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LONG-TERM VISION FOR A CYBERINFRASTRUCTURE FOR EARTHQUAKE ENGINEERING

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SUMMARY

During FY 2005 - FY 2014, the U.S. National Science Foundation will fund the earthquake engineering community to conduct research and education activities using the newly developed NEESgrid cyberinfrastructure. NEESgrid networks 15 earthquake engineering experimental research facilities across the U.S. with computers, information technology, and communications technology to deliver simulation and collaborative services that will enable the earthquake engineering community to work together efficiently and effectively on grand challenge research projects that will lead to new knowledge in earthquake engineering and new methodologies and technologies for earthquake loss reduction.

INTRODUCTION

Earthquake disasters cause significant damage to physical and societal infrastructure, resulting in direct and indirect economic losses, disruption in community services, and loss of lives. Although significant advances have been made in understanding the behavior of materials, structural, geotechnical, and coastal systems, and the nature of earthquakes, the process of learning has been slow since many contributions to the knowledge base and changes to design codes historically are made as the result of damage observed and lessons learned after a major earthquake event. The George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) provides the ability to test these systems through physical modeling at larger scale and as more complete systems to accelerate the knowledge base. NEES will be comprised of 15 state of the art earthquake engineering experimental facilities across the U.S. that include: single (outdoor), dual, and triple *shake tables* at the University of California, San Diego; State University of New York at Buffalo; and University of Nevada, Reno, respectively; *geotechnical centrifuges with in-flight robotic and two-dimensional shaker capabilities* at the University of California, Davis, and Rensselaer Polytechnic Institute; the world's largest *tsunami wave basin* at Oregon State University; *large-scale structural, soil-foundation-structure interaction, and lifeline testing laboratories* at the University of California, Berkeley; University of Colorado, Boulder; Cornell University; University of Illinois, Urbana-Champaign; Lehigh University; and University of Minnesota, Twin Cities; *mobile geotechnical and structural field testing equipment* at the University of California, Los Angeles, and University of Texas at

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Austin; and *permanently instrumented field sites* in southern California operated by the University of California, Santa Barbara. These facilities will be fully operational by September 30, 2004. As part of NEES, these 15 experimental facilities form a national shared use infrastructure for earthquake engineering research and education that welcomes external users through both teleparticipation features and on site facility usage. Each facility, with the exception of one field facility, has allocated 50% time annually for use training and experimentation by external users. The facility consisting of two permanently instrumented field sites in southern California will be 100% shared use since the instruments will remain operational round-the-clock to capture earthquake ground motion in this seismically active region. More information about these facilities is available at the NEES Consortium, Inc., (Consortium) web site [1].

Through the NEESgrid cyberinfrastructure, the 15 experimental facilities and their teleparticipation capabilities are networked with a community curated data repository, collaboration and visualization tools, and unprecedented access to leading edge compute resources and open source simulation tools. As such, NEES will transform the environment for earthquake engineering research and education through collaborative and integrated experimentation, computation, theory, databases, and model-based simulation to develop new fundamental knowledge in earthquake engineering, seismic design methodologies, mitigation technologies, and computational tools. Ultimately, the goal of NEES is to reduce earthquake losses in the U.S. through improved seismic design and performance of civil infrastructure systems.

From October 1, 2004 – September 30, 2014, the Consortium will operate the NEES infrastructure (15 experimental facilities and NEESgrid cyberinfrastructure), along with conducting education, outreach and training activities. The Consortium was formally incorporated as a public benefit, nonprofit organization in January 2003. In its leadership role in the U.S. for NEES, the Consortium will also coordinate the scheduling of experimental research time at the experimental facilities; facilitate research planning by potential proposers to funding agencies; lead education, outreach, and training activities; and develop connections with U.S. and international partners. A critical role of the Consortium is to develop and implement policies governing open access to the NEES experimental facilities and experimental and analytical data. The Consortium will also foster broad participation in NEES by all sectors of the earthquake engineering community, including researchers, teachers, students, and practitioners. NSF envisions that other major earthquake engineering experimental facilities and data resources that bring unique capabilities to NEES, both within the U.S. and abroad, will actively participate in NEES.

NEESgrid CYBERINFRASTRUCTURE

The term *infrastructure* – well known to civil engineering professionals – has been used for almost a century to refer collectively to buildings; highways; bridges; railroad and mass transit systems; ports and air transportation systems; electric power transmission and distribution systems; telecommunications systems; water, gas, liquid-fuel, and sewage systems; and other public works that support the day-to-day functions of an industrial economy. The newer term *cyberinfrastructure* is used to define an emerging infrastructure which is "…based upon distributed computer, information, and communication technology…of enabling hardware, algorithms, software, communications, institutions, and personnel" [2, p. 5] that form "…reliable, well-specified, and interoperable connections…that allows people to discover, learn, teach, collaborate, disseminate, access, and preserve knowledge in their domain…extends from the scientific instrument to the desktop of the working scientist and encompasses networks, models, data sets, metadata, data archives, data analysis and manipulation tools, as well as communication and collaboration tools and environments" [3, p. 2]. An advanced cyberinfrastructure is underpinned by the "…highest-performing technology and its use in the most leading-edge research" [2, p. 5]. For many research communities, massive amounts of data will be created as the result of collaborative experimental research. Data-intensive science and engineering, distributed computing for advanced numerical simulations and visualization, and use of experimental facilities by geographically distributed users cutting across multiple

disciplines is loosely termed the "*grid*." The *grid* is as important and useful to scientific and engineering communities as the *web* has been to business and the general public. Combining and utilizing various grids that include digital libraries, data systems, visualization and general collaboration through these systems forms the cyberinfrastructure. Foster and Kesselman [4] present a comprehensive discussion of grid technology, its evolution, and applications.

As cyberinfrastructure tools and capabilities evolve, more research domains will turn to cyberinfrastructure for research facilitation. NEES forges new ground in merging a domain (earthquake engineering) with cutting edge, grid-based cyberinfrastructure tools and services. As such, the NEESgrid cyberinfrastructure [5] is a pioneering effort within the U.S. to develop and operate an integrated system of state of the art geographically distributed earthquake engineering experimental research equipment, computing, communications, and information resources, tools, and services designed to advance earthquake engineering research and education. Figure 1 shows the concept for NEES.

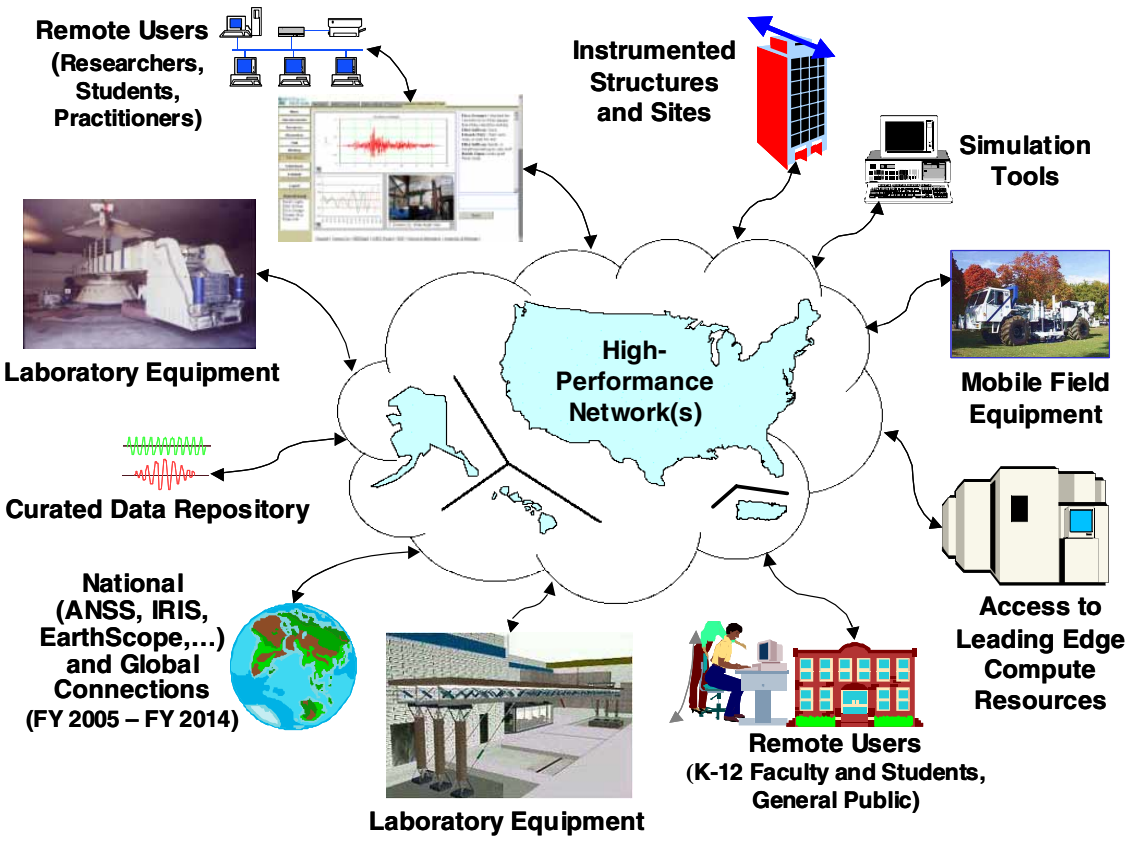

Figure 1. NEES Concept

NEESgrid is being developed by the University of Illinois, Urbana-Champaign, in partnership with Argonne National Laboratory, Mississippi State University, Pacific Northwest National Laboratory, University of California at Berkeley, University of Michigan, University of Southern California, and Washington University. NEESgrid builds upon the existing U.S. Internet network, National Middleware Initiative software and grid framework [6], Globus toolkit [7], and the CompreHensive collaborativE Framework (CHEF) [8]. The result will be a layered modular architecture that allows the NEESgrid system to be adapted during the ten-year operations of NEES to accommodate new applications, services, user requirements, and experimental equipment. When fully linked, these resources will form a seamless,

integrated laboratory. NEESgrid is the result of the collaborative effort among earthquake engineers, computer scientists, and social scientists. The design of NEESgrid evolved over a five-year period (FY 2000 – FY 2004) to address the extensive user requirements extracted from the earthquake engineering research community. Final NEESgrid software versions will be released during summer 2004. Complete information about NEESgrid is available at the neesgrid.org web site [5] and after October 1, 2004, will be available at the nees.org web site [1].

NEESgrid brings tools never before available to the earthquake engineering community as summarized in reference [9]:

1. CHEF – web-based collaborative tools and services that allow users to access computing facilities, communicate in discussion forums and via text chat, collaborate using scheduling and data sharing and exchange teamlets, and visualize data through data viewers.
2. Data repository services to manage data and metadata about NEES and other experiments. This includes local repositories at the experimental facilities and a central repository and archiving services operated by the Consortium, linked by a set of service protocols. The Consortium is currently drafting a community-based data archiving and sharing policy for projects funded by NSF and conducted at the experimental facilities during the shared use time. The policy will address data definitions [curating, archiving, sharing, types (raw, corrected, processed, curated, final packaged data)], data release dates to researchers and general public, data archiving (data and metadata models, data ingestion, data curation), and access rules.
3. Telepresence mode services that provide an interface and display to users using web browsers. Viewers can remotely view lab space and physical experiments via remote telerobotic video cameras.
4. NEESgrid Teleoperations Control Protocol (NTCP) to enable remote applications to control aspects of a physical experiment. For example, various components representing parts of a large structural system might be tested in different NEES laboratories through distributed experimentation and the NTCP. In addition, fast hybrid methods based on real-time dynamic testing are being developed at several NEES equipment sites and could lead to more efficient ways of testing critical components, making use of NTCP.
5. NEESgrid Streaming Data Service to subscribe to and access remotely streaming data from experiments and simulations during their execution.
6. Data acquisition reference implementation to the LabView framework.
7. E-Notebook services to create electronic versions of laboratory notebooks.
8. Numerical simulation capabilities such as open source simulation software – OpenSees [10] and FedeasLab (a Matlab toolbox) [11] - and a simulation portal.
9. Grid services for user authentication and authorization.

The NEESgrid cyberinfrastructure has been designed to be extensible and scalable so that nationally and globally rsearchers and educators can participate in or observe experiments. If the ultimate goal of earthquake engineering research is to reduce losses, then understanding of a multidisciplinary complex society is necessary. NEESgrid allows users to share and merge knowledge across disciplines, conduct multidisciplinary grand challenge research, and tap into available knowledge globally – enabling creation of a knowledge-based systems network for the earthquake engineering field.

The NEESgrid cyberinfrastructure joins part of a broader information technology-driven integration occurring across all of the sciences, engineering, and beyond. Table 1 shows recent cyberinfrastructure projects in science, engineering, and medical fields.

Table 1. Examples of Science and Engineering Research Community Cyberinfrastructure Projects

Acronym	URL/Web Site	Description
BIRN	www.nbim.net	Biomedical Informatics Research Network
GEON	www.geongrid.org	Cyberinfrastructure for the Geosciences
GriPhyN	www.griphyn.org	Grid Physics Network
IVDGL	www.ivdgl.org	International Virtual Data Grid Laboratory
LEAD	lead.ou.edu	Linked Environments for Atmospheric Discovery
NEES	www.nees.org	George E. Brown, Jr. Network for Earthquake Engineering Simulation
NNIN	www.nnin.org	National Nanotechnology Infrastructure Network
NSDL	www.nsdl.org	National Science Digital Library
SEEK	seek.ecoinformatics.org	Science Environment for Ecological Knowledge
SPARC	www.windows.ucar.edu/sparc/	Space Physics and Aeronomy Research Collaboratory

VISION FOR THE NEESgrid CYBERINFRASTRUCTURE

NEES is truly a pioneering project in the U.S. as the first national and geographically distributed cyberinfrastructure project to address a compelling national need, i.e., earthquake loss reduction. While NEESgrid represents a major change in how research and education is conducted through the collaborative and shared resources and, as such, requires a learning curve for the community, it brings the promise of transforming the earthquake engineering community to one with resources that can be readily accessed and utilized by all to accelerate the knowledge base in the field. At the heart of NEES is the central data repository, which for the first time in the earthquake engineering community, will curate and archive experimental and analytical data for use and reuse by researchers and educators around the U.S. At the end of ten-year operations, NEES will be successful only if the full capabilities of the NEESgrid cyberinfrastructure and experimental facilities are extensively utilized. The earthquake engineering community must seize opportunities to partner with computer and social scientists to renew, upgrade, and advance the cyberinfrastructure over the ten-year operations as tools for both research and education. As indicated in Table 1, strong cyberinfrastructure partnerships among domain experts and computer and social scientists have already been formed in other domains. NEESgrid development partnered earthquake engineers with computer and social scientists; for NEES to be successful as a resource that meets the needs and user requirements of the earthquake engineering community, such partnerships need to continue during ten-year operations.

Opportunities for Earthquake Engineering Research

The NEES infrastructure – NEESgrid cyberinfrastructure and experimental facilities - provides unique opportunities to pursue high-priority research, to demonstrate the validity of design concepts and guidelines, to speed the transfer of research into seismic design guidelines and specifications, and to develop well-informed preparedness and recovery strategies. To help guide NEES research through the next decade, a panel organized by the National Research Council (NRC) of the National Academies has developed a long-term research agenda for the earthquake engineering research community [12]. In addition, the Earthquake Engineering Research Institute published a research and outreach plan for earthquake engineering [13]. The NRC study outlined six areas for grand challenge research in earthquake engineering:

- Economical methods for retrofit of existing structures
- Cost-effective solutions to mitigate seismically induced ground failures within communities
- Full suite of standards for affordable performance-based seismic design

- Convincing loss prediction models to guide zoning and land use decisions
- Continuous operation of critical infrastructure
- Prediction and mitigation strategies for coastal areas subject to tsunamis

In August 2003, NSF initiated the first year of the planned ten-year competitive George E. Brown, Jr. Network for Earthquake Engineering Simulation Research (NEESR) Program Solicitation [14] to utilize the NEES infrastructure. Research projects funded under this solicitation must make use of one or more of the 15 experimental facilities operated by the Consortium. Under NEESR, research will be funded for different modes of collaboration:

- Individual Investigator (II) - individuals and small research teams to address a significant problem in earthquake engineering.
- Small Group (SG) - cross-disciplinary, and preferably multi-organizational, teams of researchers to address a significant problem in earthquake engineering requiring extensive use of the NEES equipment sites.
- Grand Challenge (GC) - geographically distributed, cross-disciplinary, and multi-organizational teams that take a comprehensive systems approach to address a significant problem in earthquake engineering requiring extensive use of the NEES equipment sites.

The NEESgrid cyberinfrastructure forms the backbone of all experimental investigations. Using the CHEF framework and collaborative tools, researchers will be able to conduct experimental pre-planning, execution, and post-experiment data processing and analyses. An important component of all NSF NEESR funded research is that all experimental data generated must be submitted electronically to the central NEESgrid data repository. Data includes all measurements, calibrations, observations, analyses, images, commentary, reports, logs, notes and/or electronic notebook entries which relate directly to the conducted experiments. Any data (as described above), which is recorded in hardcopy of any form, must be transcribed/converted into an appropriate searchable format on to electronic media. In addition, this information must be properly characterized with appropriate metadata descriptors and then subsequently stored into one of the NEES accepted digital formats to facilitate archiving in accordance with the data, metadata, and formats and policies established by the earthquake engineering community through the Consortium and the NEESgrid system integration project.

Opportunities for Earthquake Engineering Education, Outreach, and Training

NEES provides national resources for developing, coordinating, and sharing new educational programs, curricular materials, and advanced visualization tools to train the next generation of the earthquake engineering workforce. The NEESgrid cyberinfrastructure has been designed to make it easy for researchers to share their expertise with educators and students, other scientists and engineers, professionals, and the public, often while experiments are being conducted. NEES can also enrich lessons for K-12 students and teachers by making them "virtual partners" in the process of experimental discovery and analysis. Learning about earthquake engineering research will make students aware of the importance of such research to society and may inspire some of them to become researchers and engineers. To facilitate the use of NEES for integrating research and education, in September 2003 NSF funded the Consortium to develop an educational strategic plan for NEES [15]. This plan will outline opportunities to leverage network experience and resources to implement programs aggressively on the national scale and to harvest the richness and diversity of local programs to develop models that can be expanded throughout the network. More information about this award, the educational strategy, and workshops are available at references [1] and [16]. The NEESgrid cyberinfrastructure offers the opportunity to nationally coordinate NEES-derived educational materials and activities with digital library initiatives such as the National Science Digital Library [17], the Digital Library for Earth System Education [18], and the Electronic Encyclopedia of Earthquakes [19].

CHALLENGES FOR THE NEESgrid CYBERINFRASTRUCTURE

While major pieces of earthquake engineering research equipment will be fairly robust over the ten-year operations of NEES, the NEESgrid cyberinfrastructure poses both challenges and promises:

- *Evolution of NEESgrid to meet user needs*. NEESgrid includes a number of complex, innovative, and emerging technologies and systems that will continue to evolve over the ten-year period, e.g., grid, security, networking, simulation, visualization, collaboration, teleparticipation at the equipment sites, E-notebook, and data components. As the need for and use of cyberinfrastructure as a tool for conducting research grows among various research communities, new tools and applications will be developed. It is important that NEES tracks user requirements, e.g., through pilot user groups and user scenarios, and cyberinfrastructure research and development for improved and new tools and capabilities over the ten-year period to remain state of the art.
- *Evolution of data and metadata*. Through the NEES experimental facilities, researchers will be able to test more complete and comprehensive civil infrastructure systems and components, including geomaterials, structures, systems, nonstructural components, and soil-foundation-structure interaction. Advances in the field will be accelerated by the use and reuse of the data generated from the seismic response of these components and systems that is archived in the central data repository. Data and metadata formats often take years to evolve within a domain and the community will need to continually evolve the NEES data and metadata structure. NEES presents the unique challenge of coordinating data among different specimens, subdisciplines, experimental facilities, sensors, and instruments. Initiatives in earth science such as EarthScope [20] and the Advanced National Seismic System [21], as well as activities of the Incorporated Research Institutions for Seismology [22], offer collaborative opportunities to develop common metadata and data formats and shared cyberinfrastructure.
- *Development of advanced simulation and visualization capabilities*. NEES can advance numerical simulation and visualization capabilities through models and analytical tools validated and derived from knowledge learned from physical testing. Through high performance computing coupled with numerical simulation and visualization, new models of seismic response can be developed that can transform how engineers as well as public policy makers and emergency response personnel understand the impacts of earthquakes. NEESgrid provides resources to integrate experimentation, computation, theory, databases, visualization, and model-based simulation. To facilitate this integration, a workshop was held at the University of Kansas in December 2003 to discuss advanced computational and visualization needs for NEES [23]. With powerful computing capabilities such as Teragrid in the U.S. and the Earth Simulator in Japan, experiments and simulation can be conducted and visualized for a community or a region rather than for only discrete systems.
- *Collaborations with global partners*. Evolving grid initiatives in the U.S., United Kingdom, Europe, Japan, and other countries will make it easier for earthquake engineering researchers and educators to collaborate using/adapting the NEESgrid cyberinfrastructure. Such collaborations must consider, for example:
  - Should there be a central international data repository or networked data repositories?
  - Is there a common language for data and metadata?
  - How will issues of intellectual property be handled?
  - How will cybersecurity be addressed?
- *Develop of a national cyberinfrastructure for earthquake engineering education.* While a number of earthquake engineering faculty and groups have been developing educational materials at the K-12, undergraduate and graduate levels, these efforts largely remain uncoordinated and not readily accessible by the broader earthquake engineering community. NEES offers the opportunity to develop

a national initiative for earthquake engineering education through extension of the NEESgrid cyberinfrastructure to develop a national repository for educational materials, building upon digital library initiatives already underway. New tools for evaluation and assessment of learning through a cyberinfrastructure must also be developed to fully understand the impact of remote learning.

CONCLUSIONS

NEESgrid is the integrating tool for the earthquake engineering community to address grand challenge research problems collaboratively, through national and global partners. Through experimentation enabled by the NEES infrastructure, researchers in earthquake engineering will be able to address compelling technical issues of full-scale testing, full complexity including nonlinearities, and completeness of testing including nonstructural components, soil-foundation-structure interactions, and systems. The sharing of experiments and experimental results with the broader earthquake engineering community through the NEESgrid cyberinfrastructure enables all to learn and to contribute to the knowledge base in earthquake engineering.

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