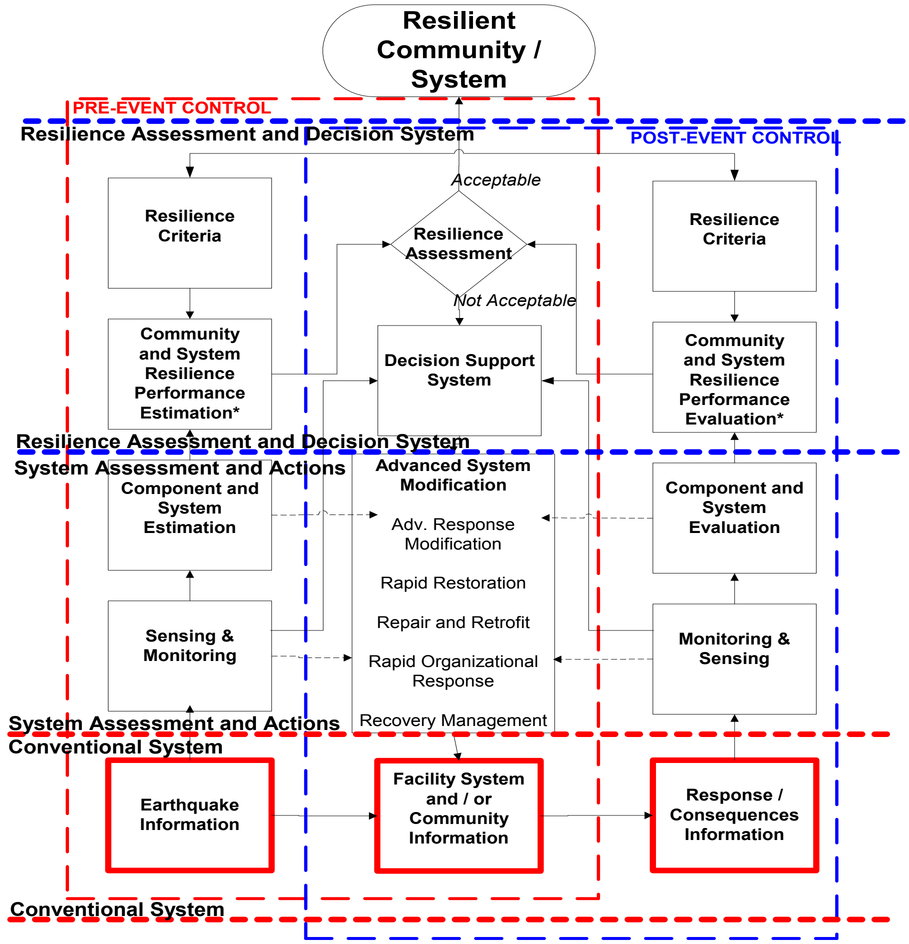

Figure 4. Systems diagram: schematic level of details.

The framework presented in Figure 4 is based on concepts that may be more familiar to systems engineers experienced with control algorithms, more specifically the open and closed loop systems theory (also referred to as “feedforward” and “feedback” loops). The open loop system, indicated by the clockwise flow of steps on the left, is applicable to actions that can be taken prior to an earthquake or other disaster, while the closed loop system, indicated by the counterclockwise flow of actions on the right, is applicable to actions that can be taken following an earthquake. An important distinction to make is that all research and development actions obviously take place prior to an earthquake. However, the feedforward and feedback loops refer to whether the developed technologies focus on pre-event actions (e.g., seismic retrofit), or post-event actions (e.g. response and recovery). An example of how the needed level of detail could be integrated into that system chart is presented by Bruneau et al., 2003.

The systems diagram presented in Figure 4 is also structured in three horizontal layers. The bottom layer is representative of the situation where no intervention is made on the existing systems; earthquakes occur, impact the systems (e.g., infrastructure), and disasters ensue. The second layer addresses a first level of actions and decisions in which decisions are made based on simple triggers; for example, a code-specified drift limit triggers some actions if exceeded during the design process (by analogy with the field of control theory, these would be referred to as semi-automated decisions, or rapid interventions). In most cases, the current state-of-practice operates at that second level. On the top level, multi-attribute information is gathered and used to make decisions. The decision systems effectively rely on advanced technical-organizational-socioeconomic information (by analogy with the field of control theory, this would be called adaptive control). Because it is derived from the field of control theory, this general framework is equally applicable to individual systems, combination of systems, and communities.

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Questions and Challenges

1) What are the links between the general framework and the structural (or non structural) systems

    a. What are the relations to the concept of performance based design

    b. What is the role of the technical aspects of resilience in the overall definition (including organizational, sociological and economical aspects)

2) How to define functionality (or quality of service) for

    a. Constructed infrastructure – bridges, buildings, etc?

    b. Organizations of services?

3) How to determine the recovery process, duration and organization

    a. Influence of technological issues

    b. Influence of organizational issues

    c. Influence of societal priorities

    d. Influence of economical – money supply

4) How to integrate multiple networks in the resilience concept

    a. How to define common functionality

    b. What are interdependencies the influence resilience

5) Is the probability framework, the most suitable for the resilience quantification

6) Can we develop a general platform for

    a. simulation of disasters?

    b. definition alternative advanced for systems – networks modifications?

    c. prediction of resilience?

    d. simulation of decision system?

7) While the quantification requires large simulations, can we determine simplified tools for decision support based on resilience concept?

SOCIETAL LEVEL META-THEMES: ARE DISASTER RESILIENT CITIES FEASIBLE?

Masayoshi Nakashima
Kyoto Univ. and E-Defense

Development of Earthquake Engineering That Complies with "Time is Money" Society

Earthquake engineering has a long history of "learning from actual earthquakes and earthquake damages." On the other hand, Japanese societal structures, particularly those in urban areas like the Tokyo metropolitan region, have changed very significantly for the past forty years. In mid 1970s, there was no high-rise office in downtown Tokyo, the metropolitan subway had far less commercial lines, waterfronts remained sparse, neither PC nor Internet was existent, very few people who do not speak Japanese lived in Japan, or the word "globalization" was not invented yet. Fortunately, our fast developed urban areas have not been tested for their robustness/vulnerability against a significant earthquake.

Placing aside the argument of a good or bad luck, would these changes in our societal structures not alter the nature and severity of earthquake damage that we foresee based on the lessons from previous earthquake damage? Or sticking to our tradition of "learning from actual earthquakes", are we ready to wait until our urban areas are hit by a serious quake?

We instantly imagine various ominous effects by the changes as randomly shown below.

- High-rises may not sustain serious structural damage, but what about nonstructural elements and building contents in the high-rises? They may be seriously damaged; then apparently the business in the buildings has to slow down.
- As an example, a recent medium quake in Chiba (2005) stopped over 64,000 elevators in buildings built in downtown Tokyo. It means that the elevator sensors were very effective. However, the number of engineers and technicians who maintain the elevators was far too smaller than what was needed after the stop. Eventually, it took full one day for complete recovery, while those who rode on unfortunate seventy eight elevators (out of 64,000) had to spend in the elevator for many hours.
- BCP (Business Continuity Plan) is a very important keyword in the industry. According to the recent statistics, about twenty two percent of the large Japanese companies whose stocks are open in the Tokyo stock market have their headquarter functions in high-rises in downtown Tokyo. The total sales of these companies amass to about thirty percent of the entire sales in Japan. Business interruption by a quake may bring a huge negative impact to the economy in Japan and the rest of the world.]
- As a very recent trend in downtown Tokyo, multiple high-rises have been built in a rather small area. Suppose that the area suffer from a medium quake, all residents working in the high-rises will likely be asked to leave the buildings. Then, what would happen – the ground left in the area is just too far small that it cannot accommodate all people being evacuated. A calamity is very plausible.
- Hospitals are the most important facilities that shall function at the time of earthquake damage. Quite a few newly built hospitals are base-isolated, by which no structural damage is expected. This is fine, but various medical facilities placed on the floors still vibrate. The vibration may be small enough not to cause any physical damage to the

facilities, but… they are very sensitive equipment and carefully calibrated for checking values using which doctors diagnose the patients. How are we sure that calibration would remain correct after the vibration? It is not easy to answer at this moment.

To avoid such calamity of Japan and Japanese, we shall not wait a moment. We have to immediately bring the best and brightest having various expertise associated with earthquake disaster and mitigation, let them carefully examine the recent changes in the society and use the most imagination possible about the potential disasters that have not been experienced before but may be realized next time, and take immediate action for identifying the scientific challenges to promote the effective countermeasures.

To this end, proposed here is an approach that consists of the following steps.

(I) Capture the facts that characterizes the contemporary urban society (*1) ;
(II) Identify the research approaches that are suited to the contemporary urban society (*2);
(III) Present scenarios that may occur in the contemporary urban society once it is hit by damaging earthquakes; and
(IV) Identify engineering issues to mitigate the expected damage to the contemporary urban society.

(*1) – An example:
(1) Huge information flow;
(2) Increasing need for efficiency and fast response;
(3) Emphasis on functionality and amenity; and
(4) Promotion of diverseness, segmentation, interaction, and inter-dependency

(*2) – An example:
(a) Client-oriented mind for the identification of problems to solve/resolve;
(b) More focus on nonstructural aspects and their interaction;
(c) Emphasis on redundancy and multiple backups regarding the various functions that the building should possess;
(d) More focus on safety and operability of life-lines interacted with buildings;
(e) Need for Fast responses to disasters, i.e., quick inspection, quick repair, etc.;
(f) Mechanism of information sharing among engineering, owners, and users.

NEES-E-Defense Planning Meeting Phase 2 Jan 12-13, 2009

Resilient Structures

✓ What does it mean?
✓ An example: Self-centering systems
✓ A need: better fire design

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1

WHAT DOES IT MEAN?

Re•sil•i•ent [The American College Dictionary, 1964]

1. *Springing back; rebounding*
2. *Returning to original form or position after being bent, compressed, or stretched*

Resilient structures…

- ***efficiency***: minimum waste of materials
  - ✓ no replacing damaged beams/cols/etc
  - ✓ no replacing entire building
- ***economy***: minimum cost
  - ✓ min. direct cost (repairs)
  - ✓ min. indirect cost (loss of building use/rent)

2

WHAT DOES IT MEAN?

Is Resilient = Sustainable ??

Yes if we consider all loads, including time dependent (e.g corrosion);
Making it resilient only for EQ does not make it sustainable

Sustainable structures ..

- ***efficiency***: minimum waste of materials
  - ✓ up front (initial construction) and through time with repairs/replacement
- ***economy***: minimum cost
  - ✓ durability = min repairs = min maintenance = min cost

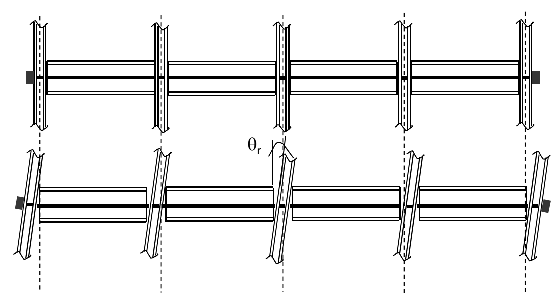
3

AN EXAMPLE: SELF-CENTERING SYSTEMS

What are self-centering systems?

- Typically involves some post-tensioning steel (strands or bars) that remain elastic and return the structure to original upright position after an EQ.

[“Re•sil•i•ent = *Returning to original form or position …”]*



4

AN EXAMPLE: SELF-CENTERING SYSTEMS

What are self-centering systems?

- Beams/columns remain elastic; energy dissipated by devices (activated by θr) that may not need to be replaced, such as friction devices.

- May have higher cost up front (e.g. no field welding but need post-tensioning system), but financial benefits follow EQ event
  - ***efficiency***: minimum waste of materials
    - ✓ no replacing damaged beams/cols/etc
  - ***economy***: minimum cost
    - ✓ direct: no repairs
    - ✓ indirect: no loss of building use/rent

5

A NEED: BETTER FIRE DESIGN

- Fire can be a primary event (e.g. accidental ignition), or a secondary event (e.g. following blast or earthquake).
- Fire leads to property and structural damage and sometimes lost lives.
- Fire following earthquake is not uncommon.

6

A NEED: BETTER FIRE DESIGN

- Study done in 2008 by C. Scawthorn for USGS: A hypothetical M7.8 EQ on southern San Andreas Fault on a typical November day ("realistic scenario") would result in:
  - ✓1600 ignitions (1200 uncontained)
  - ✓200 million square feet burnt area
  - ✓Economic loss 40 to 100 billion $$

- "Whether a structure has been damaged or not, ignitions will occur due to earthquake."

- 1906 San Francisco EQ, 80% of damage = fire

7

A NEED: BETTER FIRE DESIGN

- "resiliency/sustainability" applies for the entire lifetime of a structure, not just to an EQ event. Since fire commonly follows EQ, need to consider this "load" as well.

- Currently, fire design (e.g. amount of fire protection) is typically decided by the architect based on a prescriptive approach that is not based on structural response.

- Performance-based fire design can be used to mitigate damage.

8

A FEW LAST THOUGHTS ...

- Is resilient/sustainable design just common sense engineering?
  - ✓ Isn't that what we have been trying to achieve before we had words such as 'resilient' or 'sustainable' to define it?
  - ✓ Perhaps the difference is that society has finally recognized such needs.
- Some possible obstacles:
  - ✓ Within the architect's boundaries of form and space are we "confronting the hopeless task of making feasible extravagant architect's dreams, with more concern to play safe than the possible economy of the work" ? [Felix Candela]
  - ✓ Are building code officials and the profession too reluctant to change (too traditional)?

9

SOCIETAL LEVEL META-THEMES: ARE DISASTER RESILIENT CITIES FEASIBLE?

Muneo Hori
Univ. of Tokyo

Development of Effective Seismic Retrofit Techniques

It is not easy to give a solid answer to the question “are disaster resilient cities feasible?” because the level of resilience that is required for earthquake disasters will change as the cities develop. In general, resilience of higher level will be required as the cities become more civilized. However, resilience of excessive level is unnecessary. The suitable level is not easily found since the level is commonly recognized until some damages occur by a large earthquake and they cannot be repaired.

While the suitable level of resilience against earthquakes is not clear for future cities, it is surely overlooked that the resilience level that is required for current urban areas is higher than late 1990’s in which North Ridge Earthquake and Hanshin Awaji Great Earthquake occurred. There are the following three major reasons for the requirement of higher resilience:

1. Although “relative” importance remain unchanged, the “absolute” importance of buildings and infrastructure systems keeps growing in accordance with the expansion of the economic activities; the capitals that are created with the buildings and infrastructure systems growing larger and larger. The current communication and information network systems are as important as nuclear power plants of a few decades ago, and they may need seismic resistance at the same level of the past nuclear power plants.
2. In the Japanese metropolitan region, nearly one-third of the entire population inhabits. Should this region be hit by a large quake and damage bee spread throughout, serious shortages of work forces will be encountered. This is because the construction industry in Japan is shrinking due to the decrease in public work budgets of national and local government.
3. According to a general framework of BCP (business continuity plan), which is being popularly adopted in Japan, the time that is required from the instant of an extreme event to the business restart is in a range of one to a few days. On the other hand, repair and rehabilitation of buildings and infrastructure systems naturally requires a few months once they are severely or even moderately damaged by a large earthquake.

As a summary, we are overlooking that higher seismic resistance is required for buildings and infrastructure systems in the current urban areas. The seismic resistance is as high as that required for nuclear power plants so that no serious malfunctioning takes place and no repairs are needed even if a large earthquake takes place. To meet the unrecognized demand for the higher seismic resistance, we have to retrofit existing buildings and infra-structures. We may put priority of retrofitting buildings and infrastructures to regions which are located in regions which seismologists have warned are of higher possibility of being hit by a large earthquake.

To achieve such retrofitting, a critical need is the development of effective seismic retrofit techniques. There are a number of seed techniques for retrofitting techniques, and we have to develop them so that the cost required for retrofitting will be much less expensive. E-Defense and NEES facilities should be used for such development. In particular, E-Defense is deemed to be the sole facility that can calibrate the validity of the developed techniques.

The Resilient City

The Resilient City is one that, by way of preparation and judicious technology implementation, skirts the earthquake disaster.

The Resilient City has made a comprehensive plan for hazard mitigation, emergency preparedness, and rebuilding, with a target schedule for when certain city functions are back on line. In this context, seismic resilience is the ability of the city to

- **contain the effects** of earthquakes through mitigation;
- **carry out recovery** activities in ways that minimize social disruption; and
- **rebuild** in ways that mitigate the effects of future earthquakes.

The comprehensive plan for the Resilient City might include a target schedule such as: emergency response facilities are **immediately functional;** household units are inspected and most are safe for inhabitants to shelter in place **within one day;** 90% of the water, power, and waste water systems are operational **within 3 days;** 90% of transportation systems, schools, and businesses are open and serving the local workforce **within 30 days;** etc.

No one knows quite what a comprehensive plan for the Resilient City would actually look like (though the San Francisco Planning + Urban Research Association (SPUR) is working on one). But the notion of such a plan can form the context for planning a seismic research program that would develop new materials and systems of enhanced performance, implement instrumentation and information technologies to speed recovery, and integrate individual components and networks of the built environment for enhanced post-earthquake performance at the systems level.

Jack Moehle
7 January 2009

Some of the ideas expressed
derive from work of SPUR's
Disaster Planning Initiative

NEES/E-Defense Phase 2
White Paper

PREPARING FOR THE BIG ONE (A REFERENCE MAGNITUDE 9 EVENT)

Prepared by
Stephen Mahin
University of California, Berkeley

Background

Today, engineering design is based on probabilistic estimates of likely earthquake shaking that may occur during the life of a structure. While frequent, rare and very rare are considered in most cases, the largest earthquake of record near the site where a structure is to be built, or the largest earthquake event that can be produced by nearby earthquake faults are not generally considered. Moreover, historic trends related to design earthquakes has been for (with limited exceptions) been to increase the level of shaking for which structures should be designed as we learn more about the nature of local seismic hazards.

Thus, future seismic events may be larger, and in some cases significantly larger, than those for which we are currently designing. The consequences of such large events in urban regions, or where critical infrastructure may be located, are profound. Examples of such larger than intended events include the recent Magnitude 8 Wenchuan earthquake in China.

In earthquakes of this size, there are several unique scientific, engineering and social/policy challenges compared to earthquakes traditionally considered in design. For instance, the area over which ground shaking is severe enough to produced damage to well engineered structures and lifeline systems is very large, and the broad geographic distribution and large numbers of structures, lifeline and transportations systems may create special emergency management and response problems that need to be considered, and the economic challenges and technical and administrative resources needed to recover from such an extreme event may require careful consideration. These are important challenges, and the NEES and E-Defense can be used as important tools in planning for such extreme events.

Given the limited number of recorded ground motions with magnitudes greater than 8, it is desirable for integrated engineering and earth science investigations into the nature and consequences of such events. However, it is considered for the purpose of this meeting, that detailed studies of the nature of extreme ground motion shaking are out of the likely scope of study of the Phase 2 NEES/E-Defense program.

Scientific and Engineering Challenges

In this case, the focus is on the "Big One" -- nominal Magnitude 8+ events, such as the 1700 Cascadia subduction zone, 1811-12 New Madrid, 1857 Ft Tejon, 1868 Ka'u (Hawaii), 1906 San Francisco, 1964 Prince William Sound (Alaska), 2002 Denali (Alaska) earthquakes in the US, or the 1896 Sanriku, 1923 Kanto, 1933 Sanriku, 1944 Tonankai, 1946 Nankaido, and 2003 Hokkaido earthquakes in Japan. Ground shaking from such extreme events is unusually intense, distributed over a large geographic area, has a long duration (measured in minutes, not seconds), and when measured near the causative fault, may have unusually large and long duration pulses that can adversely affect a range of structures in ways not seen previously. Many of these large events are produced by subduction zone faulting. The effects of such faulting have not had extensive study in the US.

The intensity and duration of shaking from extreme events may result in larger than anticipated demands on structures. These may be due to:

1. Unusually large lateral displacements ground displacements (10+ m);
2. Unusually large ground velocities or other pulse like effects associated with fling or directivity effects near the causative fault,
3. Larger than anticipated ground accelerations;
4. Less intense, but very long duration motions in the low frequency range at more distant sites (higher demands on long period structures),

Response characteristics and failure modes not seen in lower magnitude events may dominate behavior of structures when subjected to extreme earthquakes. These include failures due to:

1. Unusually large demands for plastic deformation,
2. Ratcheting type instabilities associated with geometric nonlinearities,
3. Low cycle fatigue,
4. Greater influence of lateral-torsional coupling in structures with light or moderate damping (beating effects), etc.

Consideration of such large events may necessitate special approaches or modification of design approaches to maintain structural safety under unprecedented amplitudes lateral displacements or under unusually large numbers of cycles of inelastic deformation. To reduce the rate of structural deterioration under such conditions, new details, structural configurations or systems, response modes, and new protective devices or elements may be needed.

Broader Impacts

The consequence of a large magnitude (Reference 9) earthquake may be disastrous for a modern urban region. It is critical that the characteristics and consequences of such events be better understood. In particular, it is important that the relation of such extreme earthquakes to the response characteristics (and engineering demands) on typical engineered structures is understood, and effective measures for resisting these demands and economically and effectively protecting public safety in the event of such extreme earthquakes be identified.

Potential Research Topics Using Unique Capabilities of NEES and E-Defense Facilities

NEES and E-Defense facilities can be used effectively to study the effect of various characteristics of extreme ground motions on a range of structures (short as well as tall buildings in concrete, steel and other materials, bridges, and so on). The effect of various near fault pulses, intense long duration shaking for low- to high-rise structures, moderate levels of long duration low frequency shaking of tall buildings, multi-directional shaking, etc. can be simulated using E-Defense and various NEES facilities, as well as through numerical simulations. Fundamental studies of the factors controlling (and mitigating) collapse due to geometric and material nonlinearity are needed. Fundamental studies are needed to better understand deterioration and failure of members, connections and structures due to low cycle fatigue, and to devise details, devices, and structural systems and configurations that are more resistant to failure due to low cycle fatigue.

Preparing for the "Big One"

Kohji Tokimatsu
Tokyo Institute of Technology

The Tokyo Metropolitan Area, like other major cities in earthquake-prone countries of the world, is confronted with substantial seismic risk of catastrophic damage to complex urban functions. The latter have resulted from an excessive concentration of population, buildings, and infrastructures, as well as economic, political, and administrative activities, among other contributory developments. The probability of an M7 earthquake occurrence in the Tokyo Metropolitan Area within 30 years is estimated to be on the order of 70%. Once such an earthquake hits the area, not only are the resulting damage and overall losses catastrophic, but economic, political, and administrative functions of the entire capital region are bound to decline and deteriorate in terms of operational efficiency.

What are the parameters of the "Big One" the Tokyo Metropolitan Area needs to prepare for?

Potential causative factors threatening the area include: shallow inland earthquakes along both an identified active fault (M7.0-7.5) and an unidentified fault (M6.9), plus earthquakes along the subduction zone between the Philippine and North American Plates (M8.0). Among these types of earthquake, an M7.3 (not the biggest) with its epicenter along the northern edge of Tokyo Bay has the highest probability of occurrence and is considered the "Big One" in Tokyo. This contrasts substantially with the San Francisco Bay Area, where a repeat of the biggest one to date, the 1906 earthquake (M7.9), remains the anticipated target event.

In 2005, the Japanese Cabinet Office calculated the damage and losses that would accrue from this anticipated large-scale Tokyo earthquake. According to their estimate, the number of fully collapsed buildings due to ground shaking is 150,000, with an additional 45,000 buildings damaged owing to ground problems including soil liquefaction. The number of burned-out buildings is 650,000, if the earthquake occurs on the evening of a windy day, resulting in over 10,000 fatalities. About 6 million people are estimated to have difficulty in returning home due to interruption of transportation services and will be obliged to stay overnight in central Tokyo. About 300,000 elevators come to a standstill, caging passengers in. It is estimated that the water and gas supply will be suspended for periods in excess of one and two months, respectively, affecting over 4,000,000 people. The estimated rubble resulting from collapsed buildings is ten times that produced in a normal year. The construction of temporary housing for those who have lost homes will require an area of 2,000 ha. (spread over a 2-year construction period). The forecast loss, direct and indirect, exceeds in a worst case scenario JPY 100 trillion, which is greater than the current annual national budget of JPY 80 trillion, exerting a tremendous impact on Japan's economy and probably also on those of many other countries around the world.

In order to attempt to reduce the scale of these estimated damage and losses, the Cabinet Office proposed two major objectives to mitigate damage throughout the Metropolitan Area:

- Assured Continuity of the Capital's Central Functions
- Enhanced Earthquake Resistance and Resilience

"Assured Continuity of the Capital's Central Functions" includes (1) the establishment and implementation of a Business Continuity Plan (BCP), and (2) a seismic retrofitting and optimal restoration scheme for critical buildings and infrastructures, as well as all lifelines. "Enhanced Earthquake Resistance and Resilience" stresses an enhancement of: (1) the resistance of buildings, (2) the fireproofing of cities, (3) care for displaced persons, (4) care for those unable to return to their homes, and (5) disaster measures for corporate entities and other businesses.

The M6.0 earthquake that occurred on July 23, 2005, in Northwest Chiba Prefecture, may be envisioned as a miniature version of the anticipated Tokyo earthquake, for example locking many people in the train and subway as well as inside elevators. Reflecting the lessons learned from this recent earthquake, the Cabinet Office established further anti-seismic measures regarding: (1) prompt information concerning seismic intensity, (2) operation of rail and subway facilities, (3) elevator operation and maintenance, (4) inspection and, if necessary, restoration of roads and highways, (5) congestion and eventual blockage of telecommunication, and (6) suspension of the public water supply.

The M6.8 Niigataken Chuetsu-oki Earthquake that occurred on July 16, 2007, should occasion further thought on the current adequacy of our Tokyo disaster mitigation measures. It also demonstrated that a failure of even one key component of any integrated infrastructural system could lead to an extended shutdown of the total system and, in addition, might well affect the operational economy of communities located away from the directly affected area. In the event, these have included the following:

- A long shutdown of the Kashiwazaki-Kariwa Nuclear Power Plant resulting in a reduction of profits, which may yet exceed in less than one year total construction costs for a single unit of the plant itself.
- Damage to two auto part plants halting almost all production lines of twelve major car manufacturers throughout Japan.
- The failure of just one stack in the waste incinerator forcing the municipality to move all waste from the region to outside the city for a four-month period.

The major cause of the damage and of the delay in re-firing of the nuclear power plant appears to be due not only to the extremely strong shaking incurred by the main seismic event but also to ground problems that include settlement~~s~~ of backfills around critical buildings. This state of affairs speaks strongly to the fact that more consideration must be accorded, during the design phase of any building or infrastructure, to performance of soil and foundation and its effects on the integrity and efficient performance of the total system during and after strong ground shaking.

NEES/E-Defense Collaborative Research Program on Earthquake Engineering

Phase 2 Planning Meeting

Meta-Theme: Mitigating Catastrophes from Low Probability, High Consequence Seismic Events

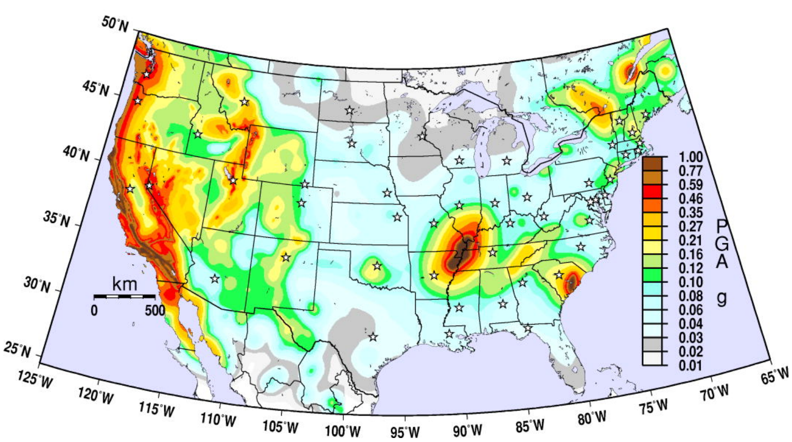
Jerome F. Hajjar
Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign

January 12-13, 2009

Arlington, Virginia

The Nature of Low Probability, High Consequence Seismic Events

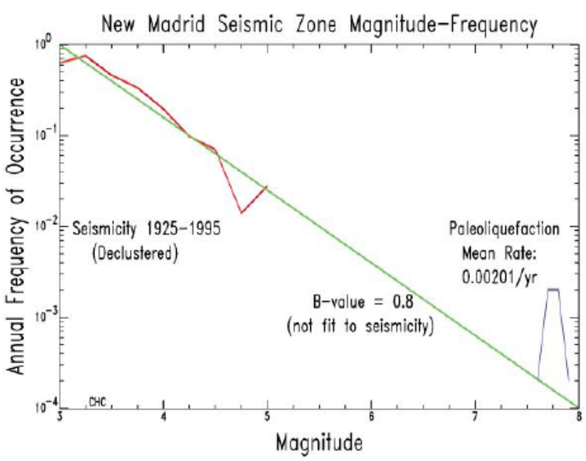
PGA with 2% in 50 year PE. BC rock. 2008 USGS

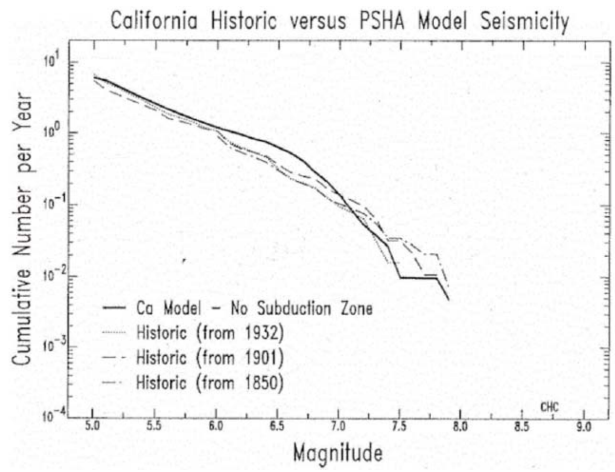


Several regions of the U.S. east of the Rocky Mountains are vulnerable to low probability, high consequence seismic events

Reference:
United States Geological Survey (2008). “2008 National Seismic Hazard Maps,” United States Geological Survey, Washington, D.C.

The Nature of Low Probability, High Consequence Seismic Events





Magnitude-Frequency relations rely on accurate and extensive data

Such data are not generally available for long recurrence rate events

References:
Cramer, C. H. (2001). "A Seismic Hazard Uncertainty Analysis for the New Madrid Seismic Zone," *Engineering Geology*, 62, 251-266.
Petersen, M. D., Bryant, W. A., Cramer, C. H., Cao, T., Reichle, M., Frankel, A. D., Lienkaemper, J. J., McCrory, P. A., and Schwartz, D. P. (1996). "Probabilistic Seismic Hazard Assessment for the State of California," California Department of Conservation, Division of Mines and Geology, Open-File Report 96-08, U.S. Department of the Interior, U.S. Geological Survey, Open-File Report 96-706.

Buildings

Many structures in these regions are not designed for modern seismic requirements, even for moderate earthquakes

When seismic design is included, the relation of physical damage to economic and social impacts is generally more approximate than in regions of high seismicity

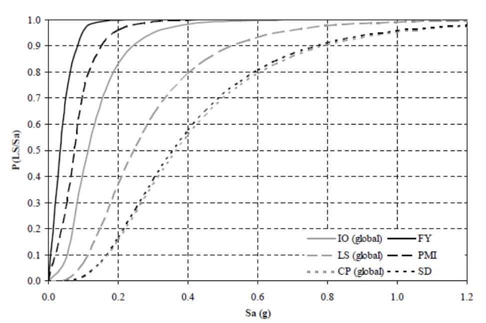
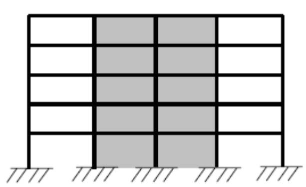
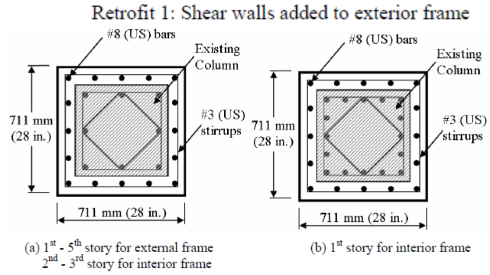


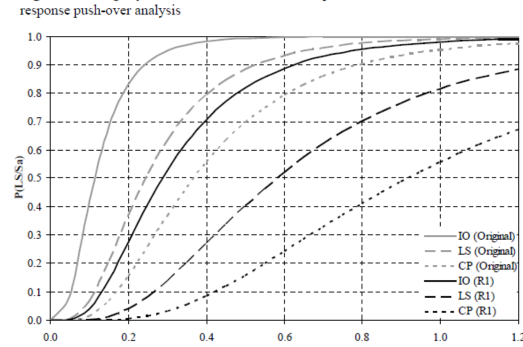
Fig. 5.27. Fragility curves based on additional quantitative limits from the critical response push-over analysis



Retrofit 1: Shear walls added to exterior frame



Cross-sectional details of RC column jacket retrofit

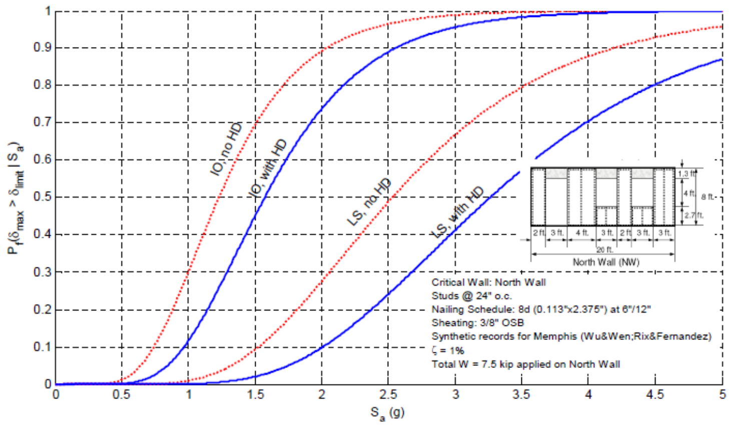


(a) Retrofit 1: Addition of shear walls

Global-level fragility curves for the retrofitted structure

Reference:
Bai, J.-W., and Hueste, M. B. D. (2005). "Seismic Fragility Analysis for a Retrofitted Five-Story Reinforced Concrete Building," *Mid-America Earthquake Center Internal Report*, Texas A&M University, College Station, Texas.

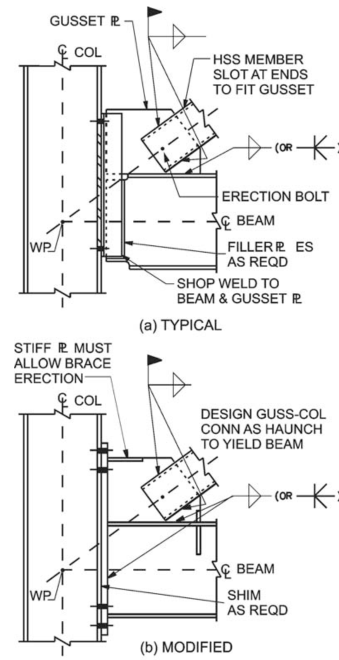
Buildings



Fragilities for one-story wood frame residence in Memphis, TN.

Construction techniques common in regions of high seismicity are often not adaptable to zones with long recurrence events

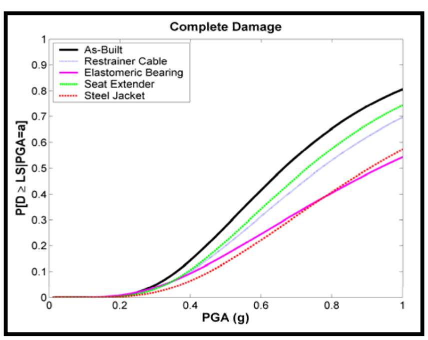
New strategies are required that fit within common modes of construction but add adequate strength and ductility to the system

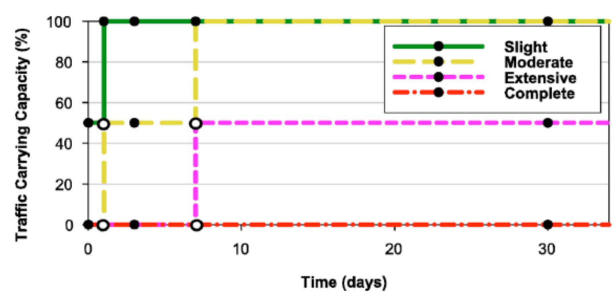


Brace Connection Details

References:
Ellingwood, B. R., Rosowsky, D. V., and Pang, W. (2008). "Performance of Light-Frame Wood Residential Construction Subjected to Earthquakes in Regions of Moderate Seismicity," *Journal of Structural Engineering*, 134(8), 1353-1363.
Fahnestock, L. A., Hines, E. M., Stojadinovic, B., Baise, L., Thompson, M., and Hajjar, J. F. (2008). "Seismic Collapse Prevention in the East," Internal Report, University of Illinois at Urbana-Champaign, Urbana, Illinois.

Bridges





Stepwise restoration functions defining slight through complete damage.

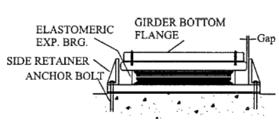
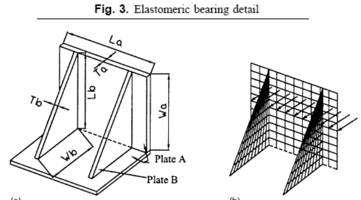


Fig. 3. Elastomeric bearing detail



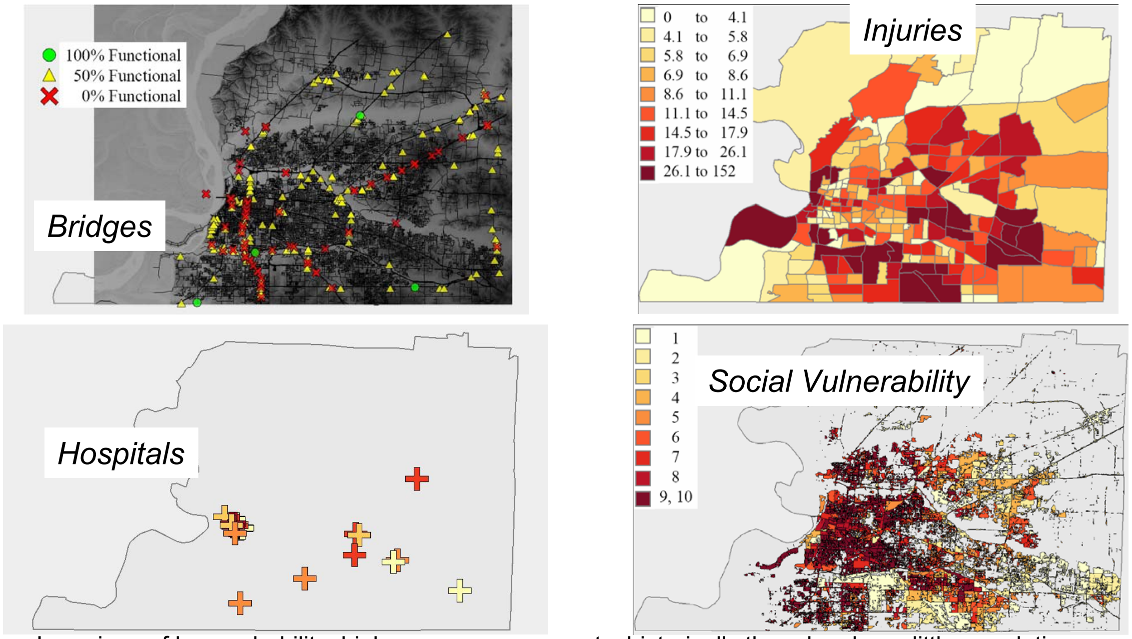
Retainer detail: (a) geometry and (b) finite-element model

Many bridges and lifelines in these regions are not designed for modern seismic requirements, and, as with buildings, new construction and retrofit strategies from high seismic regions are often not applicable

In regions with inadequate seismic mitigation for large events, issues such as repair rates and lifeline system interdependencies gain increasing importance

References:
Padgett, J. E., and DesRoches, R. (2007). "Bridge Functionality Relationships for Improvised Seismic Risk Assessment of Transportation Networks," *Earthquake Spectra* , 23(1), 115-130.
Maleki, S. (2004). "Effect of Side Retainers on Seismic Response of Bridges with Elastomeric Bearings," *Journal of Bridge Engineering*, ASCE, 9(1), 95-100.

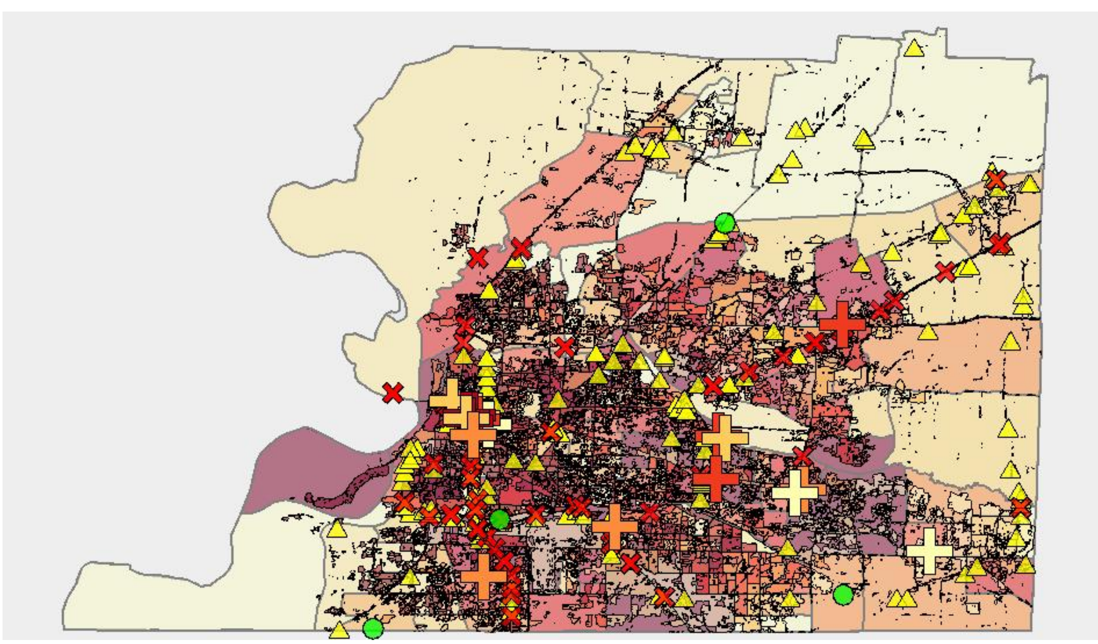
Regional Seismic Risk: Disaggregated Analysis



In regions of low probability, high consequence events, historically there has been little correlation between engineering damage and societal impact

Reference:
Steelman, J. S., and Hajjar, J. F. (2008). "Capstone Scenario Applications of Consequence-Based Risk Management for the Memphis Testbed," *Mid-America Earthquake Center Internal Report*, University of Illinois at Urbana-Champaign, Urbana, Illinois.

Regional Seismic Risk: Aggregated Analysis

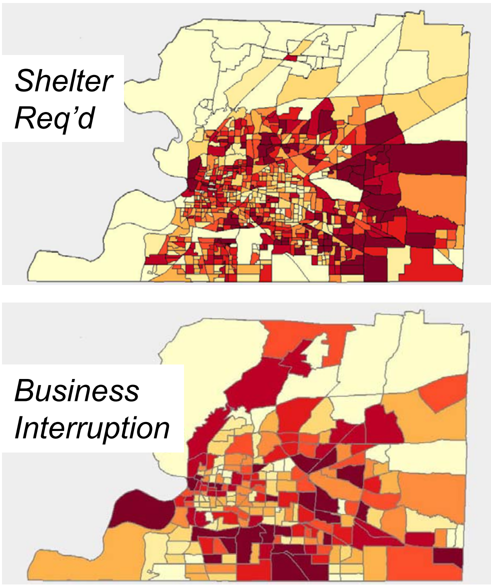


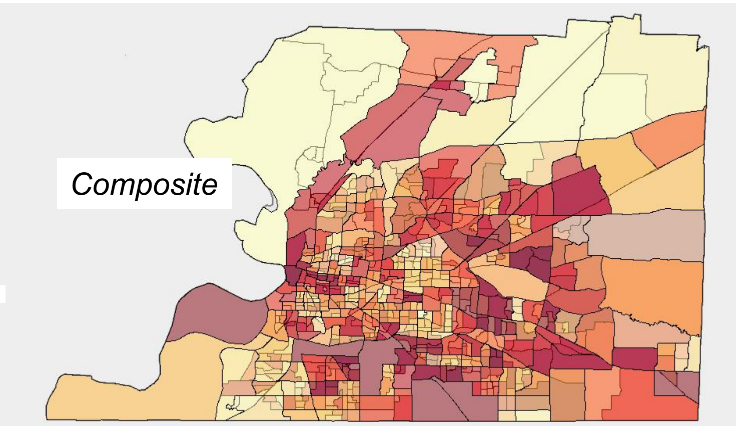
While engineering damage data can often now be assessed on a pointwise basis (e.g., building by building), much demographic information remains available only on a census track level

Reference:
Steelman, J. S., and Hajjar, J. F. (2008). "Capstone Scenario Applications of Consequence-Based Risk Management for the Memphis Testbed," *Mid-America Earthquake Center Internal Report*, University of Illinois at Urbana-Champaign, Urbana, Illinois.

J. F. Hajjar
University of Illinois at Urbana-Champaign
January 12-13, 2009

Regional Seismic Risk: Aggregated Analysis





Significant work remains to link engineering damage cohesively to algorithms that predict traffic disruption, lifeline functionality, business disruption, and societal impact

Reference:
Steelman, J. S., and Hajjar, J. F. (2008). "Capstone Scenario Applications of Consequence-Based Risk Management for the Memphis Testbed," *Mid-America Earthquake Center Internal Report*, University of Illinois at Urbana-Champaign, Urbana, Illinois.

Discussion Topics

- Regions with low probability, high consequence events are especially challenging from a political and societal viewpoint, as the cost-benefit of retrofit, new construction, and disaster preparation are often challenged by local governments, businesses, and the general population. How can engineering solutions for regional resilience be best integrated with high priority societal needs such as regional growth?
- Seismicity data is often scarce, little may be known about characteristics of near-fault events, and liquefaction data may be sparse. How can this uncertainty be propagated comprehensively into engineering solutions and decision support?
- New construction methods often cannot mimic those used in regions of high seismicity. What aspects of innovative seismic engineering are best adapted to regions of low probability, high consequence events, and what new innovations are needed to allow seismic engineering to gain wide acceptance in these regions? Examples include:
  - Modular and replaceable components that function as expendable fuses for moderate events to help maintain functionality in regions that are not well prepared for widespread damage
  - Inexpensive (low reliability) secondary systems that are engaged to enhance ductility and collapse prevention only during rare events

Discussion Topics (cont.)

- Prioritization of retrofits regionally becomes an increasingly network-based problem for larger magnitude events. Much work remains to correlate quantitative engineering damage to lifeline functionality and interdependencies, business disruption, economic loss, and decision support. This is especially important in regions of low probability, high consequence events, as the probability of occurrence often skews the decision support algorithms and results. How best can proper new construction and retrofit decisions and prioritizations be made accounting quantitatively for these interdependencies and uncertainties?

- Much data required for regional loss is unattainable due to being in private hands, and much retrofit and reporting of critical private facilities (e.g., distribution pipelines, critical food and health distribution businesses, construction materials distribution) is often not required in these regions. What are approaches for accessing this data or accounting integrally for its absence in regional loss predictions?

- What are the best ways to shift the risk management culture in the business communities in these regions towards constructive engagement of the issues that arise with low probability, high consequence events?

SOCIETAL LEVEL META-THEMES: MITIGATING CATASTROPHES FROM LOW PROBABILITY, HIGH CONSEQUENCE EVENTS

Kazuhiko Kawashima
Tokyo Institute of Technology

What are event with low probability and high consequence?

What is unique issue raised by "mitigating catastrophes from low probability and high consequence events" and what is this meta-theme different from the meta-theme on "preparing for the big one (M9 event)"?

Mitigating catastrophes from low probability and high consequence events can be extremely important in US because there exist regions which have seismicity ranging from almost zero to very high. New Madrid earthquakes in 1811 and 1812 and Charleston earthquake in 1886 can be typical examples of such an event. Catastrophic damage can occur once a region where no seismic consideration is provided is hit by a big one. It may be very difficult to make people to realize the seismic risk and take actions for mitigating damage.

On the other hand, what are events with low probability and high consequence in Japan? Japan is earthquake prone country in the entire territory. Fear to seismic damage is essential in mind of most Japanese, In particular extensive damage in 1923 Kanto earthquake made the public to be aware of the terribleness and fear to earthquakes. Seismic zoning map used in seismic design of buildings and civil infrastructures in Japan has 3 zones (Zone A, B and C) with less difference of zoning modification factor. Seismic intensity ratio of C/A is 0.8 in buildings and 0.7 in most civil infrastructures. Probabilistic seismic intensity distribution for a certain return period has much larger difference depending on regions, but the minimum ratio C/A is limited as 0.8 and 0.7 for securing safety of structures in low seismicity region.

However mitigating catastrophes from low probability & high consequence earthquakes is equally important in Japan. The reasons can be summarized below:

1. We have earthquakes which occur at subduction zones along the Pacific Ocean and inland earthquakes. Earthquakes at subduction zones occur repeatedly with return period of several tens to hundreds years. Consequently target of seismic design for structures was to mitigate damage against those earthquakes. On the other hand, earthquakes which occur along active inland and near coastal zone earthquakes have much longer return period. Number of victims was generally larger in inland and coastal zone earthquakes than subduction zone earthquakes. For example, number of victims was 7,273 in 1891 Nobi earthquake (M8.0), 2,925 in 1927 Kita-Tango earthquake (M7.3), 1,083 in 1943 Tottori earthquake (M7.2), 2,306 in 1945 Mikawa earthquake (M6.8), 3,769 in 1948 Fukui earthquake (M7.1), and 6,434 in 1995 Kobe earthquake (M7.3). It is noted that until 1995 Kobe earthquake a major inland earthquake did not occur for 47 years since 1948 Fukui earthquake. Seismic engineering was much progressed during this period.
2. Currently 98 faults are identified by Japanese government as major active inland and coastal zone faults. They have very long return period. For example, an earthquake with M7.5-8.5 developed by faults including Gofukuji Fault along Itoigawa-Shizuoka Tectonic Line has an estimate return period of about 1,000 years. Probability of occurrence of this event in the next 30 years is 14% which is highest among the 98 major faults. A fault at west ridge of Kiso Mountain has an estimate return period of 4,500-

24,000 year. Considering that return period assumed in engineering for evaluating design ground motions is generally in the range of 1,000-2,000 year at longest, return periods of the 98 major faults are extremely long.

2. Eighteen major earthquakes occurred since March 1982. However recent earthquakes (2007 Noto Peninsula, 2007 Off-Chuetzu, and 2008 Iwate-Miyagi) occurred at unknown inland or near coast faults. There must exist other unknown faults. We have to consider that the background risk threatened by unknown faults is high in the entire region.
3. 1995 Kobe earthquake can be a good example for low probability & high consequence earthquakes. The damaged region was regarded as low seismicity area. Although faults were identified prior to the earthquake, they were not well known by engineers and the public. There was essentially limited warning for earthquake disaster preparedness in the region.

Based on the above points, "events with low probability and high consequence" in Japan can be major events developed by inland and near coastal zone faults. For example earthquakes with estimated magnitude near 8 include an earthquake developed by faults including Gofukuji Fault along Itoigawa-Shizuoka Tectonic Line (M7.5-8.5, return period=1,000 years), an earthquake along Fujigawa River fault (M8+/-0.5, return period=1,500-1,900 years), an earthquake along west coast of Biwako Lake (M7.8, return period=1,900-4,500 years), and an earthquake along east bound of Ishikari low land (M7.9, return period=3,300-6,300 years). The Median Tectonic Line (MTL) is the longest fault in Japan. Along MTL, at least five earthquakes with magnitude ranging from 7.7 to over 8 are identified.

There must be many other earthquakes which are not well identified yet. It is important to note that those earthquakes are not well known by engineers and their effect is not yet properly included in seismic design of structures.

What should be investigated?

Inland earthquakes are characterized with near-field ground motions having very strong intensity and long duration. Fault displacement can be a future target of seismic design. Research theme may be identified as follows.

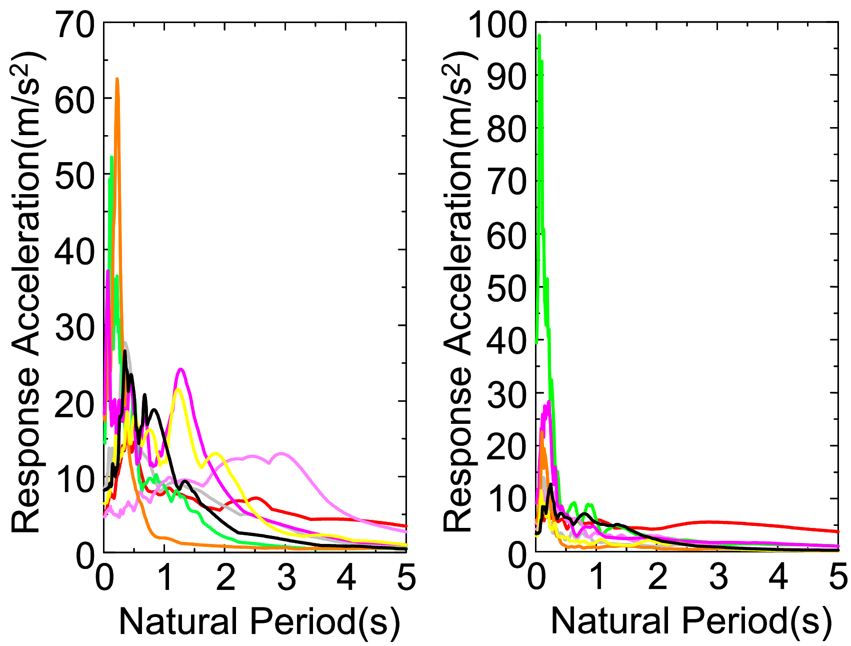
1. **Strong intensity of lateral component**

   Fig. 1(a) shows response accelerations of 8 near-field ground motions (JMA Kobe and JR Takatori (1995 Kobe), JMA Kawaguchi and Kariha Village (2007 Niigataken Chuetsu), Ichinoseki-nishi (2008 Iwate-Miyagi), Sylmar (1994 Northridge), Shihkang (1999 Chi Chi)). Response acceleration at short period is approaching to 10g, and it is noted that over 2.5g response acceleration occurred at 1.3 s.
2. **Strong intensity of vertical components**

   Fig. 1(b) shows response acceleration of the above 8 near-field ground motions. The peak response acceleration exceeded 9.5g. Such a high vertical component can result in tension in structures. Effect of the vertical component has to be carefully investigated.

3. **Long duration**

Figs. 2 and 3 show strong motion records at Wolong and Bajiao and their response acceleration. Because they were probably recorded at rock site, response accelerations are not as high as the ones shown in Fig. 1. However duration is quite long. Effect of long duration ground motions has to be carefully studied.

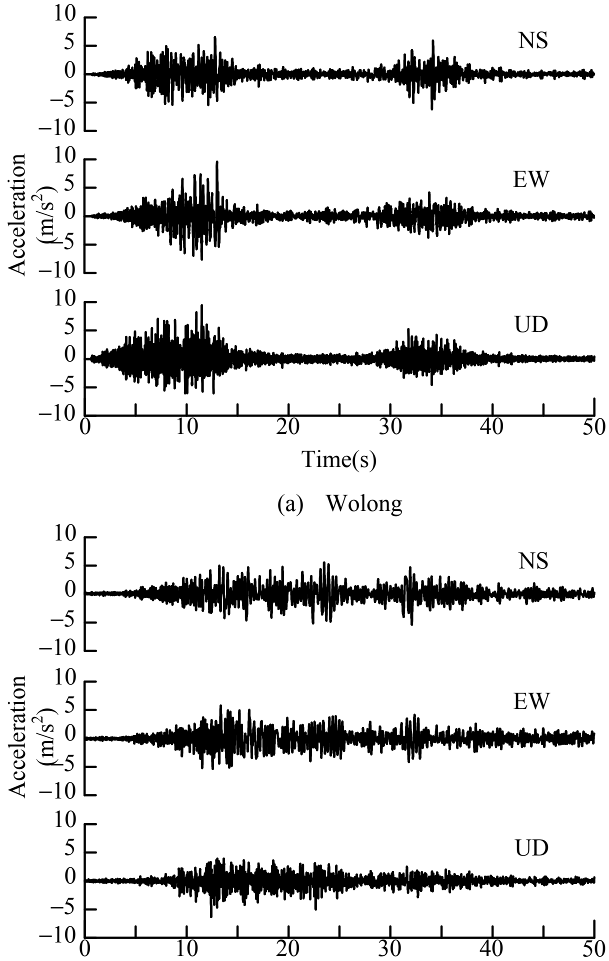


(a) Lateral components (b) Vertical Component

Fig. 1 Response accelerations of 8 near-field ground motions

4. **Fault displacements**

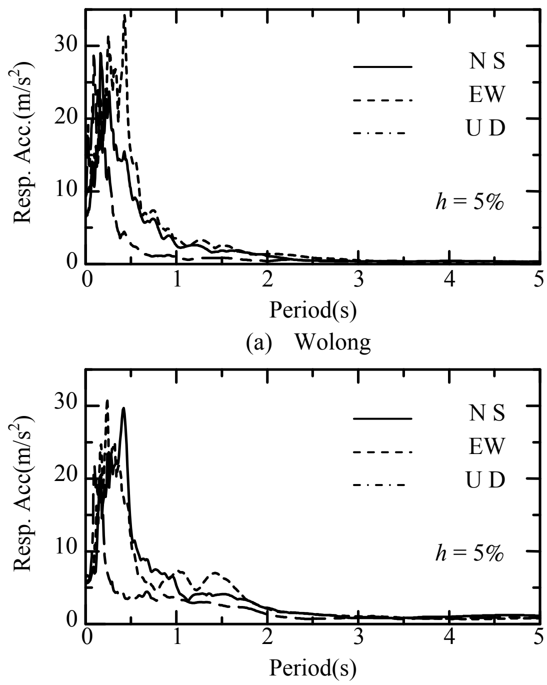
At a fault zone, large surface rupture is generally developed, and this resulted in extensive damage along surface rupture. Mitigating damage of structure is very difficult, but it is a challenging study.



(a) Wolong

(b) Bajiao

Fig. 2 Accelerations



(a) Wolong

(b) Bajiao

Fig. 3 Response Accelerations

ENGINEERING CHALLENGES: *BUILDINGS*

Toshimi Kabeyasawa**
ERI, Univ. of Tokyo

Verification of Damage Control Structural Systems and Quick Damage Detection Devices for Reinforced Concrete Buildings by Shake Table Tests and Component Tests

To plan and elaborate the research procedure for the mitigation and detection of the expected damage to buildings, an approach that consists of the following steps is proposed.

(I) **Review of recent experimental research themes at E-Defense**
(II) **Summarize past discussions on possible full-scale test plans at E-Defense**
(III) **Identify current states and future needs on experimental verification/analytical models towards resilient buildings structures**
(IV) **Propose example proto-type theme structures at E-Defense and research objectives in the next phase**
(V) **Identify related component/assembly/scaled-model tests using NEES facilities**

(VI) Review of recent experimental research themes at E-Defense
The main projects and the theme structures conducted at E-Defense from the inauguration in 2006 are listed as below:

[1] Dai-Dai-Toku project (April 2005 – March 2007)

1. Timber (existing timber houses, effect of strengthening)
2. Medium/low-rise reinforced concrete buildings
   a. 6-story collective house:
   b. 3-story school buildings:
3. Foundation and soil
   a. Pile and soil under liquefaction
   b. Retaining wall

[2] US-Japan project(April 2007 – March 2010)
1. Steel buildings (Full-scale, lower part of high-rise building)
2. Soil/Foundation
3. Bridges

[3] Other projects
1. Hospitals, earthquake resistant/base isolation (Jan 2009)
2. and many others

The outcome and findings are summarized below in cases of the full-scale tests on reinforced concrete buildings:

1. The first test demonstrated seismic response behavior of a typical medium-rise full-scale building structure, including such as:
   - Story mechanism due to higher modes and shear failure
   - Effect of overstrength and strain rate
   - Lateral load carrying capacity much higher than code specified calculation
   - Distribution of shear into wall and frame

2. The second test demonstrated
    - Input energy loss with swaying base foundation
    - Effect of strengthening with steel attached frames
    - Fail-safe design against extreme motions

It may be concluded that the tests were generally successful verifying above peculiar behavior only through the full-scale dynamic tests. Also, they were significant as the world first visible experiments to collapse behavior, which might be instructive to large number of researchers as well as structural engineers.

Although they were significant as academic or technology development, the test results have not reflected explicitly in the revision of codes or guidelines yet. The results were specific or particular to the specimens, and many future needs on research have been left for more experiments.

(VII) Past discussions on possible full-scale test plans at E-Defense

The followings [1] through [4] are part of the discussions on the feasible test structures and research objectives, which are quoted without modification[Kabeyasawa, 2005], at the time of the planning the first 6-story specimen at E-Defense.

[1] Objectives of the test

Possible research objectives of the full-scale testing of reinforced concrete buildings have been discussed in the RC committee as well as at US-Japan meeting in April 2004. They are analyzed and classified as follows here:

1. Objective types of structures: (S1) Existing structures before/after strengthened, (S2) Non-ductile/ductile structures, (S3) Irregular/regular structures, (S4) Innovative structural systems with isolation and/or dampers, (S5) Non-engineered structures such as infilled RC, reinforced/bare masonry, adobe, (S6) Structures with fixed/flexible/inelastic foundation, (S7) Structures with non-structural components/installation/furniture,
2. (Objective types of performances: (B1) Overall/story/progressive collapse mechanism, (B2) Ductile/limited ductile/brittle failure mode, (B3) Earthquake/gravity load carrying capacity, (B4) Higher mode/3-D/torsional response, (B5) Damping or energy dissipation capacity, (B6) Structural integrity/stability, (B7) Post-earthquake residual capacity, (B8) Fail-safe capacity,
3. Objective demand characteristics: (D1) earthquake intensity: moderate/strong/extreme, (D2) Characteristics of earthquake motions: far field/near field motion, (D3) 1D/2D/3D earthquake motion,
4. Objective limit states: (L1) Serviceability/reparable damage limit, (L2) Safety/ultimate limit, (L3) Overall structural collapse or overturning,
5. Objective tools: commonly experimental verification for (T1) Seismic performance of structures, (T2) Evaluation methods for design, (T3) Analytical models, (T4) Sensing technologies, (T5) Post-earthquake assessment methods.

[2] Selected research items

As the first test at E-Defense, there are several prerequisites in the viewpoints of not only research oriented but also demonstration to public, such as:

1. The specimen shall be “full-scale,” in “3-Dimentional,” behavior up to 800ton, 15mx20m area and 20m height. A lot of possible plans were drawn and a 6-story and 2x3 bay frame was selected.

2. The specimen shall be tested under the capacity of the table “to collapse.” Therefore the ultimate base shear coefficient at the formation of mechanism would preferably be less than 0.5, for which one wall is good enough to attain the capacity.
3. The specimen shall be planned as “a part of long term plan,” although only one specimen is available in 2005 and probably another in 2006. Therefore, several research objectives shall be included considering possible other serial projects in the future.
4. "Standard experimental technique" for full-scale testing on reinforced concrete structures shall be established, such as instruments for measurement, backup for safety, and setup and remove. A new method of testing shall also be tried.
5. The test results shall be the "benchmarks" for conventional and future analytical tools, which would be verified as generally as possible. Therefore, the structure shall not be too simple but not too complicated, and shall represent practically designed structures in general.
6. The available term for E-Defense table is fixed as "two months" from 1 December 2005 to 31 January 2006.
7. The budget was fixed in January 2005, which would be available for "one full-scale specimen," for the fiscal year 2005.

[3] Selection of the structural plan

We could select either from the following alternatives, and we have selected basically the first one for the structural plan in the first test:

1. Regular vs Irregular: Regular type would be necessary even if irregular type is adopted
2. Wall-frame vs Open frame: Open-frame would be too simple as benchmark for analytical modeling
3. Existing vs New construction: Research themes on existing structures are more general than new development, such as non-ductile collapse mechanism of structure, which should be investigated further in detail, while ductile and stable behavior would be too simple.

As a result, the structural plan and elevation shown in Figure 1 and Figure 2 are selected for the test specimen.

[4] Research themes for the full-scale testing

Main research items have been discussed by the committee, which could generally be assigned to past, current and future projects as follows, although some of them were duplicated among several projects.

1. Past project on pilot is (1999-2003): Soft first story
2. Preliminary tests 2002-2004: Eccentricity, Dynamic effect, Flexible/fixed foundation, Multi-directional input
3. Full-scale test 2005: Collapse behavior, Wall-frame interaction, Damage evaluation, Scale effect, Non-structural component
4. Full-scale test 2006: Design code or detail, Strengthening, Repair, Flexible foundation
5. Future full-scale projects: Damper, Sensor, Monitor, IT, Base-isolation, Vertical motion, Slab integrity, Beam-column joint, etc.

[5] Research themes for the full-scale test in the next phase

Many research themes are still remained and unsolved, which would be significant towards the mitigation of the possible earthquake damages and could be achieved by the large-scale shake table tests, such as:

- Higher mode responses,
- Effects of viscous damping,
- Dynamic failure to collapse, axial failure, non-ductile failure,
- There-dimensional responses, torsional, structural integrity,
- Fail-safe design against extreme motions,
- Response to long-period motions,

(VIII) Current states and future needs on experimental verification/analytical models towards resilient buildings structures

(to be added, and also need referring to on going projects related towards the revision of Japanese Building Standard Law)

[1] Experimental or analytical simulations

A key problem in experimental verification, analytical simulation with damage observation in the field might be that the damage rates observed in the recent major earthquakes, such as Northridge(1994), Kobe(1995), Kocaeli (1999), Niigata-Chuetsu(2004) and Niigata-Chuetsu-Oki(2007), the observed damages were apparently lower than the simulation, using strong motions recorded in the free fields, esp. for the damages to low-rise reinforced concrete buildings. Seismic performance of existing buildings, input energy loss at foundation or real response in the structures should be identified with tests, analysis and observation in the field. On the other hand, inexperienced motions in recent earthquakes, such as with long period (low frequency) components or extremely high accelerations could be effective to the responses of high-rise or low-rise buildings. Damage control or fail-safe assurance design should be verified.

[2] Monitoring or quick damage detection

Seismometers and other devices for the quick damage detections have not yet been in practical use but still under development. Further development needs for the devices would be economical efficiency, accuracy and long-term stability, reliability or redundancy. The accuracy should be verified through shake table tests as in realistic manner as possible.

(IX) Example proto-type theme structures at E-Defense and research objectives in the next phase

To comply with the discussion above, example theme structure may be planned as below with specific focus on associated scientific and technical research objectives:

[1] High-rise building

Reinforced concrete frame, up to 30-stroy, 1/3scale, with focus on:

a. Response to the motion of long period and long duration,
b. Higher mode responses, column strength to ensure beam-yielding mechanism,
c. Seismic performance incorporating beam-column joint failure,
d. Development and verification of quick damage detection devices or monitoring,
e. Effect of isolation and dampers,
f. High strength or new materials,
g. Damages to non-structural elements.

[2] Medium-rise or low-rise building

Irregular reinforced concrete frame, 4 to 6-story, with walls, limited ductility, with focus on:

a. Comparison of story-collapse vs overall-collapse,
b. Dynamic progressive axial collapse,
c. Comparison of strong-type vs ductile-type,
d. Effect of soil-structure interaction,
e. Fail-safe design against extreme motion,
f. Seismic performance of existing and damaged buildings in the past earthquake
g. Effect of strengthening.

[3] Full-scale dynamic component test of columns under high gravity load

Full-scale component/assembly test on the shake table, such as a column under high axial load, with focus on:

a. Seismic performance of column incorporating axial/shear failure,
b. High strength or new materials,
c. Effect of design parameters, reinforcement details, and so on.

(X) Related component/assembly/scaled-model tests using NEES facilities
(to be added including other relative issues)

Reference:

[1] Toshimi Kabeyasawa, Taizo Matsumori, Hideo Katsumata, and Kazutaka Shirai, Design of the Full-Scale Six-Story Reinforced Concrete Wall-Frame Building for Testing at E-Defense, The First NEES/E-Defense Workshop on Collapse Simulation of Reinforced Concrete Building Structure, Berkeley, July 6-8, NIED and PEER, 23-46, 2005

[2] Toshimi Kabeyasawa, Taizo Matsumori, Toshikazu Kabeyasawa, Toshinori Kabeyasawa, and Yousok Kim, Design of The Three-Story Reinforced Concrete Buildings with Flexible Foundations for Testing at E-Defense, Proceedings of The Second NEES/E-Defense Workshop on Collapse Simulation of Reinforced Concrete Building Structure, March 2007, pp. 225-242

ENABLING TECHNOLOGIES AND FUNDAMENTAL KNOWLEDGE: *BUILDING SYSTEMS*

Jack Moehle
PEER, University of California, Berkeley

Preliminary documents for the Phase 2 Planning Meeting suggest three meta-themes. Each hints a different program direction for buildings, though there are many overlapping aspects.

The **Resilient City**, with undertones of low damage, quick recovery, and sensible rebuilding, needs new building materials, technologies, and systems that efficiently control damage, as well as smart structures that can "tell you where it hurts."

Preparing for the Big One incorporates concepts of the Resilient City – how to avoid the downward spiral to a New Orleans Hurricane Katrina scenario. It also suggests new structural materials, technologies, and systems that control the rate of deterioration of the lateral force-displacement relationship when displacements exceed the maximum values here-to-for contemplated.

Mitigating Disasters from Low-Probability, High-Consequence Events likewise envelopes the preceding two concepts in many ways. Interpreted from the perspective of a massive earthquake on the San Andreas in Southern California or mega-earthquake off the coast of Japan, this theme links well with the preceding two. Interpreted from the perspective of a large earthquake in the central United States, the implications for buildings research are wholly different because of the differences in construction types and social perspectives in traditionally "seismic" and "non-seismic" regions.

An informal query of several buildings engineers and researchers in the United States returned several responses mainly related to **The Resilient City**. For this reason, this is the focus of the discussion for the remainder of this brief report.

The Resilient City

As a starting point, it is assumed that the Resilient City is one that has made a comprehensive plan for hazard mitigation, emergency preparedness, and rebuilding, with a target schedule for when certain city functions are back on line. In this context, seismic resilience is the ability of the city to

- **contain the effects** of earthquakes through mitigation;
- **carry out recovery** activities in ways that minimize social disruption; and
- **rebuild** in ways that mitigate the effects of future earthquakes.

The comprehensive plan for the Resilient City might include a target schedule such as: emergency response facilities are **immediately functional;** household units are inspected and most are safe for inhabitants to shelter in place **within one day;** 90% of the water, power, and waste water systems are operational **within 3 days;** 90% of transportation systems, schools, and businesses are open and serving the local workforce **within 30 days;** etc.

The Question

If we had a Resilient City out there, looking for technology to achieve the goals it had established, what would we give them?

The following text gives some example to spur discussion. Examples are limited to things that require physical experimentation or that suggest physical experimentation to validate a concept.

High-Performance Buildings

These structures perform well whatever (within reason) is thrown at them, and sustain damage that can be quickly found and repaired. High-performance structures that are economical are especially sought so they can be more widely used. Some specific ideas:

- **Structures with clearly defined and replaceable fuses.** If the fuse is clearly identified beforehand, it can be quickly inspected and replaced if necessary, reducing costs and speeding the recovery process. The fuse might be designed using a performance-based approach (perhaps more suitable for a highly seismic region) or it might be some inherent or prescriptive fuse that does not require detailed calculation (perhaps more suitable for a less-seismically active region).
- **Self-centering structures.** These structures are inherently resilient as structures because of the self-centering nature. Some examples have been explored already, but their applicability seem restricted and they are therefore not widely used. The concept needs to be generalized to use more common construction technologies, and these need to be validated through component tests and complete structural system shaking table tests. Examples include unbonded post-tensioned cast-in-place walls, seismic isolation, rocking/uplifting systems, etc.
- **Buildings with improved nonstructural systems.** Examples abound, but this could include development of new systems for contents, interior nonstructural components, cladding, etc.
- **Unibody construction.** "Unibody" residential construction could make effective use of all the partitions to resist seismic loads (e.g., think about how the auto industry moved from fenders on frame systems to welded unibody systems). Can the idea be scaled up to larger buildings?
- **Homeowner solutions.** If a goal is for residents to be able to shelter in place, what simple, cost-effective, versatile systems can be developed to enable this to become an achievable goal for homeowners?
- **Superhard buildings.** Rather than attempt to raise the performance of large populations of buildings, focus on selective hardening of a smaller number of buildings. This concept would promote a more free-thinking approach, less encumbered by the staggering economics of large urban regions. Such superhard facilities would not only improve the resilience of a city, but provide margin for earthquake shaking exceeding MCE levels. Both new and retrofit approaches could be considered.
- **New, high-performance materials.** Many examples exist or can be engineered. A well-known example is tensile-strain hardening fiber reinforced concrete, which offers good potential for achieving structural systems with enhanced damage tolerance while

allowing for simplifications in transverse reinforcement detailing. Effective use of these materials in a range of structural components and systems needs experimental validation.

- **Improved acceptance methods for new systems and materials.** Many technologies have been around for decades but are impeded by onerous acceptance criteria (e.g., seismic isolation). Technology implementation in general is impeded by the regulatory process. A program to "grease the wheels" would help.

Structural Health Monitoring

The Resilient City is one that can rapidly assess the condition of its building stock (or individual buildings) after an earthquake. Rapid access to actual response data and means to visualize those data are essential if we are to have any chance to make a reasonably rapid post (mega)-event assessment of functionality, level of damage, time and cost of repairs. This system must be flexible, inexpensive, and resilient. Flexible to accommodate various sensors, data rates, etc., inexpensive only if use of sensors are ubiquitous, and resilient in the sense that the DAQ systems must have sufficient memory, redundant communications, local computing, etc.

For such an effort, one might form research teams with interests in complex experiments (SFSI, complete systems), health monitoring (use of novel sensors, data communication, management and visualization), and simulation. The teams could focus on smaller scale (NEES) quasi-static and shake table tests of systems that include both lateral- and gravity systems including diaphragms and possible foundation/soil systems. Development work could be done on smaller scale test structures (quasi-static, dynamic) and in the field (ambient- and forced-vibration), with a final test of maybe two systems using E-Defense facilities. In this way, testing, monitoring, and simulation would be integrated and focused on providing the information, or at least the framework, for eventually achieving a disaster resilient city. The medium term goals would be to provide the framework to make a more robust instrumentation program (including novel sensors, data visualization, rapid post-event response) that at some future data would provide the wealth of data to enable us to make huge leaps in our understanding of complex system behavior.

Nonstructural Systems and Contents

by

Manos Maragakis

University of Nevada, Reno

NEES – E-Defense Planning Meeting Phase 2
Washington DC, January 12-13, 2009

Points of Discussion

- Types of Nonstructural Systems
- What is the problem and its importance?
- Seismic Response of Nonstructural Systems
- Future Research and Needed Outcomes
- Available NEES sites and equipment
- Current Research
- Payload opportunities

Types of Nonstructural Systems

Nonstructural components and systems are defined as the elements of a building that are not part of its gravity and/or seismic loading resisting structural system.

Classification according to system/functionality:

- **Exterior building elements**: parapets, chimneys, exterior facing windows
- **Interior building elements**: partitions, ceilings, fixtures
- **Building utilities**: equipment, piping, ducts, HVAC, electricity, gas, communication systems, elevators
- **Building contents**: furnishings, equipment, bookcases, cabinets

Types of Nonstructural Systems

Classification according to sensitive response parameter:

- **Interstory –drift –sensitive elements**: masonry walls, partitions, doors, windows
- **Acceleration-sensitive elements**: suspended ceilings, boilers, ducts, tanks, light fixtures
- **Drift and acceleration-sensitive elements**: fire sprinklers, pipes

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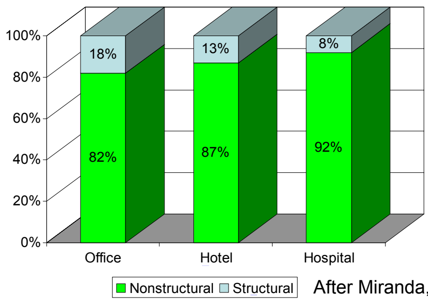
Why are Nonstructural Elements Important?



After Miranda, 2003

Nonstructural damage accounts for 79% of the total earthquake damage

- Nonstructural systems are subjected to the dynamic environment of the building
- Seismic damage to nonstructural systems can be triggered at response intensities smaller than those required to produce structural damage

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Importance of Nonstructural Elements on Buildings

- Seismic response of nonstructural elements is very important for the overall seismic performance of buildings
- Property losses
- Loss of functionality
- Fire hazard
- Potential for loss of life

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Damage in Recent Earthquakes

- Northridge Earthquake
- Kobe Earthquake
- Nisqually Earthquake
- Izmit Earthquake
- Chi-Chi Earthquake
- Kona Earthquake

Affected nonstructural components and systems: ceilings, pipes, partitions, equipment, contents, cladding, elevators, electrical networks.

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Hawaii 2006

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Northridge 1994

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Northridge 1994

10

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Miyagi-oki 2005

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Miyagi-oki 2005

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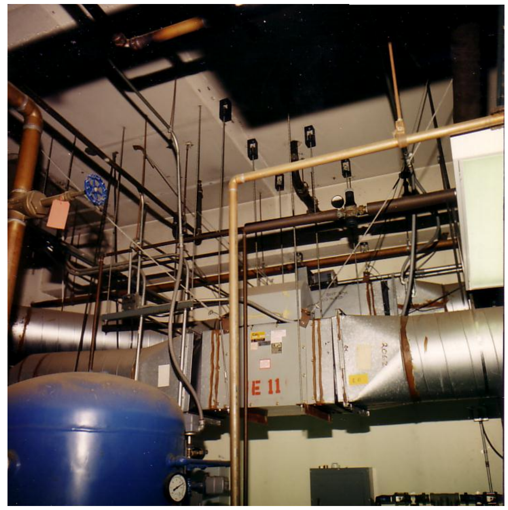
Seismic Response of Nonstructural Systems

Challenging Problem

- Complex Systems
  - A variety of components and subsystems
  - Complex geometry
  - Complicated boundary conditions



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Seismic Response of Nonstructural Systems

Nonstructural Seismic Response Depends on:

- Response of supporting structure
- Size and weight of the component/system
- Location of the component/system in the building
- Flexibility of the component

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Seismic Response of Nonstructural Systems

Structural Seismic Response Depends on:

- Ground motion
- Soil conditions
- Type of structural system

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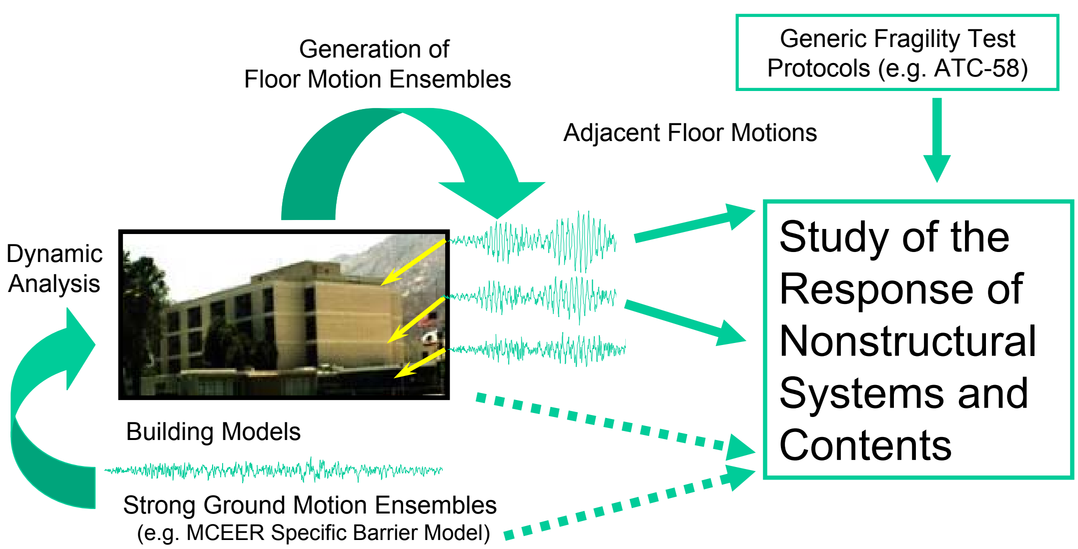
Concept of Seismic Research of Nonstructural Systems



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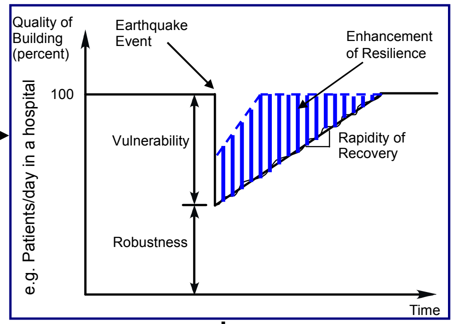
Effects of Effective Nonstructural Seismic Performance on Enhancement of Resilience

For individual buildings, effective seismic design of nonstructural systems will:

- Decrease the risks to life and property
- Limit loss of functionality after an earthquake



- Reduce failure at the metropolitan scale
- Improve the community's ability to recover after an earthquake

Enhancement of community resilience

Quantify the impact of the research on the individual building and metropolitan scales - Implementation

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Characterize Ground Shaking Hazard

Perform Structural Analysis of Structural System	Perform Structural Analysis of Nonstructural Systems
Form Structural Response Function	Form Nonstructural Response Functions
Form Structural Fragility Function	Form Nonstructural Fragility Functions
Form Structural Damage Function	Form Nonstructural Damage Functions

Predict Loss as a Function of Damage

Fig. 2-2, **FEMA 445**, *Program for Development of Next-Generation Performance-based Seismic Design Guidelines for New and Existing Buildings*, October, 2004

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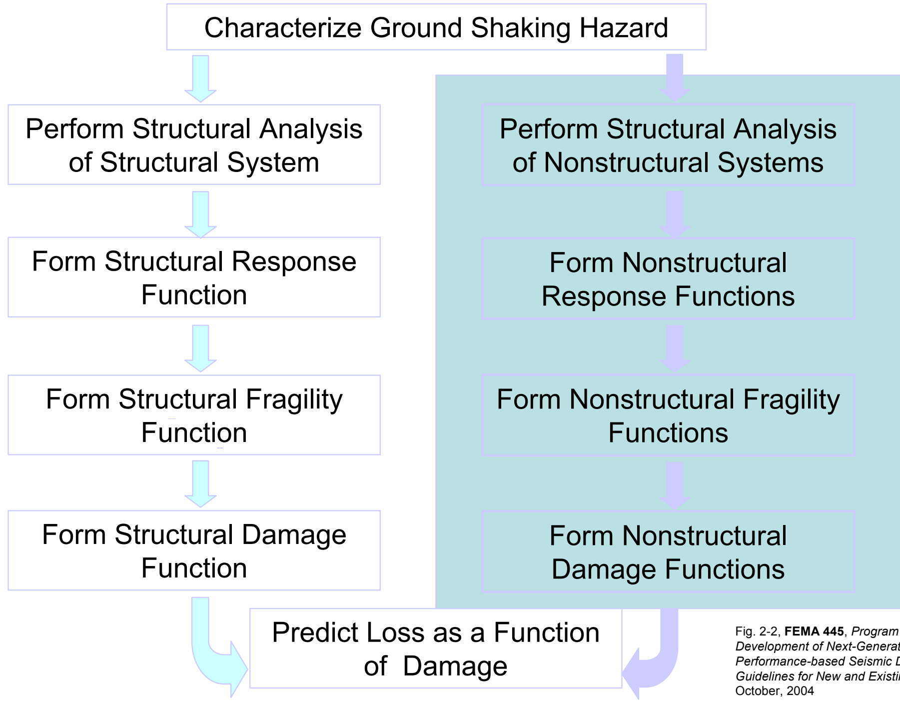

Fig. 2-2, **FEMA 445**, *Program for Development of Next-Generation Performance-based Seismic Design Guidelines for New and Existing Buildings*, October, 2004

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Nonstructural Systems and Components to be Considered for future Research – Needed Outcomes

- Performance-based seismic design makes the harmonization of the performance levels between structural and nonstructural systems vital
- Interaction between nonstructural and structural systems needs to be studied – study nonstructural behavior at component and system levels
    - Flexible structures
    - Stiff structures
    - Isolated structures
    - Frequent vulnerabilities of nonstructural systems are due to clashing with other structural or nonstructural systems
- Ceiling – Piping-Partition Systems
- Mechanical Piping

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Nonstructural Systems and Components to be Considered for future Research – Needed Outcomes

- Distributed Systems (piping and electrical) using different bracing systems
  - Wire tension bracing
  - Compression bracing
- Elevator Systems
- Staircases
- Electrical Systems
- What is the response and behavior of components that have been seismically qualified when installed in a building and tested for large earthquake motions?

Nonstructural Systems and Components to be Considered for Future Research – Needed Outcomes

- Determine functionality of critical equipment subjected to intense floor motions – validation of operational state
- Interaction/behavior of stacked equipment
- Criteria for qualification of anchorages
- Swinging Systems
  - Hung piping
  - Pendulum lighting
- Intensive Care Units
- Raised floors, glazing, and facade systems

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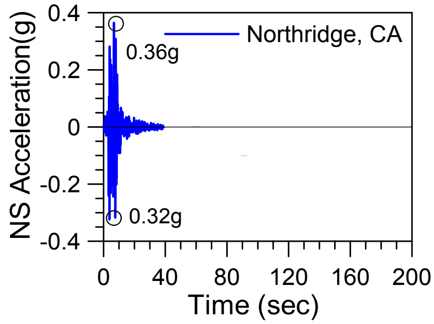
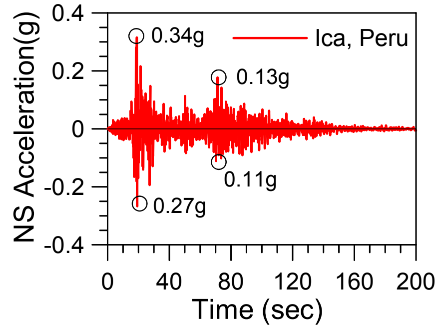
Nonstructural Systems and Components to be Considered for Future Research – Needed Outcomes

- Evaluate the effects of earthquake duration on the response of structural and nonstructural systems.

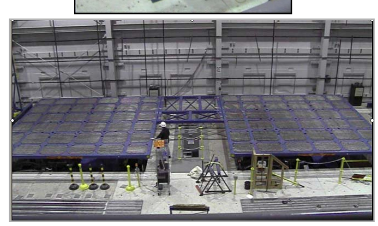




Available NEES Sites for Nonstructural Research

1. UB - NEES Site

- Nonstructural Component Simulation (NCS) Testing System
  - Multiple subsystem/component experiments
  - Large stroke and velocities allow for full-scale horizontal floor motions
- Two shake tables allow tri-axial excitation



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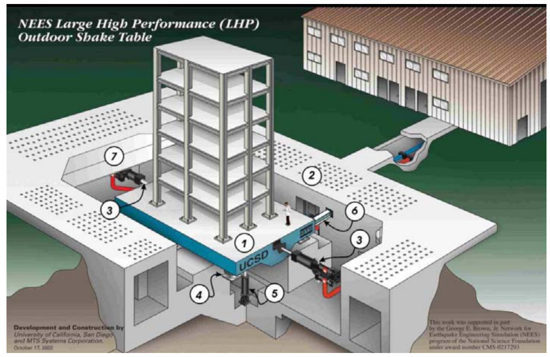
Available NEES Sites for Nonstructural Research

2. UCSD - NEES Site

- One 25ft by 40ft outdoor shake table
- Able to test large structures
- Capable of simulating devastating earthquakes



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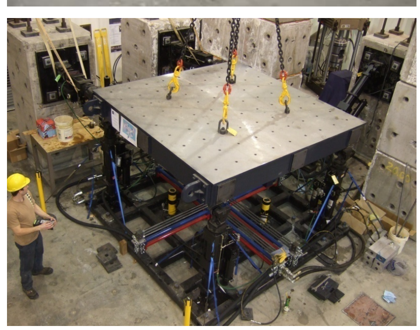
Available NEES Sites for Nonstructural Research

3. UNR - NEES Site

- Three shake tables allow for large scale test-beds
- Large stroke and velocities allow for full-scale horizontal ground motions
- A fourth shake table with large strokes and six degrees of freedom will be available soon



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Research on Nonstructural Elements

- Existing research focuses on the component or subsystem level
- Structural/Nonstructural interaction has been neglected
- Interaction among nonstructural systems has been neglected
- Limited experimental and analytical studies
- Design methodologies are empirical

Ceiling Test and UB

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Piping Test at UNR

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Bookshelf Test at UNR

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NEESR-SG: Experimental Determination of Performance of Drift-Sensitive Nonstructural Systems under Seismic Loading

- Project Focuses on:
  - Precast Concrete Cladding
  - Punch-out Windows
  - Glass Curtain Walls
  - Vertical Plumbing Risers
- Experimental studies include four full-scale, one-story pseudo-dynamic experiments
- Analytical studies focus on the development of force-displacement relationships of the nonstructural components considered and modeling tools to predict their response

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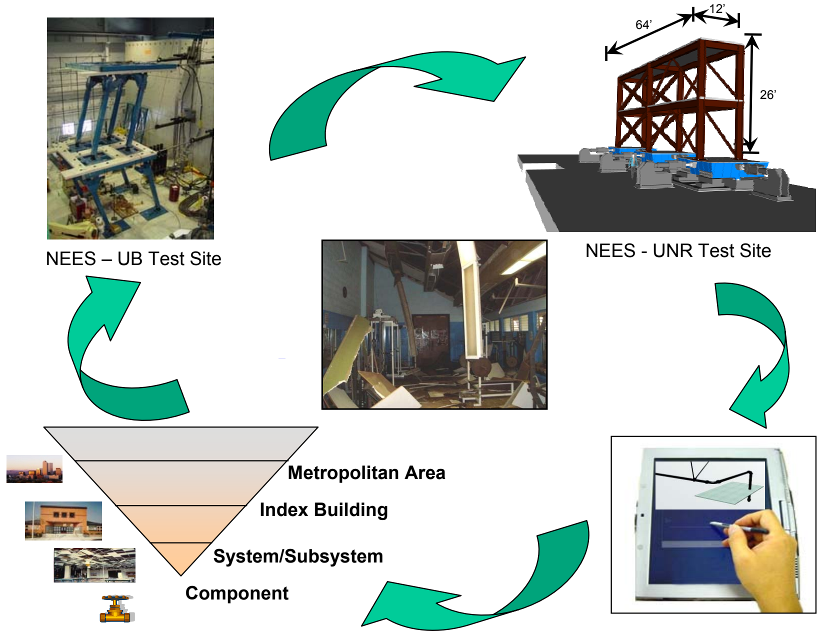
NEESR-GC: Simulation of the Seismic Performance of Nonstructural Systems



CUREE
Georgia Tech
North Carolina A&T State University
NC STATE UNIVERSITY
RUTHERFORD & CHEKENE
University at Buffalo
UCSD
AGEP!

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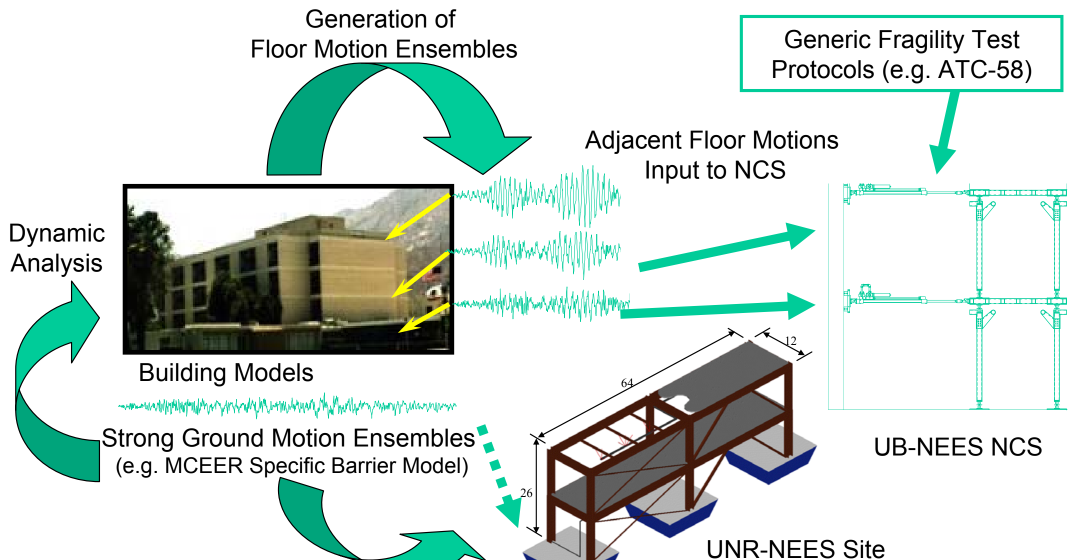
Experimental Protocols for the GC Project



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Conducting Future Experimental Research of Nonstructural Components and Systems

- Research funding is tight
- For nonstructural research emphasize on payload opportunities
- Payload projects are cost effective and present great opportunities for advancing the state-of-the-art
  - Form a NEES/E-Defense committee
  - Committee should examine all future building experiments and consider including nonstructural systems
- Future payload opportunities for Nonstructural Research in NEES sites

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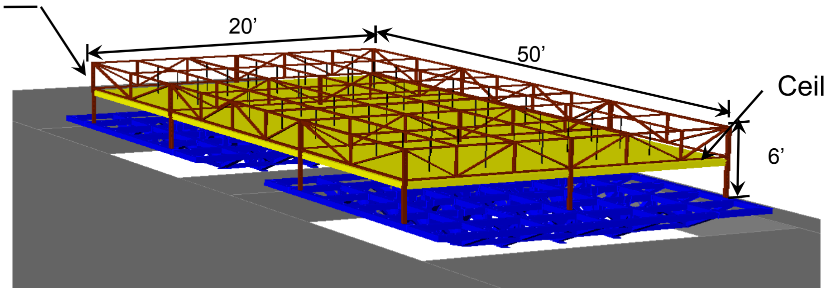
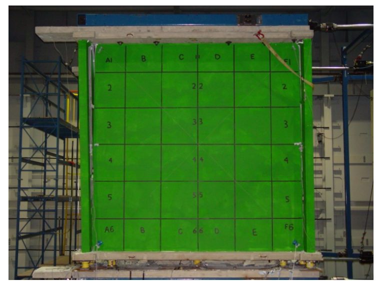
Payload experiments at the UB – NEES Site



•Test-bed for large-scale ceiling experiments

•Payload experiments using the NCS

- •Partitions
- •Pipes



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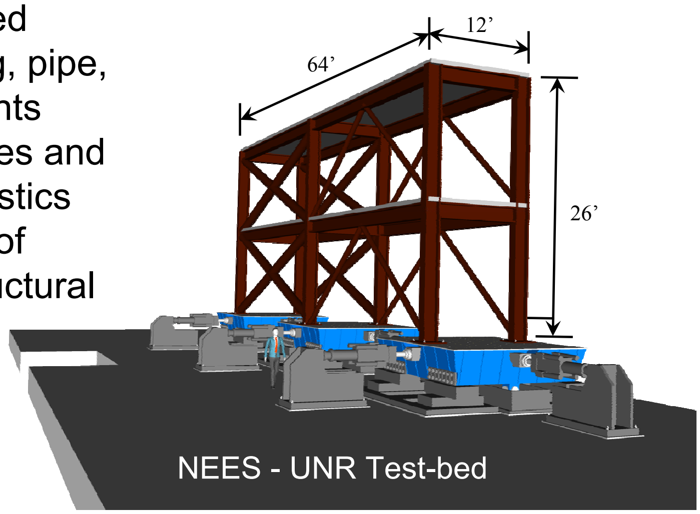
Payload experiments at the UNR – NEES Site

- 64'x12'x26' test-bed
- Large-scale ceiling, pipe, partition experiments
- Tunable frequencies and yielding characteristics allow for studying of nonstructural / structural system interaction



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Payload Experiments at E-Defense

- Large-scale steel building experiments
  - Building with dampers
  - Building with isolators

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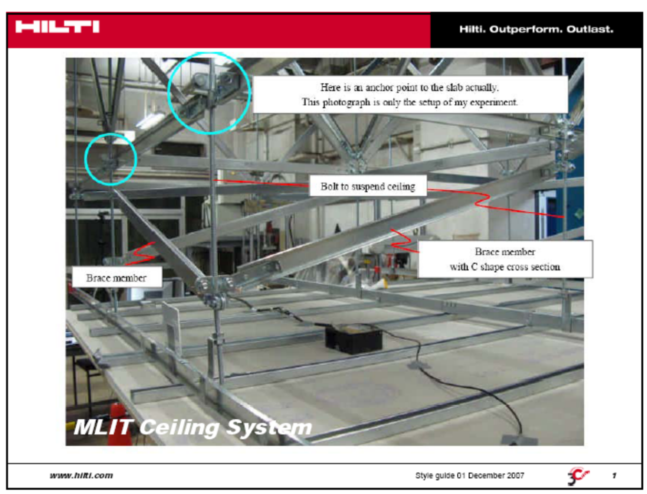
Example of a payload experiment by Hilti using the E-Defense

- Hilti's experimental objective is to obtain data on anchor loading characteristics and load distribution over a spatially distributed system (ceiling)
  - Use of E-Defense steel base-isolated building



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Thank You

ENGINEERING CHALLENGES: SOCIO-ECONOMIC CONSIDERATIONS

Gregory G. Deierlein
Stanford University

Modern performance-based earthquake engineering approaches for buildings (e.g., such as embodied in the ATC 58 guidelines, www.atcouncil.org) are organized around quantifying performance metrics that are meaningful for building owners, building code officials (representing the public interest), and other key stakeholders, such as financial and insurance interests. As such, performance-based design methods provide an effective framework to relate scientific engineering research, of the type that involves testing and computational simulation conducted through the NEES and NIED/E-Defense programs, to socio-economic interests and the wellbeing of society. Applied at regional, state or national levels, performance-based engineering can provide the quantitative basis to inform public policy decisions on seismic safety and loss mitigation, such as through minimum building code requirements for new buildings, assessment and retrofit requirements of existing buildings, emergency preparedness, establishing appropriate insurance rates and requirements. Applied at a more local level to individual buildings or small campuses, performance-based engineering provides important data for design professionals, building owners and other stakeholders to make tradeoff decisions regarding desired building system performance and other risk management strategies.

Performance-based engineering metrics consist of statistics to quantify (1) risk of collapse and the associated casualties, (2) risk of damage and the associated repair or replacement costs, and (3) risk of building closure and downtime, which have large implied costs associated with the displacement of building occupants and business interruption. Quantifying these parameters begins with first being able to calculate the response and damage of the building structure, the nonstructural components, and the building contents. These data in turn provide the basis for then evaluating (1) the repair (or replacement) measures and costs and (2) expected downtime to complete repairs (or reconstruction). To the extent that earthquake engineering research supports the development of data, models and tools for quantifying these metrics, the research will impact socio-economic issues in earthquake hazard mitigation.

To the extent that research supports the advancement of performance-based engineering technologies and/or applies these technologies in the development of innovative solutions to reduce earthquake risks, there is broad range of potential research areas that address socio-economic issues. Some potential research areas and their links to socio-economic considerations through performance-based engineering are as follows:

- **Collapse and Fatality Risks:** Development, calibration and validation of accurate tools to assess structural collapse remains a significant challenge in earthquake engineering. Presently, models to simulate collapse of ductile steel and concrete moment frames (code-conforming "special moment frames") are fairly well developed, though even these are lacking data to calibrate highly nonlinear response at large deformations. Models to simulate other structural system types, including less-ductile (ordinary) moment frames, braced frames, shear/bearing walls, wall-frame systems are less well developed. To provide more accurate assessments of fatality risks, research on collapse should go beyond assessing the onset of collapse toward quantifying the likely collapsed building condition.

- **Damage/Repair States to Structural Components:** While many tests have been conducted in the past on a wide variety of structural components, most have emphasized the hysteretic response characteristics and data on damage and repair states have not been reported in a consistent manner. Tests where damage/repair state data is systematically reported would greatly facilitate the development of damage models for performance-based design. The NEES data repository would facilitate archiving and access to this information.
- **Damage/Repair States for Non-structural Components:** Similar to the need for described in the previous point structural components, data is likewise needed to systematically characterize damage and repair limit states in nonstructural components. Emphasis should be on those components that contribute most to earthquake losses.
- **Building Closure and Post-Earthquake Safety:** The decision to close a building for safety reasons (i.e., "red-tag") after an earthquake has major implications on the downtime for a facility. Improved knowledge on the earthquake safety of damaged buildings and guidelines to assess this would lead to more informed decisions on building closure and more consistency in those decisions. Testing and analysis of post-earthquake safety, considering damage to the buildings and collapse risk to aftershocks, would lend themselves to these questions.
- **High Performance Building Systems:** Ultimately, society will be well-served by the development of innovative new building systems that cost-effectively minimize risks from earthquakes. Through the use of nonlinear analysis and calculation of the performance metrics outlined above, performance-based earthquake engineering methods can accelerate the development and adoption of cost-effective building system innovations. Implicit in this development is the need for large-scale testing to calibrate and validate assumptions and models for new developments in structural and nonstructural building components. Examples of innovative concepts include: structural systems that self-center during an earthquake (rocking systems or systems with active post-tensioning), partition walls and cladding that can accommodate large story drifts, enhanced seismic isolation concepts (moving beyond conventional base-isolation to isolation systems within the structure), limited ductility/enhanced strength systems for low-rise residential construction, etc. It is of paramount importance for implementation and adoption of these new systems to have accurate construction cost and performance data to demonstrate the improved benefit-cost ratios of these compared to conventional construction.
- **Design Strategies for Rapid Repair and Restoration:** In most conventional seismic resisting structural systems, emphasis is on sacrificing the structure to provide for life safety with little if any thought given to how structures will be repaired after a large earthquake. Thus, from a life-cycle perspective, it may be cost-effective to design structures with more explicit thought given to easy and economical ways to reduce repair costs. For example, this could involve designing the inelastic fuse elements of building systems to be easily replaceable after an earthquake, e.g., designing the link elements in eccentrically braced steel frames or the coupling beams of coupled shear walls with connections to facilitate replacement. Design for repair is a concept that is driven by socio-economic considerations but requires thoughtful research and engineering to accomplish.

To a large extent the research topics outlined here are not particularly new to the engineering research community. However, what has often been lacking in the past have been studies to describe the research objectives and findings in ways that relate to building stakeholders. Emerging performance-based methods provide the framework for making such connections. It is up to researchers and engineering design professionals to follow through to create the linkages between engineering innovations and socio-economic factors.

ENGINEERING CHALLENGES: *BUILDINGS*

Masayoshi Nakashima
Kyoto Univ. and E-Defense

Enhancement of Seismic Safety for a Cluster of High-Rises in Downtown

In the meta-theme named "Development of Earthquake Engineering that Complies with "Time is Money" Society", an approach that consists of the following steps is proposed.

(I) Capture the facts that characterizes the contemporary urban society ;
(II) Identify the research approaches that are suited to the contemporary urban society;
(III) Present scenarios that may occur in the contemporary urban society once it is hit by damaging earthquakes; and
(IV) Identify engineering issues to mitigate the expected damage to the contemporary urban society.

(I) Capture the facts that characterizes the contemporary urban society

The contemporary urban society is likely to be characterized by the following facts. Apparently, "IT", "quality of life", "Time is Money", and "Complexity" form the bases.

1. Huge information flow;
2. Increasing need for efficiency and fast response;
3. Emphasis on functionality and amenity; and
4. Promotion of diverseness, segmentation, interaction, and inter-dependency

(II) Identify the research approaches that are suited to the contemporary urban society

Structural engineers can no longer stand alone and dictate the earthquake disaster mitigation. They have to carefully interact with all kinds of stakeholders to realize workable, practical, and practicable solutions. Those that they have to interact include: owners, users, architects, engineers engaged in life-lines and utilities, among others. The needed approaches are:

a. Client-oriented mind for the identification of problems to solve/resolve
b. More focus on nonstructural aspects and their interaction;
c. Emphasis on redundancy and multiple backups regarding the various functions that the building should possess;
d. More focus on safety and operability of life-lines interacted with buildings;
e. Need for fast responses to disasters, i.e., quick inspection, quick repair, etc.;
f. Mechanism of information sharing among engineering, owners, and users.

(III) Present scenarios that may occur in the contemporary urban society once it is hit by damaging earthquakes

Here is one scenario that may occur in an area where a cluster of high-rise offices are located once the area is hit by a medium to medium-large ocean-ridge earthquake characterized by a long duration and long period.

1. Serious shaking occurs only in high-rises; old wood houses and short RC apartment and short steel office buildings nearly vibrated.
2. Inhabitants in the offices are asked to evacuate from the buildings, but elevators stopped because of very sensitive "earthquake sensors."
3. The inhabitants have to use a staircase to move down to the ground.
4. The available outside space is very limited compared to the number of inhabitants being evacuated. An extreme congestion leads many people to collapse out of annoyance, but they cannot be moved fast to a hospital because of too much congestion.
5. They are asked to return to their homes, but the entrances nearby subway station cannot accommodate the mass of people at one time; eventually a queue of five km is formed, and they needed to wait for full one day before finally get onto the train.
6. They become very curious when they see the old houses and buildings in the neighborhood did not suffer any damage. The high-rise offices where they work are supposed to be the best structures, seemingly much safer than those old houses/buildings, but… Their curiosity grows, and they become less confident about the "structural engineering."
7. The vacant high-rises have to be checked for both the structural and nonstructural damage. Who does it, no one else but structural engineers, but are they able to enter into the building or should they stay away due to the fear of aftershocks? No one can make any decision, and the buildings have to remain untouched for some time.
8. Two weeks after the main shock, the construction firms that have been asked to check the damage by the owners decide to get into the building. They, however, found a serious shortage of engineers and technicians who have the expertise of checking and diagnosing the damage. This significantly retards the rate of checking.
9. At the same time, they recognize the difficulties in locating the damage, because the structural elements are all covered by interior and exterior nonstructural elements. The process was extremely tedious. In the end, it takes full eight months to check the damage.
10. By the checking, a few beam-to-column connections sustained fracture and they have to be patched. Unfortunately, there is no standard procedure stipulated for such repair, and in the end they are forced to use the procedure adopted in the 1995 Kobe earthquake in which all of the repaired connections were not for high-rises but for low- to medium-rises.
11. In the end, the repair work for the high-rises is completed eighteen months after the main shock. On the other hand, the building owners and clients decided to leave the high-rises two weeks after when they recognize that the safety check and according repair would not be completed within a couple of weeks.
12. Many more unpleasant effects continue for years to come.

(IV) Identify engineering issues to mitigate the expected damage to the contemporary urban society.

In light of the scenario described above, what shall we do if we want to see such a situation? Many engineering challenges are immediately drawn. Here are examples.

- Development of super-fast damage detection devices
- Development of structural systems in which damage location is known a priori
- Development of structural systems in which damage can be repaired very quickly
- Development of nonstructural members and systems that are less prone to damage
- Development of vertical lifeline systems that are less prone to damage or recoverable instantly

Highly Resilient Highway Systems for Seismic Loads

Ian Buckle
University of Nevada Reno

NEES/E-defense Planning Meeting, January 12-13, 2009

University of Nevada, Reno
Statewide • Worldwide

Resilience

- What is a resilient (highway) system and why is resilience important ?
  - One that recovers quickly following a damaging event, to minimize socio-economic impact
- What factors influence resilience?
  - Structural vulnerability (fragility)
  - Network redundancy (alternative routes)
  - Available resources for emergency response and recovery (repair)
  - Other…

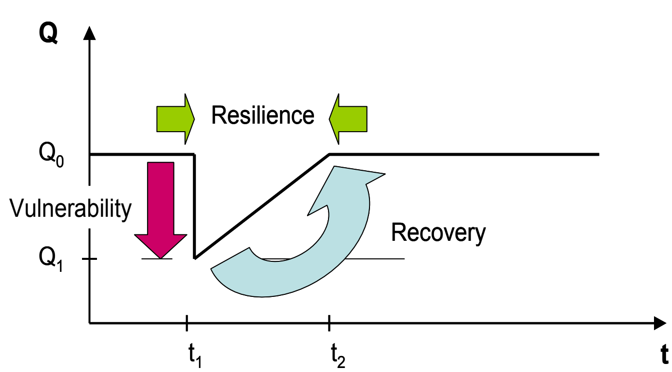
Resilience

- Hence a system that has
  - 'robust' structures
  - a dense road network, and
  - adequate resources for emergency response and recovery (repair) …

may be expected to be 'resilient'… and vice versa.

This subjective definition for 'resilience' may be expressed graphically:

Resilience



Resilience

But if a quantitative measure for resilience could be found it would be possible to:

- Identify factors influencing resilience and their relative importance
- Enable relative levels of resilience to be defined such as:
  - Not resilient
  - Resilient
  - Highly resilient
- Develop rational methods for allocation of resources to achieve higher levels of resilience

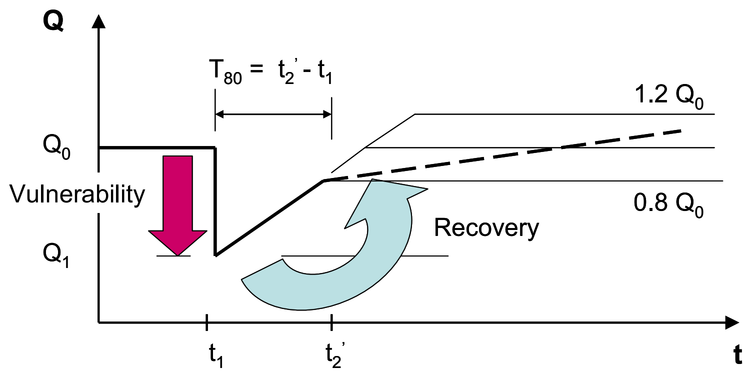
Resilience Index

- Various measures for quantifying resilience have been proposed (e.g. Bruneau et al), but one simple index is given by

$$R = \frac{\text{Time to Recover to Pre-Event Condition}}{\text{Time to Rebuild Assuming Total Loss}} \quad \%$$

The relative level of resilience is then obtained from R and the intensity of ground shaking.

Resilience continued



Resilience

- As a consequence of
  - past research
  - more rigorous code requirements, and
  - comprehensive retrofit programs, in some states,

  many highway systems are believed to be resilient… but to an unknown degree
- Performance during recent earthquakes (Loma Prieta … Nisqually) suggest that the current level of resilience is barely adequate, and these systems are not 'highly' resilient

Resilience Project

- A Resilience Project is therefore proposed to develop highway systems that are ‘highly’ resilient to earthquake ground motions.
- Two major steps are involved:
  – quantify system resilience and determine factors influencing resilience, and
  – develop cost-effective innovations and technologies for a quantum improvement in resilience

Resilience Quantification

- As noted above, resilience may be quantified by the time taken to recover to pre-event condition
- Loss Estimation Tools (e.g. REDARS, HAZUS) may be used to estimate this time
- But the reliability of these tools depends on:
  - Completeness of the structure database (inventory)
  - Detailed understanding of the seismic and geotechnical hazards throughout system, at different return periods
  - Applicability of existing fragility models to estimate damage states for new and existing bridges, straight, skewed, curved, retrofitted, near fault bridges…
  - Applicability of existing recovery (repair) models

Strategy	Research Needs	NEES / E-defense
I. Quantify Resilience		
(a) Quantify resilience (b) Identify governing factors	Expand and validate library of fragility functions and repair models for highway structures (bridges, tunnels, slopes, retaining walls, pavements…)	Yes, in collaboration with FHWA, Caltrans, PWRI?
II. Improve Resilience		
(a) Reduce structure fragility	Develop and validate design and retrofit strategies to meet stringent functionality requirements. For example: -Smart earthquake protection devices -Self-centering structures -Innovative materials -New bridge configurations such as those used for Accelerated Bridge Construction	Yes, in collaboration with FHWA, Caltrans, PWRI? …
(b) Reduce repair time		
(c) Improve redundancy/emer - gency response	Provide for detours, deployment of temporary structures, alternative modes of transportation / clear debris, inspect…	By others

Example: FHWA Project at UNR

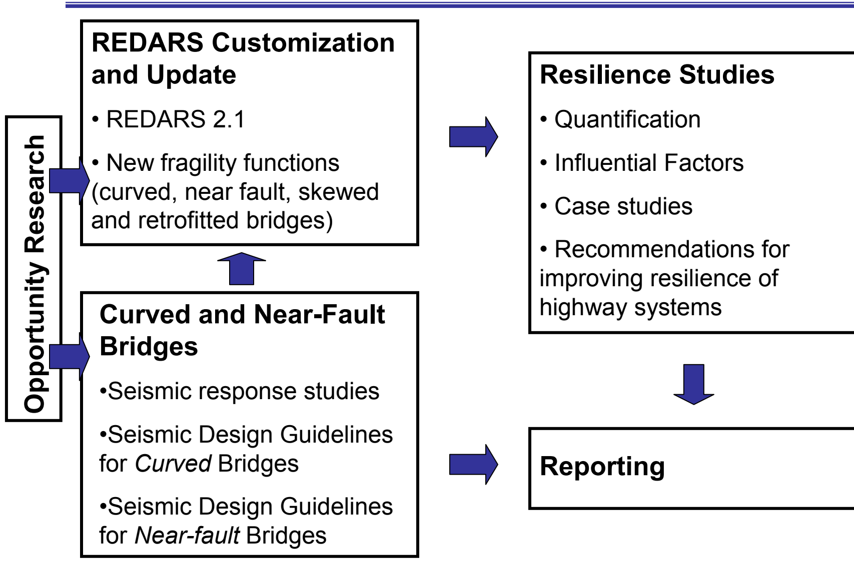
Objective: To study the seismic resilience of highway systems and recommend strategies for improving their resilience to damaging earthquakes by

- customizing REDARS for the quantification of resilience
- expanding the library of bridge fragility functions in REDARS
- conducting case studies of highway systems
- identifying key parameters
- developing recommendations

Example: FHWA Project at UNR

- **Research Team**:
  - University of Nevada Reno
  - The REDARS Group
  - University of California, Berkeley and
  - University of California, Irvine
- **Duration**: 5 years (Sep 2007 – Aug 2012)
- **NEES-Shared Use Project**
  - Laboratory fees are shared equally between FHWA and NEES
  - FHWA contributed 50% towards cost of new (4th) Shake Table at UNR

Example: FHWA Project at UNR



University of Nevada, Reno

Statewide • Worldwide

ENGINEERING CHALLENGES: BRIDGES & TRANSPORTATION SYSTEMS

Kazuhiko Kawashima
Tokyo Institute of Technology

Enhancement of Seismic Safety of Bridges & Transportation Systems

In the meta-theme named "Development of Earthquake Engineering that Complies with "Time is Money" Society", an approach that consists of the following steps is proposed.

(I) Capture the facts that characterizes the present-day urban society ;
(II) Identify the research approaches that are suited to the present-day urban society;
(III) Present scenarios that may occur in the present-day urban society once it is hit by a significant earthquake; and
(IV) Identify engineering issues to mitigate the expected damage to the present-day urban society.

(I) Capture the facts that characterizes the present-day urban society associated with transportation systems

The present-day transportation systems in urban society are likely to be characterized by "high risk," "fragile," "enormous loss propagation," "maintain of quality of life of mass peoples," and "safety and secured life."

1. Suspension of transportation systems can result in extensive loss of social, industrial and economical activities in an urban area. Interaction and propagation of loss are enormous in an urban area.
2. In an old day, it was very common that peoples died by disease, accident and poorness. As a result of economical improvement, quality of life is much upgraded in the present day. Major concern of the present peoples is "safety" and "secured life." However day by day life of peoples in urban areas depends on fragile transportation systems.
3. "Just in time system" in product industries is supported by fragile transportation system. Suspension of transportation system at only a location can come to a halt of production in the entire country or worldwide.

(II) Identify the research approaches that are suited to the present-day urban society

Structural engineers consider that the seismic performance goals of structures are to "keep function against small to moderate events" and "prevent collapse against major vents." It may be true in developing countries, however demand of peoples seeking "safety and secured life" in advanced countries is not any more satisfied with the current seismic performance goals. They demand more reliable and safe society.

For example, we conducted a questionnaire survey to 862 publics on 1) how long downtime they can bear, 2) how much more money they can allow to spend for constructing damage-free bridges, and 3) how they evaluate the current seismic performance goals (prevent collapse no matter how damage is extensive against a major event) under the assumption that urban areas are hit by an extreme earthquake and extensive social and structural damage occurs at many locations. We first inquired their awareness of seismic risk and fragility in urban areas in the future earthquake. Then we asked how shortly they want damaged bridges be restored. We explained that it is possible even now to construct bridges which are free from damage based on existing technology, however it is more costly. We asked how much more money they allow us to spend for constructing damage-free bridges. Finally we told that the current seismic performance goal of bridges and buildings worldwide is to prevent collapse against an extensive event no matter how structures suffer extensive damage. Then we asked how they evaluate such a performance goal.

Figs. 1-3 show their replies. 89.3% peoples replied that bridge should be restored within a week. 80.4% peoples replied that they can accept to build damage-free bridges if the cost increase is less than 30% the current level. 80.7% peoples replied that bridges should be designed based on the performance goals that bridge should be repaired immediately even after a significant earthquake or damage should be avoided. Only 4% peoples supported the current seismic performance goal that bridges should be designed for preventing collapse no matter how they suffer extensive damage.

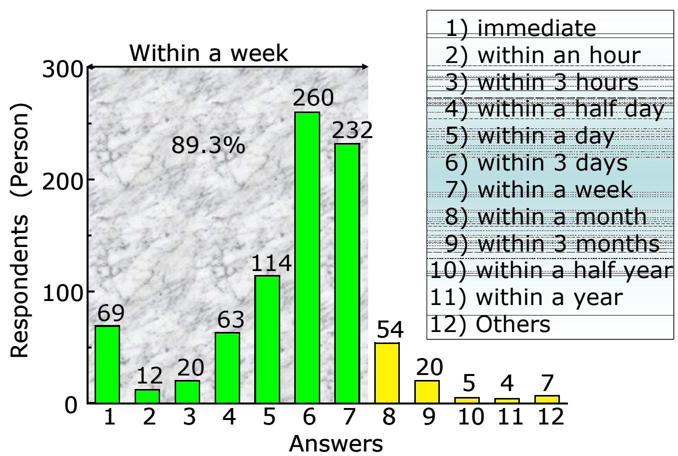


Fig. 1 How shortly the public demand restoration of bridges after a significant event

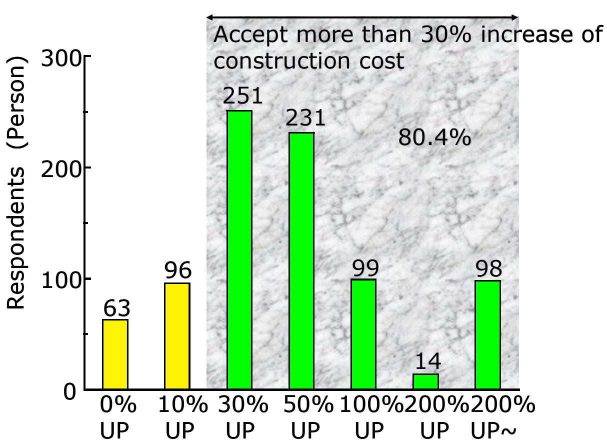


Fig. 2 How much more money the public allows to spend for damage-free bridges

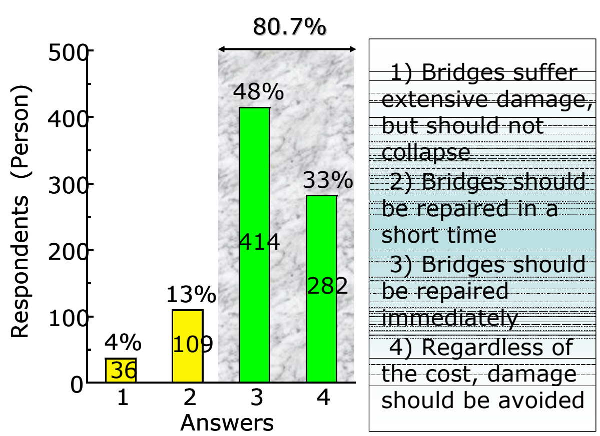


Fig. 3 How the public evaluates the current seismic performance goal

On the other hand, Figs. 4 and 5 show how much cost increase is required to satisfy the current design requirements for 1.75g (current), 2g, 3g, 4g and 5g design response accelerations. Obviously bridges designed using 3g or higher response acceleration have limited inelastic response under the strongest near-field ground motions ever recorded in the world. Increased cost of substructures compared to the current design is 1.47 and 1.14 times the current level in Type II and III ground, respectively, however increased const of a whole bridge system is only 1.08 and 1.04 times the current cost in Type II and III ground, respectively. It is therefore possible to build damage-free bridges using the existing technology. However more improved technology makes it possible in a more smart way to build damage-free bridges. Development of such a technology contributes to realize resilient urban society.

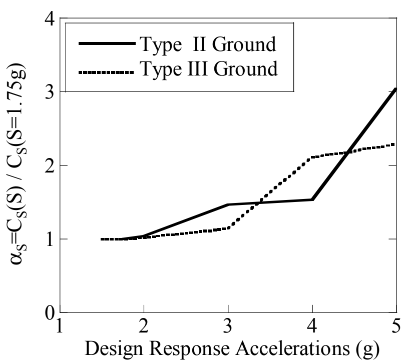


Figure 4. Dependence of cost increasing ratio of substructures on the design response acceleration

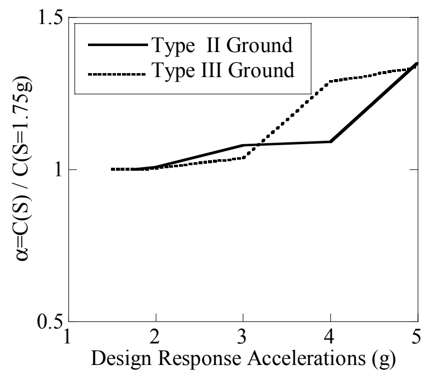


Figure 5. Dependence of cost increasing ratio of a whole bridge on the design response acceleration

The needed approaches in transportation systems for realizing resilient urban society are:

a. Public-oriented mind for the identification of problems to solve/resolve
b. Need for more reliable bridges (damage-free bridges) which can keep function even after a significant event
c. Need for almost-damage-free bridges which can keep function after a significant earthquake without any emergency repair (permanent repair can be required later)
d. More focus on safety of traffic on bridges
e. Need for fast responses to disasters, i.e., quick inspection, quick repair, etc.
f. Mechanism of information sharing among owners, engineers, and public.

(III) Present scenarios that may occur in the present-day urban society once it is hit by damaging earthquakes

Here is one scenario that may occur in an area where complex transportation facilities are located once the area is hit by a large earthquake characterized by strong near-field ground motions.

1. Collapse and extensive damage occur in a number of urban viaducts on national roads, toll expressways and railways. Collapse of bridges directly resulted in a number of victims and casualties, and it immediately suspended transportation system for vehicles and railways. In a congested urban area, collapse of a viaduct could suspend roads and railways under the viaduct.

2. Necessary disaster countermeasures highly depend on what time an earthquake hit urban area. Suppose it occurred at day time during week days, urban areas were full of commercial and social activities. After disaster, preventing damage extension and secondary damage, rescue for injured peoples, supply of medicine & medical equipments, and supply of emergent food and water were the top priority issues. Thus, fire fighting, rescue of seriously damaged peoples and control of transportation were urgently required, however fire cars, police cars and ambulances could not get in touch with those demands because transportation systems were suspended.
3. An important fact which was not known before the earthquake was that bridges on especially important roads and expressways which were designated as Regional Emergent Transportation Roads were designed to have not higher seismic performance goals than others but only standard seismic performance goals (bridges should not collapse during an extreme event). Such seismic performance goals resulted in extensive damage and even collapse of bridges on Regional Emergent Transportation Roads. Once Regional Emergent Transportation Roads suffered damage, emergent mass transportation of medical equipment and rescue activities, construction machines and equipments for road evacuation, food and water could not be smoothly conducted as planned in regional disaster relief program. It also prevented evacuation of peoples from fire.
4. There were a number of vehicles with drivers left on urban viaducts. The viaducts did not collapse but suffered extensive damage. There were a number of vehicles which crushed by bumping with deck gaps and damaged expansion joints due to large relative lateral and vertical displacements. Many cars badly bumped with gird rails due to loss of control and dropped from viaducts. Relative displacement of viaduct oscillation was over +/- 0.5m, which drivers never experienced.
5. It was regarded that bridges could be possibly repaired shortly after an earthquake if they did not collapse. However in reality, it took months for repair. Function of the urban area was seriously damaged for long. For example, a 20 m long I girder bridge of Tokyo Metropolitan Expressway suffered damage due to fire associated with overturning of a tank truck in summer in 2008. The deck settled 0.7m due to deformation of heated I-girders. It took more than two months and $ 20 M for repair. But economical loss due to suspension of traffic at only one location was $ 3 M per day. Loss resulted from extensive damage of transportation systems at many locations in urban area must be uncountable.

(IV) Identify engineering issues to mitigate the expected damage to the present-day urban society.

In light of the scenario described above, what shall we do if we want to see such a situation? Many engineering challenges are immediately drawn for realizing damage-free bridges. Here are examples.

- Develop structural systems which enable to reduce structural response and residual drift
- Develop structural systems which absorb plastic deformation without damage

ENGINEERING CHALLENGE: PROTECTION OF LIFELINES FROM EARTHQUAKE EFFECTS—WITH EMPHASIS ON RAILWAY TUNNELS

Ikuo Towhata

(1) World and our society in near future

The recent situation in our world is characterized by two issues. The first is the desire for better environment, and the second is the fear for shortage of natural resources. The high price of oil, which we experienced in 2008, is one of the evidences that people are afraid of the future supply of energy resources. Consequently, there are discussions everywhere about sustainability of our civilization.

The increasing of world population is not a forgettable issue. The increased population would result in the shortage of food and energy on one hand, and on the other hand the growing of urban population. Many people would flow into cities, hoping that they could get job and food there. In consequence to this situation, there are many mega cities in the world now that have population of more than 5 million and possibly 10 million. Those mega cities have appeared not only in developed countries but also in developing countries. Due to insufficient development of urban transportations, many mega cities suffer from traffic congestion in streets and air pollution caused by exhausted gas from automobiles.

Since 1980s and more likely since 1990, many cities in the world have been aware of the problems of relying on automobiles as a major urban traffics. Hence, construction of urban railways such as subways and LRT (light rail transit) has been pursued. Due to limitations of available land for new railways, those construction projects took time and have been completed only in the recent times. In order to realize the significant shift of transportation mode, however, construction of a few railway lines is insufficient and a convenient railway network is important. This is because people still want to start their trip by car if train service cannot take them directly to any destination of their trip. Unfortunately most mega cities in the world do not yet have this convenient public urban railway network. It should be stated that many mega cities in the world are prone to seismic effects. Examples of such cities are Beijing, Taipei, Tehran, Istanbul, and Mexico City among many others.

(2) Public transportation in Japanese big cities

Public transportation in Japanese big cities started in late 19th Century by constructing surface tram railways. High-speed train networks were constructed mainly in suburban areas. In the second half of the 20th Century, however, the increasing car traffics in streets made many local governments give up maintaining the street trams any more and major cities started to construct underground subways. Those subways offered direct and convenient connections to suburban railways, and therefore mass transportation in big cities heavily relies on railway services. This construction of railway network was facilitated by the fact that construction started at relatively early times when there are still lands for new construction.. This convenience is probably one of the important reasons why traffic jam in present Tokyo is not so bad as in 1960s and 70s.

Earthquake is a big threat to urban subways. This is particularly true because urban activities heavily rely on the convenience of subways. The problem is that tunnels are situated in soft alluvial soils which are subjected to strong seismic motion. Another seismic danger of a tunnel is found at a boundary between hard and soft soils where differential ground motion is significant. It is noteworthy, furthermore, that many stations in Tokyo connect several subway lines and are of complicated geometry, being comprised of connecting tunnels, underground halls, and vertical shafts. Seismic response of such a complicated underground structure is not well understood.

Subway tunnels are constructed by several technologies. The most classic one is of the cut-and-cover type. The seismic failure of Daikai Station in Kobe demonstrated the problem of this type of structure (Fig.1) and subway stations of a similar type were retrofitted nation-wide. In addition to the complicated underground station structures as mentioned above, more earthquake hazard is found in a shield tunnel (Fig.2) that is made of bolt-connected segments. It is pointed out that distortion of a shield tunnel structures caused by consolidation settlement and other types of ground deformation produces unexpected stresses in the tunnel and consequently reduces its earthquake resistance. It is certainly true that differential motion of tunnels across geological boundaries produces unexpected distortion and stresses.

There are tunnels that run under river bed. A few of those tunnels were constructed by sinking steel boxes into water, connecting them, and backfilling. The seismic stability of submerged tunnels may be affected by liquefaction of backfill materials. Since the unit weight of water-saturated sandy material is greater than that of water, the buoyancy force at the time of sand liquefaction is significant, possibly being able to cause floating of the tunnel body. It is easy to imagine that a huge amount of river water would flow into subway tunnels in case of breaching of submerged tunnels.

Fig. 1 Daikai subway station destroyed by 1995 Kobe earthquake

Fig. 2 Shield tunnel for urban highway in Tokyo

(3) Tunnels in mountainous regions

The advantage of railway traffic over road traffic holds true for mid-distance intercity transportations as well. From the viewpoint of energy consumption and generation of CO_2 gas, railway traffic is more advantageous. Since the role of railway is substantial in the national economy, seismic resiliency of intercity railways should be discussed.

One of the earthquake-prone parts of railway traffic is a tunnel in mountain regions. In early days, tunnels were believed to be stable even during strong earthquakes. For example, the Tanna Tunnel which was then under construction survived the 1930 Kita-Izu earthquake despite that a causative fault crossed the tunnel. Tanna tunnel did not collapse although the fault movement closed the excavated tunnel’s cross section. Another example is the Manjil Tunnel in Iran that crossed the causative fault during the earthquake in 1990 and survived with only minor distortions.

In contrast, there are reports on seismic damage of tunnels during recent earthquakes. Those tunnels were situated in soft rock or debris that was subjected to significant earthquake response.

Hence, it is reasonable to say that only tunnels in hard rock are safe during earthquakes because surrounding ground prevents large deformation of the tunnel structure. Fig.3 presents statistic information on causes of tunnel damages during past earthquakes. While slope failure at the entrance is the majority, tunnel deformation due to unstable surrounding ground and difficult geological conditions affected the earthquake resistance of tunnels.

NATM tunnel has an earthquake problem as well. Being an abbreviation of **N**ew **A**ustrian **T**unneling **M**ethod, NATM tunnel produces its stability from the rigidity of surrounding ground. To achieve this goal, the wall of a tunnel is stabilized by shotcrete immediately after excavation and then installation of rock bolts so that the surrounding ground would not deform and lose its rigidity. In Japanese practice of NATM, steel reinforcement is frequently installed along the tunnel wall in addition (Fig.4). The earth pressure is supported by this strengthened ground. It is important that many NATM tunnels are now constructed in soft rock and even in soil at shallow depth where seismic ground deformation is significant. Lack of rigid concrete structure around a tunnel may result in significant deformation in the NATM structure and possibly a collapse of an entire tunnel.

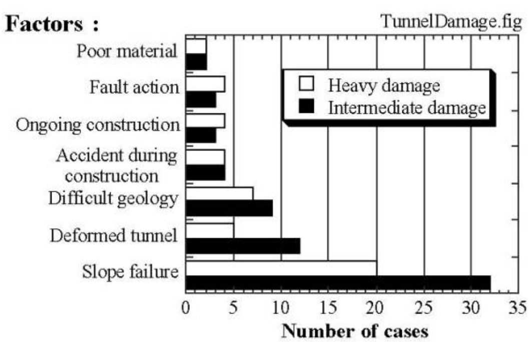


Fig. 3 Factors that govern earthquake damage of tunnels

Fig. 4 NATM tunnel under construction

Table 1 Schematic list of seismic risks of tunnels

	Relatively dangerous	Relatively safe
Urban subway tunnels	Soft soil and geological boundary Shallow depth 沈埋 tunnel Shield tunnel in special geological conditions Complicated station structure*	Firm soil Deep depth Retrofitted tunnel
Mountain tunnels	Soft rock and soil NATM in soil at shallow depth	Hard rock Rigid tunnel

* Stations are not necessarily vulnerable to seismic risk. It is hereby meant that seismic response of complicated station structure is not well understood.

(4) What to be done

The preceding sections discussed the importance of railways as measures for urban and intercity mass transportation. This is particularly true from the viewpoints of energy consumption and environmental protection from air pollution. Reliable operation of railways is important for both urban activities in normal times and restoration of natural disasters in emergency situations. In spite of these, subway tunnels and tunnels in mountainous regions are subjected to seismic risk. Table 1 tabulates seismically safe and dangerous situations for tunnels. In case of insufficient safety, seismic retrofitting is necessary. Accordingly, it is essential now to propose what to be done for improving the seismic resistance of tunnels and avoiding negative effects to the public that are caused by the lack of railway operation for a long time after an earthquake. What should be done are:

1. Model tests for better understanding of soil-structure interaction. Attention should be paid to underground rigid walls and geometric complications.
2. Model tests on a shield tunnel at shallow depth. Effects of initial distortion of tunnel structure and differential ground motion at geological boundary are focused on.
3. Model tests on a NATM tunnel at shallow depth. Response to large ground deformation is important.
4. Model tests on a submerged tunnel subjected to liquefaction of surrounding soil and significant floating of the tunnel body.
5. Reproduction of observed dynamic behavior by three-dimensional numerical analyses.
6. Model tests to validate technologies for seismic retrofitting of existing tunnels.
7. Publication of knowledge thus obtained at the earliest convenient times so that public sectors can refer to and consider them in future public policies.
8. Since the structure of stations, shield tunnels, and NATM tunnels are important, model tests should be run with a large size. On the other hand, overburden pressure (depth of tunnel) does not have to be very deep because seismic problems are expected to occur near the surface where soil is soft and earthquake response is remarkable.

GEOTECHNICAL RESEARCH FOR LIFELINE AND OTHER INFRASTRUCTURE SYSTEMS

A white paper for the NEES/E-Defense Phase 2 Planning Meeting
NSF, Arlington, VA, January 12-13, 2009

Prepared by:
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The purpose of this white paper is to identify some specific areas of Geotechnical research applied to lifeline and infrastructure systems other than buildings and bridges that: (1) would potentially result in innovative and transformative approaches to earthquake loss reduction, and (2) require large scale testing to adequately simulate the system behavior. Systems of interest include buried structures which are part of lifeline systems (subways, tunnels, etc.), water and wastewater systems, power generation and distributions systems, telecommunication systems, ports, levees, dams, and others. The seismic response and resilience of these systems are often controlled by geotechnical and soil-structure interaction (SSI) aspects. Therefore, geotechnical and SSI research are critical to improving the procedures used to analyze and design these systems. It is recognized that many of the geotechnical and SSI issues relevant to these lifeline and infrastructure systems are also relevant to buildings and bridges.

Four criteria were considered in searching for geotechnical topics of interest to the US that would be most appropriate for a collaborative effort of large-scale testing at E-Defense and NEES facilities.

1. The problem/system needs solution and is relevant to earthquake engineering applications & performance-based design.
2. The problem/system requires large-scale testing to address specific scientific issues.
3. Tests at the E-Defense facilities would provide specific advantages that clearly extend research options beyond those provided by other 1g shaking table, lab/centrifuge, or field experimental capabilities.
4. The expected findings have a strong potential for innovative and transformative approaches to earthquake loss reduction.

Two main general research areas are identified which are directly relevant to Criterion 1 above:

- Need for better evaluation and mitigation of effects of seismic ground deformations. Many of the lifelines and other systems of interest are geographically distributed over significant distance, which exposes them to many different subsurface soil conditions. Some of the systems (e.g., ports), involve extensive use of artificially deposited soils. Therefore, performance-based design of the systems requires: (1) ability to predict ground deformations in a range of soil conditions and deformation hazards, (2) ability to remediate ground deformations in a range of soil conditions, and (3) performance-based evaluation and design strategies that consider the system response and resiliency when setting performance targets for components.
- Need for better response evaluation and performance prediction of structural and foundation components and the surrounding ground when subjected to seismic shaking, especially in the presence of soft or liquefiable soils as well as after application of some ground improvement strategy.

In the process of identifying preferred research topics, the authors of this White Paper did the following:

- Reviewed relevant parts of the 2003 EERI Research and Outreach Plan in Earthquake Engineering entitled “Securing Society Against Catastrophic Earthquake Losses.”
- Reviewed relevant parts of the 2008 EERI White Paper on Earthquake Risk Reduction: Addressing the Unmet Challenges,
- Reviewed relevant parts of the NEHRP's 2009-2013 Strategic Plan,
- Reviewed the descriptions of all funded NEESR projects containing relevant geotechnical and SSI research within their scopes, and
- Consulted with a group of US geotechnical researchers as well as with Professors Tokimatsu and Towhata.

The authors of this White Paper subsequently propose the following four topics as potentially well-suited for NEES/E-Defense research programs. Topic A relates to underground structures, whereas the other three are cross-cutting topics. An alternative framing of issues around systems of interest, rather than cross-cutting research topics, is also listed at the end of the document.

<u>Topic A: Performance of underground structures</u>

- Post-earthquake functionality of pipelines, utilities, tunnels, subway stations, and other underground structures can be essential to the resiliency of an urban area.
- Structural approaches for accommodating ground deformation, such as introducing flexible joints into pipeline or tunnel structures, may be able to effectively mitigate ground deformation hazards in some cases. The issues in the design include the optimal placement of flexible connections and the deformation demands placed on those elements.
- Large-scale 1-g shaking table tests can enable more detailed modeling of different underground structures and their configurations. Issues that could be addressed include (1) the investigation of deformation mechanisms of tunnels/pipelines in liquefiable soils to verify previously lessons from centrifuge testing; (2) investigation of demands applied to buried structures that span across geologic boundaries between soils that do, and do not, liquefy during shaking; (3) investigation of the behavior of flexible structural connections and the demands placed upon them in challenging ground conditions. In all of these areas, large-scale testing provides the ability to model the geometric complexity of the problems in greater detail.
- Supporting studies using smaller-scale shaking table or centrifuge tests, the split-box facility at Cornell, and computational efforts would be important, but would not eliminate the need for the large-scale capstone tests.

<u>Topic B: Innovative ground improvement and remediation strategies:</u>

- Substantial economy may be gained by developing ground improvement design methods that reduce inherent conservatisms and can confidently predict different levels of performance. Existing design methods tend to be inherently conservative in representing certain behaviors due to the absence of seismic performance data; e.g., reinforcement and drainage effects of sand/stone columns, cracking potential in soil-cement walls, influence of spatial variability in treatment/densification results.
- Innovative ground improvement methods (e.g., biocementation, colloidal silica grouting, air sparging, rammed aggregate piers) offer potential economy by expanding available options.

- Innovative ground improvement strategies to reduce, rather than eliminate, ground displacements (e.g., treatment zones that restrain lateral spreading of adjacent zones) offer potential economy.
- Structural approaches to resisting or restraining ground deformations, such as the use of large-diameter shafts or the introduction of flexible joints in tunnels and pipelines, can be an effective remediation strategy in some cases.
- Large-scale 1-g shaking table tests would enable more detailed modeling of: (1) the ground improvement processes that are known to strongly affect in-situ behaviors, (2) the interaction of structural elements with deforming ground, and (3) ground improvement strategies that involve complex spatial arrangements of improvements or structural features.

Topic C: Predicting ground deformation hazards for challenging soil types

- Procedures for the evaluation of seismic ground failure hazards are only well established for cohesionless soils such as clean sands and non-plastic silty sands. Much less is known about other, relatively challenging, soil types such as gravels, gravelly sands, marginal plasticity soils, organic soils, and peats.
- The potential for liquefaction, strength loss and deformation in materials other than clean sands and non-plastic sand-silty mixtures cannot be confidently evaluated with existing engineering methods, which leads to conservative evaluations and costly remediation efforts.
- Large-scale 1-g shaking table tests of the aforementioned challenging soils would enable: (1) evaluating both existing and new in-situ testing methods before and after seismic loading, (2) obtaining unique experimental data on the seismic behavior of the soils, and (3) evaluating engineering methods for predicting ground deformations that are based on different in-situ test data.
- Supporting studies using smaller-scale shaking table or centrifuge tests, field studies, and computational efforts would be important, but would not eliminate the need for the large-scale capstone tests.

Topic D: Ground deformation mechanisms in heterogeneous profiles

- One of the fundamental unresolved problems in geotechnical earthquake engineering is the need for accurate methods for predicting ground deformations during liquefaction and seismic loading. Current methods such as Multiple Linear Regression (MLR) empirical models and the Newmark sliding block analysis with residual strength do not capture the fundamental physics of the problem. Both the magnitude and the distribution of ground deformation are important for assessment of performance of underground structures and deep foundations that pass through the deforming soil.
- More rigorous computational models attempt to capture the physics, but at present, these advanced models have not been adequately validated for complex soil deposits. For example, pore water may accumulate beneath impermeable layers, thin permeable layers may transmit pore pressures laterally causing failure of denser soils, or deformations may localize on a thin plane or be nonuniformly distributed. Large-scale testing is needed because influences of grain size distribution and particle size effects are difficult to model on the centrifuge and it is difficult to create models on a small scale that include detailed control of heterogeneous layering.

- Large scale shaking table tests should be complemented by smaller-scale shaking table or centrifuge tests and a significant computational validation effort.

<u>Alternative framing of issues around systems of interest:</u>

- Performance of ports: issues related to ground improvement, pile-supported wharves, and quay walls would be candidates for large-scale tests.
- Performance of levee systems: candidates for large-scale tests would include tests to investigate deformation mechanism for levees on peaty foundation soils and issues related to ground improvement.
- Performance of underground structures (identical to Topic A above).

Geotechnical Engineering Challenges with Emphasis on Problems in the Tokyo Metropolitan Area

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The Tokyo Metropolitan Area has materialized and developed over deep alluvial deposits underlain by bedrock formed in the Mesozoic and Paleozoic eras occurring at depths from almost zero to 3 kilometers. The different geological profiles within the area often produce different ground motions and have resulted in various sorts of damage, such as severe local site effects, in a number of past earthquakes. The deep alluvial deposit overlying the bedrock frequently induces long-period surface waves. Typical examples of earthquake damage associated with the effects of long-period motions include: (1) the collapse of tall buildings in Mexico city 350 km from the epicenter during the 1985 Mexico Earthquake and (2) the failure of oil tanks and subsequent outbreak of fires, both caused by oil sloshing amplified by long-period ground motions during the 1964 Niigata and 2003 Tokachi-oki Earthquakes. Numerous recently constructed high-rise buildings and large-scale bridges in the Tokyo area have little experience of such long-period motions.

Poised atop the alluvial deposit in the Tokyo Metropolitan Area are soft/ loose soils as well as reclaimed lands filled with extraneous soils or waste disposal. Those surface soils have been more or less extensively associated with most of the catastrophic disasters during past earthquakes. Various structures including buildings, bridges, and port facilities, as well as earthen structures, such as road and railway embankments and levees, are either directly founded on those soils or supported on pile foundations penetrating them. Consequently, these are all vulnerable to local site effects and such ground failures as soil liquefaction and lateral ground spreading. The 1995 Kobe Earthquake demonstrated the following typical examples:

(1) Non-liquefied surface soil amplified ground motions significantly, leading to extensive damage to buildings and bridges, or alternatively shear failure at pile heads.

(2) Soil liquefaction occurring in areas of reclaimed land deamplified ground motions, particularly in the period range of less than 1 s, reducing the damage to superstructures in the area.

(3) Soil liquefaction and lateral spreading increased ground displacement and, therefore, kinematic effects, leading to damage pile foundations beneath buildings and bridges.

Lifelines and various other structures buried in the ground are more strongly affected by failure and response of the soil around them. Lifelines in or across soft soils, in particular, have never survived undamaged during past catastrophic earthquakes. During recent earthquakes many manholes were uplifted due to increased buoyancy as a result of the liquefaction of backfills. Poor performance of backfill was also observed during the 2007 Niigata-ken Chuetsu-oki Earthquake. Most backfills around critical buildings at the Kashiwazaki-Kariwa Nuclear Power Plant suffered significant settlement due to strong ground shaking, inducing numerous disorders among ducts and pipes directly founded on them. Numerous underground structures in Japan, such as subways, tunnels, underpasses, and shopping complexes, have little experience of huge earthquake events, except for the major collapse of the Taikai subway station in the 1995 Kobe earthquake.

Damage to a part of an infrastructure and/or a lifeline may not only lead to the complete loss of its critical function but also cause secondary disaster and/ or disaster chains. Two thirds of all fires after the 1995 Kobe earthquake occurred more than two days after the quake, reportedly owing to the encounter of gas leakage from broken pipe at the switch-on of electricity after restoration work had been completed.

The key dynamic soil behaviors associated with various types of damage during past earthquakes thus include: (1) local site effects involving, above all, effects of long-period motions, (2) ground failures including soil liquefaction, and (3) various sorts of soil-structure interaction.

One should also take into account the following socioeconomic aspects of the Tokyo Metropolitan Area that could serve to worsen damage associated with the above-mentioned ground problems.

(1) One-third of the total population of Japan is now domiciled in the Tokyo Metropolitan Area, thus constituting the largest and, at the same time, the most densely populated community anywhere in the country. Various networks such as railways and roads, as well as lifelines, are significantly longer and more complex, and thus more fragile, than

those of any other urban area in Japan.

(2) The presence of older wooden houses, substandard or sub-code buildings in other materials, and, in general, infrastructures whose estimated seismic performance is far below current design standards would be prone to extensive damage.

(3) Due to long-time dewatering, more than 20% of the Tokyo Metropolitan Area is presently below sea level and yet inhabited by millions of people. Even a single collapse and/ or failure of a dike, a levee, or a floodgate protecting this zone, might lead to long-term inundation of the whole.

(4) Various inherently dangerous facilities, such as petrochemical complexes and oil storage tanks located on soft soil, as well as the presence of important port facilities and Haneda Airport on reclaimed islands, pose additional risks.

Based upon above geological and social considerations affecting the Tokyo Metropolitan Area, which are liable to contribute to further extensive damage during strong earthquakes, the following key areas of research must be further explored:

(1) Enhanced evaluation of long-period ground motions during strong earthquakes and documentation of their effects on performance of large-scale structures in extreme events;

(2) Further understanding of soil-structure interaction in extreme events;

(3) Better understanding of seismic behavior of underground structures, such as subways, tunnels, underpasses, and shopping complexes, and seismic evaluation and retrofitting technique for these;

(4) Advanced techniques to discover and repair damaged portions of underground lifelines, and strategic techniques such as those to minimize repair time, as well as the area affected by the damage, in order to prevent or minimize secondary disasters and disaster chains;

(5) Development of advanced ground improvement and reinforcement methods, including those for backfills, to achieve optimal performance during strong shaking; and

(6) Enhanced detection and evaluation of ground deformation occurrence and its reimplementation through an improved performance-based design of soil and soil-structures.

White Paper on Computational Simulation

NEES/E-Defense Phase 2 Planning Meeting
National Science Foundation, Arlington, Virginia
January 12-13, 2009

Muneo Hori[1] and Gregory L. Fenves[2]

Computational modeling and simulation of structural and geotechnical systems has a rich history in earthquake engineering. From the earliest years of the field, researchers and practitioners developed computer applications to determine the effects of earthquake ground motion on buildings, bridges, and other structure-foundation-soil systems. It is now routine for design engineers to use computer-based analysis of a structure to determine the forces and deformation under earthquake loading, typically assuming linear material behavior and small displacements for equivalent static loads or a response spectrum analysis. Engineers are increasingly using nonlinear static analysis with simple component models, often referred to as pushover analysis, to evaluate deformation capacity, particularly for retrofit design. In geotechnical earthquake engineering, the analysis of site response and foundation systems is generally based on equivalent linear analysis methods, although behavior of piles may be represented in a nonlinear static analysis of a soil-structure system. Although there have been advances, the limitations of the models and analysis methods used in practice do not provide engineers with the information about the expected performance of a system, such non-structural damage, structural damage, residual effects, and collapse.

Whereas thirty years ago, earthquake engineering pushed the limits of computing, today the state-of-the-art in earthquake engineering modeling and simulation lags behind the enormous advances in computing capability in computer architecture, software engineering, data fusion, and scientific visualization. Computational science and engineering have transformed other fields that had been reliant exclusively on testing. For example, computational fluid dynamic simulation for aerodynamic design of aircraft replaces much of the wind tunnel testing, and large-displacement analysis for automobile crash design replaces much of the vehicle crash testing. The potential for computational simulation to transform earthquake engineering has not yet been tapped.

Our goal in earthquake engineering research should be to develop the capability to simulate the full range of damage mechanisms of structure-foundation-soil systems all the way to collapse under a wide range of earthquakes, including the uncertainties associated with the design, construction, and health of the structure in addition to the inherent uncertainty of the hazard. Achieving this goal of simulating scenarios, and ultimately distributions of performance, for individual structures and inventories of structures would provide many benefits in terms of improved performance, higher reliability, and reduced construction costs.

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A radical transformation in the way we use computational modeling and simulation in earthquake engineering requires several key ingredients. The first is a true integration between experimentation and simulation modeling so that each experiment is designed to improve one or more simulation models, and each model is validated against well-designed experiments. Second, a new effort is needed to improve dramatically the fidelity of models for materials and components, particularly for non-ductile modes of behavior such as fracture and shear, degradation of strength and stiffness under cyclic loads for structural components, large-strain deformation of soils, and the complex nonlinear behavior of foundation-soil interaction. Third, new algorithms and software systems need to be developed to take advantage of modern computer architectures from the multi-core processors now on laptops to the massively parallel processor computers that are becoming increasingly available for routine computation. Fourth, the uncertainty in behavior must be represented throughout the modeling and simulation process so that engineers understand the distribution of performance that may be expected.

The extensive experimental research that is now being conducted by E-Defense in Japan and NEES in the U.S. provide valuable data that should be fully utilized to validate computational models. In many cases the models have been found to be inadequate in capturing complex nonlinear behavior, indicating clearly that research in model development is lagging. While it is recognized that the primary goals of these two programs is experimental research, testing should not be an end to itself. The research and practice communities, and our educational enterprise, would benefit by an equally ambitious program for improving computational simulation.

For the purpose of planning future E-Defense/NEES activities, the following “big picture” issues should be considered:

1. The simulation models and methods for cumulative damage in structural components under long-duration ground motion with many cycles are not adequate for assessing damage potential and estimating repair/replacement costs (or other decision variables). Coordinated tests and model simulation methods are needed to obtain the data and improve the models. New simulation methods such as multi-scale procedures, discrete particle methods, and others can be validated with experimental data. It is essential that local behavior be measured (strain, fracture, buckling) in tests for fine-grain model validation.
2. The capability to simulate collapse of 3D structural systems is inadequate. There is an urgent need for a comprehensive program to test different systems to collapse and validate computational models through the entire range of collapse scenarios. Large-scale shaking tables tests and hybrid (including multi-site) tests are needed to investigate collapse.
3. The uncertainties in structural behavior need to be assessed through experiments on a number of samples. The data can be used to characterize the distribution of demand and damage and incorporated into models.
4. The interaction between a structure and its foundation and soil has a large impact on structural and non-structural performance. Coordinated SFSI interaction tests at a range of scales and methods (shaking table, centrifuge, hybrid) are needed to improve simulation models for the complete system.

There are many other areas of research necessary for improving computational simulation (e.g. high-fidelity models, robust and scalable algorithms, high-performance computing, visualization of behavioral phenomena and for simulation steering, data fusion of simulated and experimental data). These are essential for improving the tools for the design of individual structural systems. Second, it is important to make progress in simulating the impacts of an earthquake on an entire urban region. A coordinated research program in experiments and simulation would allow combining the empirical approach for loss estimation, urban resiliency, and urban resumption planning with sound scientific simulation of earthquake scenarios.

HEALTH MONITORING AND CONDITION ASSESSMENT

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Can Health monitoring be really effective to identify the condition or ready to become a fundamental scheme for civil structures?

Earthquake engineering has really contributed to designing and constructing earthquake-resistant structures. By "learning from actual earthquakes and earthquake damages," as mentioned by Nakashima, structural engineers have accumulated very significant information on how to enhance the seismic reliability of civil structures or how to decrease the induced damage to a structure in order to produce more earthquake-resistant structures. Having said that, however, I would say that this contribution of earthquake engineering is relevant to how to prepare for a coming earthquake or the "pre-earthquake" preparation, and thus such a role is a so-called "conventional" aspect of earthquake engineering.

Along with the recent, rapid development of modern computer technology and information science, the idea or concept of structural health monitoring has appealed the attentions of the engineers for nearly the last two decades. Unlike the conventional characteristics of earthquake engineering which was mentioned in the above, health monitoring is a technology relevant to the health condition assessment for "in-the-middle-of-earthquake" or "post-earthquake." The key issues of health monitoring are such as what kind of response information should be measured utilizing by what kind of sensors, in which structural elements or in which floors those sensors are implemented, how or what kind of algorithm the condition assessment is achieved, in particular in judging whether a severe damage may happen to which story or which structural elements when the structure is subjected to a severe seismic excitation.

One of the significant backgrounds which triggered the propelling of structural health monitoring was the academic and practical development of active control strategies for civil structures. Since most of such control strategies are based upon certain response feedback control scheme, sensors and a central computer or multiple distributed computers are implemented into the controlled civil structures. The conducting of structural health monitoring also needs to involve sensors and computer(s) within structures. In this regard, it is quite natural that the development of health monitoring goes along with the development of structural control. In addition, as structural control has become a matured technology with many practical applications, more academic interests and attentions of research engineers have begun to move the field of health monitoring. As a matter of fact, the world's health monitoring researchers community overlaps somewhat more or less the structural control researchers community. The International Association for Structural Control (IASC), which was established in 1994 with the longest history as an academic society of structural control, added several years ago the word *monitoring* to its original name, now being "International Association for Structural Control & Monitoring (IASCM)."

With the above-mentioned background, however, structural health monitoring is still in the middle of development as compared with the matured level of computer-based structural control, and has not practically demonstrated its effectiveness. Of course, many of engineers have realized the significance and potential of structural health monitoring recognizing the possibility of the collapse of building and bridge and recognizing the fact that there are many civil structures that are required to keep their functions even during and after severe seismic excitation. In this regard, a reliable and rapid condition assessment strategy, whether off-line or on-line, should be really established integrating modern sensing and information technologies. Indeed, several real bridges and buildings in some countries have recently employed health monitoring systems and have accumulated the data responding to small-seismic/strong-wind excitations or traffic loads. However, those systems have not obtained such data as the structures are severely damaged, fortunately or unfortunately. Although a variety of algorithms for the damage condition assessment have been proposed, they are not practically demonstrated to be effective during a severe seismic event. In this regard, solutions should be given to the following issues:

- Is it possible to identify which structural elements are damaged in a structure subject to seismic excitation? In establishing such a methodology, what kind of information is needed?
- Is it possible to identify in what extent the structure is damaged or how damaged the structural elements are? In establishing such a scheme, what kind of information is needed?
- Will it be possible to establish such a structural monitoring scheme for a high-rise building as to identify which structural elements among a huge number of elements are damaged in what extent?
- Related to the above issue, what kind of sensing or monitoring system is implemented accounting for the hugeness in the longitudinal direction? Perhaps, an autonomous-decentralized monitoring system is established for a high-rise building. In doing so, what kind of sensor network is established for a high-rise building?
- In seismic regions around the world, there are a great number of bridges within and on the boundaries of big cities. Since these bridges are necessary lifelines for the lives of the people, it would be really great to identify the possibilities of collapsing before or soon after an earthquake or to identify which parts are damaged soon after the earthquake utilizing the response information during the seismic event. In establishing such a health monitoring or damage detection scheme, what kind of information should be collected by implementing what kind of sensor network?
- There is no structural health monitoring system implemented in an actual civil structure which has obtained the real response data during a severe seismic event or when experiencing the process of collapse. A variety of sensors should be examined. Or maybe an appropriate sensor for a building or bridge structure should be developed. (Most of the sensors utilized in the present health monitoring systems are not those sensors which have not been developed for civil structures.) It would be helpful to obtain a variety of response data in many of structural elements when subjected to a severe seismic excitation or experiencing severe damages.

As compared to the conventional aspect of earthquake engineering, health monitoring has not reached at all the matured level of technology at the current stage, even though this research field has appealed to the interests of researchers as well as research founding agencies for this decade and is considered to be instrumental for realizing more reliable civil structures. By conducting real-size structural model experiments subjected to severe seismic excitation, health monitoring technology should drastically step up to more practical stage.

Structural Health Monitoring, Resiliency and NEES

Anne Kiremidjian
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NEES Workshop
January 12-13, 2009

NSF
Washington, DC

Objectives of SHM

- Provide timely, reliable and cost effective structural
  - Diagnosis
  - Prognosis
- Under
  - Normal operating conditions
  - Extreme events

Resiliency–Extreme Events

- Emergency Response
  - Timely identification of critically damaged structures
    - Collapsed
    - About to collapse
  - Provide information in format usable
    - Regional damage identification – within GIS or with other visualization tools
      - Location
      - Criticality
    - Provide decision support for prioratizing response activities
  - Prevent or reduce injuries and casualties
  - Provide information on healthy structures for relocation of people, operations, etc.

Resiliency–Extreme Events – cont'd

- Recovery Period
  - Provide automated *damage diagnosis* of *large number of structures* – currently primarily done by visual inspection by limited number of engineering personnel –i.e. provide help with tagging

    (again this can be connected to local building inspection offices)
  - Provide structural prognosis – residual life and strength
  - Decision support for reconstruction alternatives – combine with online building permit process
- This can greatly reduce reconstruction and recovery costs (to government, individual owners and occupants)

What is needed and how can NEES research help?

- Validation and testing of
  - New sensors and sensing technologies
  - Fidelity of data collection
  - Fidelity of data transmission –wired and wireless
  - Scalability of data communications – wired and wireless
  - Information delivery – results of damage algorithms
- Provide for parallel monitoring system installation
  - Different sensors/sensing systems
  - Different sensor locations

What is needed and how can NEES research help?

- Design testing protocols that address needs for SHM damage algorithm testing and validation – diagnosis and prognosis
  - Recreation of various
    - Levels of damage
    - Types of damage
    - Global structural level
    - Local component of joint level
  - Use multiple measurements/algorithms for cross validation of measurements, damage diagnosis and prognosis
- Test decision support systems
  - Serve as the command and control center of the SHM
    - For communication to the SHM system
    - Information/data retrieval and delivery
    - Decision making/ recommendations for follow-on actions
    - Communication with central authorities (as needed)

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