13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2497

THE NEES GEOTECHNICAL CENTRIFUGE AT UC DAVIS

Daniel W. WILSON[1], Ross W. BOULANGER[2], Xin FENG[3], Bernd HAMANN[2], Boris JEREMIC[2], Bruce L. KUTTER[2], Kwan-Liu MA[2], Carlos SANTAMARINA[4], Kenneth S. SPROTT[5], Steven A. VELINSKY[2], Gunther WEBER[6], S. J. Ben YOO[2]

SUMMARY

The Center for Geotechnical Modeling at UC Davis operates a 9.1-m radius geotechnical centrifuge equipped with a 2 m x 1 m servo-hydraulic shaking table. This equipment has been used in geotechnical earthquake engineering research since 1994. In October 2000, UC Davis was selected as a host equipment site on the National Science Foundation's George E. Brown, Jr., Network for Earthquake Engineering Simulation. This four-year upgrade project represents a $5M investment in the UC Davis centrifuge facilities by NSF with an additional $1M from UC Davis.

NEES at UC Davis capitalized on the size of the centrifuge and innovations in instrumentation and information technology to enable generation of higher resolution information (control, sensors, and images) and to create more realistic physical models. With NEES the Center for Geotechnical Modeling is working to implement advanced instrumentation, digital video, robotics, and geophysical testing to increase the quality and quantity of data that can be collected; to increase the capacity of the centrifuge; and to develop a biaxial shaking capability. These improvements will allow us to extract more detailed and more accurate information from experiments and simulations, maximizing the information and knowledge that can be gained from these experiments.

The Center for Geotechnical Modeling facilities are intended for use by researchers from academia and industry, from both the US and abroad. The centrifuge at UC Davis will be a shared-use facility under NEES, with experiments being performed by teams of researchers. New hardware and software developments are currently being implemented as part of the NEESgrid System Integration project. These new resources will allow teams to collaborate regardless of their physical location. Remote researchers will be able to control their experiments at UC Davis as easily as local researchers. Further information about the UC Davis NEES site can be obtained at http://nees.ucdavis.edu, or by email to cgm@ucdavis.edu.

[1] Research Engineer, University of California, Davis. Email: dxwilson@ucdavis.edu
[2] Professor, University of California, Davis
[3] Research Engineer, University of California, Davis
[4] Professor, Georgia Institute of Technology
[5] Professor, California State University, Sacramento
[6] Post-doc, University of California, Davis

(a)

(b)

(c)

Fig. 1: The Centrifuge facility at UC Davis. (a) In 1989, spinning in the open. (b) In 2004, the centrifuge is enclosed in the rotunda to the left. A new 470 m^2 building houses model preparation space, the visualization / control room, and offices. The original centrifuge support building visible in (a) has been remodeled and is now the network operations center. (c) The centrifuge today can be operated at up to 75 g at an 8.5 m effective radius.

INTRODUCTION

The UC Davis centrifuge has the largest radius and largest platform area of any geotechnical centrifuge in the US; it is one of the top few in these categories in the world. The centrifuge can carry five ton payloads and operate at 75 g (at the effective radius of 8.5 m).

Typical geotechnical model testing in the past used very limited amounts of instrumentation, which yielded observations at selected points in a physical model. Progress in earthquake engineering was hindered by incomplete and ambiguous data sets that allowed for subjective and potentially mistaken interpretation. The development of the NEES Centrifuge at UC Davis capitalized on the size of the facility and innovations in instrumentation and information technology to enable researchers to generate much higher resolution information (more control, sensors, and images) and to create more realistic physical models that will provide unambiguous experimental data for assessments of Model Based Simulation theories.

In 1978, in response to a broad agency announcement from NSF, UC Davis collaborated with NASA on a successful $2.5M proposal to construct and install the four ton payload, 9.1-m radius, 300 g National Geotechnical Centrifuge at NASA Ames Research Center. The centrifuge was first operated at NASA Ames in 1984.

In 1987 the centrifuge was disassembled and hauled to UC Davis. Using funds from Tyndall AFB, Los Alamos National Laboratories, NSF, and the University of California, the centrifuge was installed in an open-air pit two miles west of the main campus. This permitted operations at centrifugal accelerations of 19 g (Figure 1a). In 1989, an NSF-funded enclosure was constructed, increasing the peak achievable centrifuge acceleration to 50 g. (Kutter et al. [1])

From 1990-1995, a large amount of effort was expended to fund, design, and develop a 1 m x 2 m shaking table for earthquake simulation mounted on the end of the centrifuge. In April 1995, the first proof tests of the shaker were performed at a centrifugal acceleration of 50 g. (Kutter et al. [2])

The large centrifuge has been used for many earthquake engineering research projects in the past ten years. Research projects have included soil-pile interaction in liquefying sands (Wilson et al. [3] and

Brandenberg et al. [4]), liquefaction and ground improvement (Balakrishnan and Kutter [5]), dynamic response of tire shreds (Rosebrook et al. [6]), and void redistribution in liquefying sands (Malvick et al. [7]). In performing this research the Center has adopted an open data sharing policy. Digital data along with reports that describe the tests in detail are archived at the Center's website for free download.

The Center for Geotechnical Modeling has collaborated with and has served as host for remote researchers from several universities. These projects have studied such problems as the seismic response of pile-supported wharf decks (Oregon State University, McCullough et al. [8]), reinforced soil slopes (UC Berkeley, Nova-Roessig and Sitar [9], and University of Nevada, Reno, Siddharthan et al. [10]), site response (UC San Diego, Elgamal et al. [11]), the response of shallow foundations (USC and UC Irvine, Gajan et al. [12]), and the seismic response of seawalls (Japan – Obayashi Corporation, Stewart et al. [13]).

In 2000, UC Davis received an award from NSF to become an equipment site of the George E. Brown, Jr. Network for Earthquake Engineering Simulation (http://nees.ucdavis.edu). The facility and equipment construction phase of this project will be complete September 30th, 2004. The centrifuge will then be operated as a host equipment site through 2014.

With NEES, the Center for Geotechnical Modeling is working to implement advanced instrumentation, digital video, robotics, and geophysical testing to increase the quality and quantity of data that can be collected; to increase the capacity of the centrifuge; and to develop a biaxial shaking capability. These improvements will allow us to extract more detailed and more accurate information from experiments and simulations, maximizing the information and knowledge that can be gained.

Major NEES upgrades include:

- increasing the centrifuge capacity from 40 to 75 g
- developing a high-speed distributed wireless data acquisition system
- four degree of freedom robot with a versatile tool interface for custom tools
- in-flight geophysical testing
- vertical-horizontal biaxial shaking table
- remote teleoperation and telecollaboration
- visualization facility with three-dimensional display wall
- sample preparation facility and office building

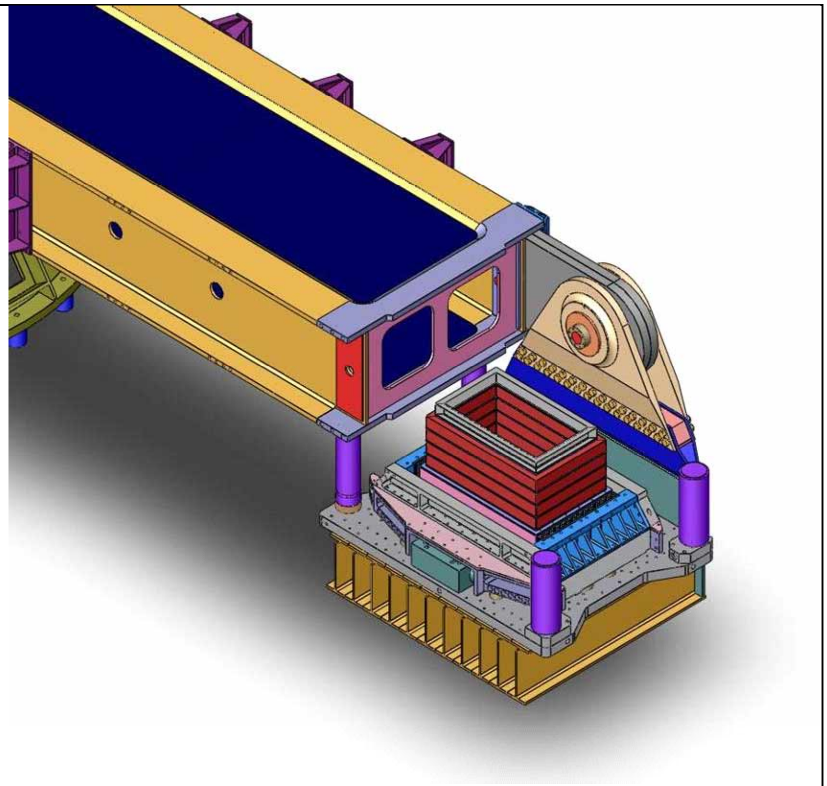
The NEES facility upgrades will soon be complete, and the Center will enter the NEES operational phase as a national shared-use resource. Teams of researchers will soon be able to take advantage of the advanced resources available at UC Davis as part of the NEES network.

THE NEES GEOTECHNICAL CENTRIFUGE AT UC DAVIS

The **9-m radius centrifuge at UC Davis** (Figure 1) can carry five-ton payloads to accelerations of 75 g. An **earthquake simulator**, mounted on the end of the centrifuge, is designed to operate in either a **biaxial** (horizontal-vertical) (Figure 2) or **uniaxial** (horizontal) shaking mode. The servo-hydraulic shaking tables are capable of simulating broad-spectrum earthquake events as well as step- and sinusoidal-wave type motions, and can vary intensity from micro-tremors to extreme shaking events.

The 2-m long x 1-m wide uniaxial shaking table is among the largest available anywhere in the world. Uniaxial models may be constructed, depending on the project priorities, using flexible shear beam

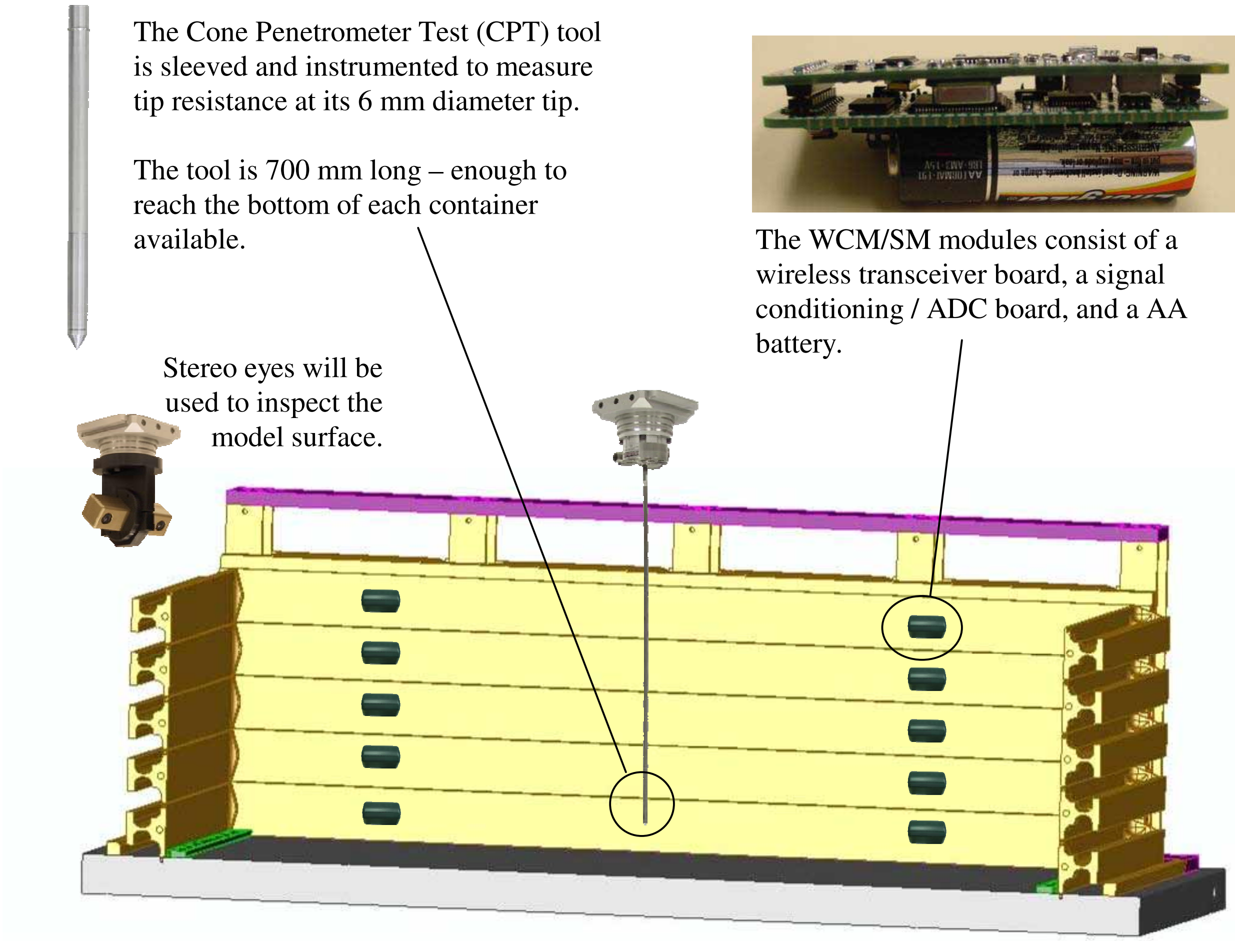
Fig. 2: The UC Davis centrifuge will support two modes of earthquake simulations: Horizontal only (1-D) and horizontal / vertical shaking (2D). The 2D shaker installed under NEES is a cascaded design taking advantage of the existing 1-D shaker



containers - designed to deform with the soil profile during shaking; a rigid container - with clear side walls for observing below grade behavior with video cameras; or a **hinged-plate container** (Figure 3) – which allows permanent lateral deformations among its advanced features. These containers are all on the order of 1.7-m long x 0.7-m wide x 0.6-m deep. The useable volumes are among the largest centrifuge model containers available in the world, and when testing at 75 g's the models simulate a site that is approximately 130 m x 50 m x 45 m in size. A 1-m long x 0.5-m wide x 0.4-m high flexible shear beam container is planned for biaxial shaking.

A **large inventory of transducers and signal conditioning equipment** can be used to monitor model behavior during an experiment. Arrays of pore pressure transducers, for example, can be used to monitor spatial variation of liquefaction. Arrays of accelerometers can be used to study nonlinear wave propagation. Many projects also include arrays of custom transducers, e.g. strain gauges on model structures. This wired data acquisition system was overhauled as part of NEES. It currently records up to 160 transducers, and can be expanded as need arises.

A **distributed high-speed wireless data acquisition system** will be used to record data from up 384 MEMS accelerometers / inclinometers in a single test (Figure 3). The system will consist of 48 miniature eight-channel high-speed data acquisition systems that can be buried in the soil. As dense arrays of accelerometers the transducers will produce higher resolution definition of spatial variability of wave propagation. As inclinometer arrays the transducers will be used to quantify the internal deformations of the soil profile. For example, a closely spaced vertical array of these sensors would produce information to define the permanent shear strain distribution within a soil deposit. Assuming a smooth shear strain distribution, the shear strain could be integrated over the depth to accurately quantify the permanent displacements within the soil deposit. Dense instrumentation arrays are discussed in more detail by Wilson and Kutter [14].



Up to 48 WCM/SM modules can be used at a time. Modules may be buried, typically near the edge of the container, or they may be mounted on structures outside of the model. Eight miniature transducers (not shown) connect to each module, resulting in up to 384 recordings.

Note: Drawing approximately to scale

Fig. 3: The Hinged Plate container will allow permanent lateral deformation when used with the uniaxial shaking table. Other prominent NEES upgrades shown include the stereo robot eyes, the CPT robot tool, and the WCM/SM wireless data acquisition systems.

A **gantry robot** with changeable **manipulator tools** and an on-board **tool rack** will be used to perform multiple tasks without stopping the centrifuge (Figure 4). Onboard robotics, for example, allow more accurate simulation of construction processes, which can, for example, control effectiveness of soil improvement and influence behavior of geotechnical systems such as pile groups. Users will be able to use the **gripper tool** to drive piles sequentially, apply load cycles to structures, and manipulate objects to simulate construction processes.

The robot will also be used to perform in-flight *in-situ* site characterization tests using **geophysical testing** methods. These tests can help relate data in the centrifuge models to field conditions and can be

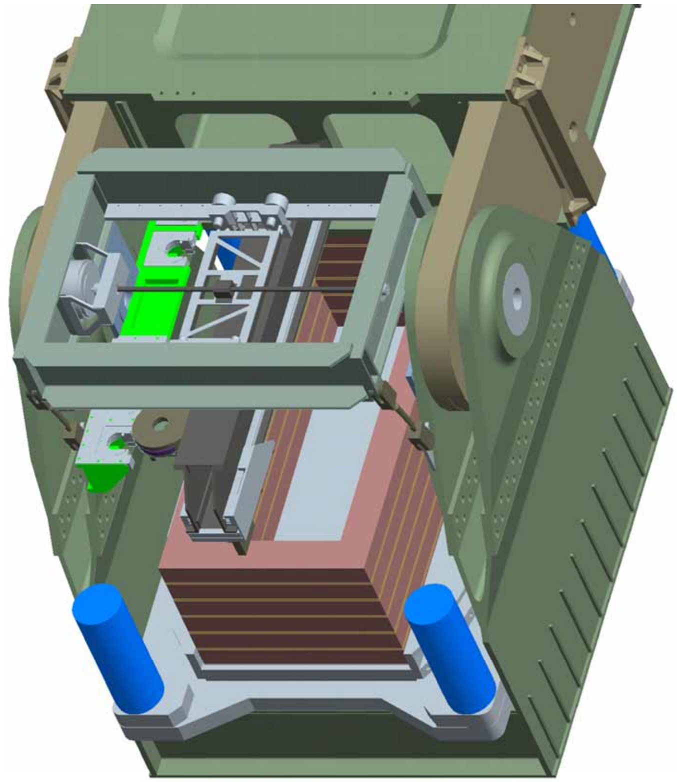


Fig. 4: A 4 degree-of-freedom robot is being added to the centrifuge. An onboard tool rack will hold up to five tools for use during in-flight inspection and construction. The robot will be fully operational with shaking table tests

used to study the evolution of material properties through a series of shaking events. Soil strengths will be indexed using the **cone penetrometer** (Figure 3) and **vane shear** robot tools. A **needle probe tool** will be used to measure porosity variation at millimeter resolution. An **ultrasound tool** will be used to measure the deformation of a submerged surface or subsurface during flight based on sound waves. Users will also be able to inspect the exposed model surface with a **stereo camera tool** (Figure 3).

The robot has a **versatile tool interface** to support future growth. For example a new tool for soil improvement could be easily incorporated. We will develop new tools on a project-specific basis as need and funding arises.

Various imaging techniques will be used to monitor evolution of the surface and interior of centrifuge models during testing. An array of **high-speed video cameras** will be used to image the surface of models and track deformations during shaking events. An eight-channel array of bender element sources will be monitored using up to sixteen receivers, allowing interpretation of shear-wave velocity distributions. An electrical resistivity tomography (ERT) system will use 48 electrodes to monitor changes in electrical resistivity between combinations of electrodes. Inversion methods will be used to create images of resistivity distribution that can be correlated to porosity distribution.

The various independent systems will be interconnected within the data acquisition network. The systems will share data and timing signals. The network structure can easily accommodate future growth or custom data acquisition systems developed on a project-specific basis.

A **470 m^2 building** (Figure 1b), opened in 2003, houses the 42 m^2 **visualization room**, where we use 3D software and our Geowall stereo display to explore sensor data collected in simulated earthquake events as shown in Figure 5. The visualization room is also outfitted with video conferencing and telecollaboration

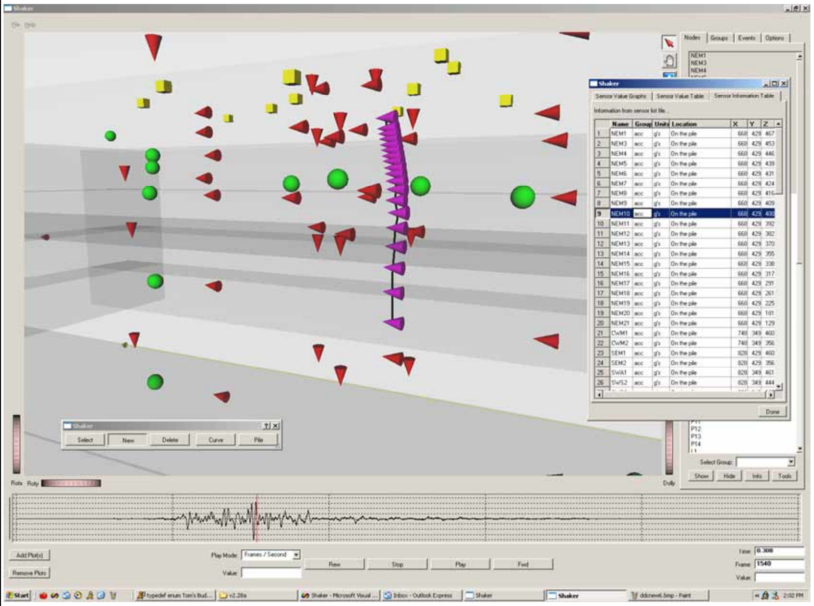


Fig. 5: Shaker.exe version 2.28a. Data and Metadata from centrifuge experiments are shown using a Geowall (http://www.geowall.org) stereo display for interactive 3D visualization during experiments. Icons representing various transducers are animated following measured response. The data shown is from DDC01 (Chang et al. 2002 - http://cgm.engr.ucdavis.edu/). Over 100 transducers are included in this example. The Geowall also supports 3D interactive exploration of the model using the robot stereovision tool.

equipment so that remote researchers can interact with local researchers and staff during experiments. Video conferencing-style displays in our control room and experiment preparation areas enable the on-site researchers to see and interact effectively with remote researchers.

The Center network is built around a Gigabit Ethernet switch connected directly to the campus edge router. The new Network Operations Center (the original control room) is now outfitted with the servers such as the NEESpop and Telepresence Servers, as well as the local data repository and data processing servers. This high performance networking environment is dedicated to supporting remote collaboration.

EXAMPLE NEES RESEARCH USING THE UCD NEES CENTRIFUGE

The UC Davis equipment portfolio is unique in that the size and available resources allow researchers to perform detailed experiments of complete geotechnical engineering systems. An example of an envisioned research project is to evaluate the efficiency of vibroflotation to mitigate liquefaction-induced lateral spreading. Tens of millions of dollars per year are spent in the US on **ground improvement to mitigate liquefaction hazards.** The fundamental effects of ground improvement by deep vibration, as just one example, are incompletely understood; deep vibration densifies the soil and increases the lateral confining pressures and the improvements are dependent on soil properties and the power of the tool. Quality control of improvement is usually monitored by before and after penetration resistance measurements. However, the changes due to ground treatment have different, time-dependent effects on the quality control measures used and on the triggering and consequences of liquefaction. Furthermore, ground improvement creates a heterogeneous distribution of soil properties in the ground, and engineers do not yet have established procedures to account for heterogeneity on the liquefaction behavior.

For this example the researcher might be interested in determining how to evaluate the composite behavior of a treated soil mass, and how far to extend treatment beyond a structure's edges to protect it from the effects of liquefaction in the surrounding soils. These and other issues can have large effects on the cost and reliability of ground improvement works.

The soil model might consist of a saturated layer of loose sand overlying dense sand, with the entire model sloping in the hinged-plate container, which will allow largely unrestrained lateral deformations (Figure 3). We would treat a portion of the loose sand with a robotic vibrating probe in flight. Measurements of pore pressures, accelerations, and geophysical properties around the vibrating probe would provide information on the treatment mechanism. The cone tool, needle probe tool, electrical resistivity tomography equipment, and bender element arrays could be used to characterize the extent and degree of treatment, as well as variations spatially within the treatment zone.

After treatment the model would be shaken to induce lateral spreading of the untreated zones. Spatial variations in accelerations and pore pressures within and adjacent to the treatment zone would provide data on the composite behavior of the treatment zone and its interaction with liquefied soils around it. Dense MEMS accelerometer / inclinometer arrays will provide the ability to study the physics of composite material behavior through measurements of the spatial variation in dynamic response, rather than inferring the physics from a few select measurement points. Post-shaking measurements would characterize changes in soil properties, and the robot stereo imaging equipment would scan the surface to map the surface manifestation of the zones of influence of the improvement.

The database from this experimental project would provide the basis for evaluating and developing Model Based Simulations for years to come because of the completeness of information obtained using the NEES equipment.

We envision that this complicated model test would be performed by a team of researchers working under the general supervision of a Principal Investigator. Operating the shaker, the robot, and the tomography equipment requires specialized training, and a single researcher cannot efficiently and safely operate all of this equipment simultaneously. The physical experiment would be managed by the lead researcher working on site. This researcher would oversee the construction of the model and ensure all of the physical equipment is in place for testing. During the experiment the lead researcher would be responsible for gathering data during seismic tests. A second researcher would be responsible for operating the robot in-flight. A third researcher would operate the tomography and imaging equipment in-flight. The second and third researchers could be remote operators, collaborating via the high-performance network but performing their work independent of location. The PI, whether local or remote, will rely on video teleconferencing, streaming video, and advanced data visualizations to interact with the research team during the experiment and to guide the progression of the test. The following sections describe some of the details about how this interaction will take place.

NEESgrid collaboration and archiving tools

NEESgrid has introduced many new technologies to the earthquake engineering research community. The following new terms will be used in describing the NEESgrid examples at UC Davis below. **CHEF** (CompreHensive collaborativE Framework) is the remote user's portal to the equipment site and to NEESgrid. A **NEESpop** is a NEES Point-of-presence server. The system's purpose is to offer a common set of services which make an equipment site a usable part of the NEESgrid. The **data repository** is being developed by NEESgrid to enable archiving, management, and access of data from experiments and simulations at NEES sites and partners. Readers can visit http://www.neesgrid.org for more information on these NEESgrid projects.

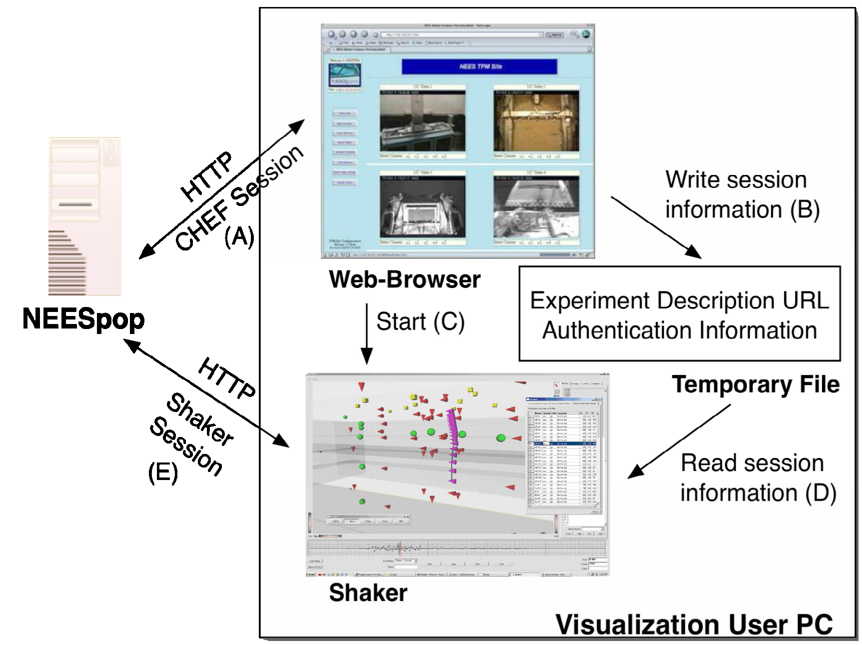


Fig. 6: Integration of Shaker into NEESgrid: A user runs an interactive CHEF session on the NEESpop (A). After clicking on a link to initiate the visualization process, a temporary file (B) is created that contains a URL referencing an experiment description file and authentication information for the running session. The file extension/MIME type of this temporary file is associated with Shaker, causing the Web-Browser to start Shaker and pass the filename of the temporary file to it. Shaker reads the temporary file (D) and uses the information contained in it to download the experiment description file (and other files referenced by it) from the NEESpop server, sending the authentication information from the temporary file as HTTP cookie (E). NEESgrid data services translate all information stored on the NEESpop into the Shaker data format.

NEESgrid example: Data Visualization

Researchers of the UC Davis Center for Image Processing and Integrated Computing and the Center for Geotechnical Modeling have developed a data visualization tool specially designed for geotechnical data from earthquake shaking experiments. Traditionally, results of geotechnical model tests are studied using a set of two-dimensional (2D) plots showing sensor readings as functions of time. Additional types of visualizations and animations are generated with analysis packages like MathCAD or MatLab. We have devised a more general and more sophisticated, OpenInventor-based visualization tool, called "Shaker," to enable visualization of data into a 3D environment. Shaker was first presented by Weber et al. [15]. In a 3D view, the general geometry of the physical model is translucently displayed and opaque icons representing individual sensors are displayed at their coordinate locations. Sensor logs recorded for one shaking event in an experiment are loaded with a mouse click, and this generates a 3D rendering of all the sensor locations. Clicking on individual sensor icons provides information (e.g., position or calibration data) about that sensor and displays a conventional 2D plot of the sensor reading versus time. Sensor icon position and size are then animated in 3D space to enable a quick visual comparison of the recordings of all the sensors. The Shaker program generates a default icon for each type of sensor (e.g., accelerometer data are represented by an arrow head, relative displacements by an oriented bar, scalar data are represented by a sphere that changes color or size in response to changes in the scalar value. Icon properties (color, animation method, size, shape) for a particular sensor type, like shape (geometry) and initial color, will be customizable by a user in an NEESML-based data format. (NEESML is an XMLbased data format developed by NEESGrid and the NEES community.) Metadata handled by Shaker so far includes sensor descriptions and positions, calibration information, and a list of earthquake events that characterize an experiment. Shaker is now being used for experiments with over 100 sensors simultaneously, including displacements, accelerations, strains, and pore water pressures.

The UC Davis NEES team is currently working to make Shaker more widely available as a "web service" through NEESgrid to the NEES research community. To this end, Shaker will be integrated into the NEESgrid service as a stand-alone visualization program, accessible by Chef, as illustrated in Figure 6. After downloading Shaker (to be available for Windows, Linux, and MacOS X platforms), a user will be able to log into the NEESpop and run a CHEF session (labeled (A) in Figure 6). Users will then be able to employ the visualization tool for experimental data stored in the NEES repository. Once an experiment is selected, the NEESgrid web-service will transmit the file (labeled (B) in Figure 6) to the user's computer with (i) a base URL (Uniform Resource Locator) referencing an experiment description file and (ii) authentication information, allowing the stand-alone client program to authenticate itself to the NEESgrid web-service. The file-type of this temporary file is associated with the Shaker application, causing the web-browser to automatically start shaker once the file is received (labeled (C) in Figure 6). The stand-alone client programs will read this file (labeled (D) in Figure 6) and download an experiment description file using the associated authentication information. The experiment description file will contain URLs of all data sources comprising the experiment. These URLs can correspond to files on the NEESgrid server or to data translation services. NEESgrid will provide data translation services that translate all NEESgrid-supported data formats for experiment descriptions into the Shaker experiment data format. During visualization, Shaker will retrieve all necessary data from the NEESgrid service, allowing users to apply it to all data stored in the repository (labeled (E) in Figure 6).

Shaker will support remote collaboration through development of streaming sensor data capabilities for real-time viewing. It is intended to be an open source visualization tool that can be modified and expanded for a variety of applications.

NEESgrid Example: Robot Control

Researchers of the UC Davis Advanced Highway Maintenance and Construction Technology Center and the Center for Geotechnical Modeling are developing a four-degree-of freedom robot for manipulating geotechnical models in flight. The robot will be used to perform *in-situ* site characterization and to perform model construction processes while the centrifuge is spinning. The robot will be controlled by the robot control computer mounted on the spinning centrifuge. Users will send commands to the robot over the Internet, either from computers at UC Davis or from remote locations. Challenges associated with the UC Davis NEES robot control are real-time, software development and remote access over the Internet (NEESgrid).

The robot will be operating in a 75 g radial acceleration field. Under these conditions a real-time capability must be ensured. Like other robots we have developed before (Velinsky et al. [16]), the robot control is based on a motion controller; in this case, it is an XMP motion controller from Motion Engineering, Inc (MEI). This controller handles all the time-critical tasks within its own 32-bit floating point DSP and communicates with the robot control computer via the PCI bus. This way, the computer handles the user inputs and network requests while the real-time operations (8-axis motion and I/O) are guaranteed by the motion controller. Furthermore, the computer runs real-time Linux operating system to ensure real-time synchronization on the system level.

Software development has become a critical task for all robotics and mechanical system development. In the verification stage through the final system integration and test, software consumes most of the development time and is prone to bugs. To make this matter even more difficult, most commercial robots

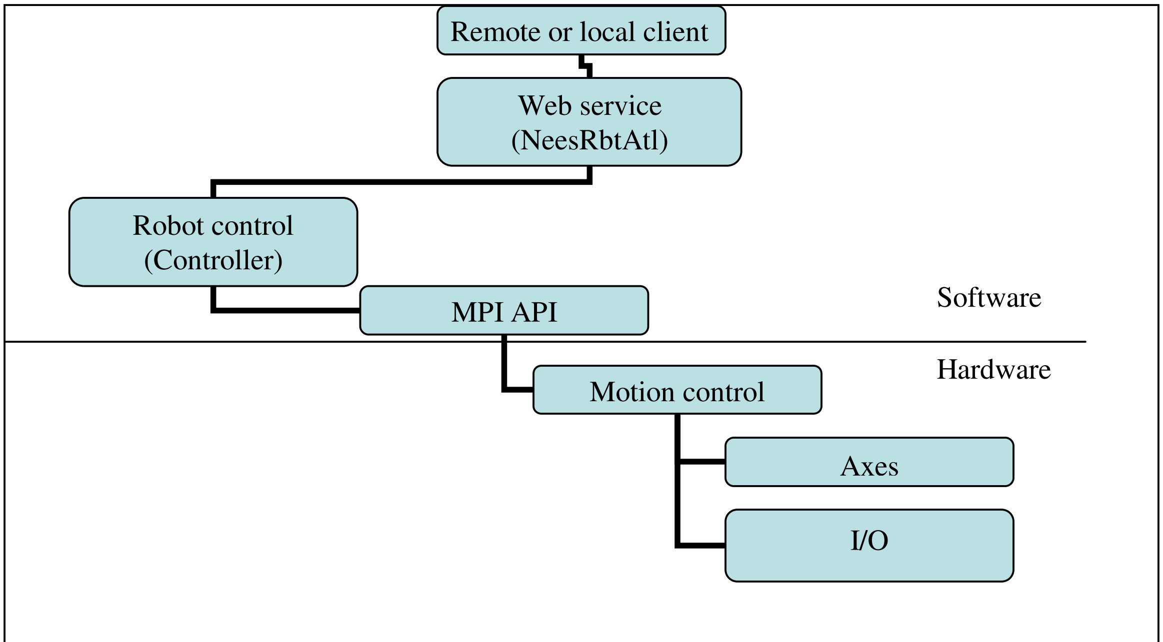


Fig. 7: Robot control software architecture

and motion controllers use proprietary languages rather than popular languages such as C or C++. Based on our experience, object-oriented and multithreaded programming is the key to reliable and feature-rich control software (Feng and Velinsky [17]). One of the main reasons for selecting the XMP motion controller is that MEI is the only one, as far as we know, to offer extensive C/C++ and object-oriented application programming interface (API). The comprehensive and very well documented Motion Programming Interface (MPI) allows control engineers and robotics scientists to create complex, multi-threaded applications in C or C++. From these API, we created a robot control C++ class, the "Controller", which handles all the robot control activities and can be easily used in all the other parts of the software that require robot access, such as the Web service described below. This architecture is described in Fig. 7.

Web services use standard Internet data formats and protocols for communication and, with it, it is straightforward to provide a Web service interface to existing code. A Web service acts as a remote procedure call, allowing one to call a function exposed by a remote Web server. The use of standard Web protocols avoids any computer or language dependencies; so the remote clients can access the service from client code written in anything from Java to C++. The robot control code is written in C++, while the NEESgrid remote clients will be written in Java.

NEESgrid has developed a control protocol called NTCP (NEES Teleoperation Control Protocol). NTCP provides a secure interface between the client application run by users and the site-specific plugin running on the control computer. In this case we are working on a Java client that goes through a NTCP server and then the Web service running on the robot control computer. The network architecture is shown in Fig. 8. For interested readers, the robot control Web service and its description are available at the following link: http://robota.ahmct.ucdavis.edu/NeesRobot/NeesRbtAtl.htm.

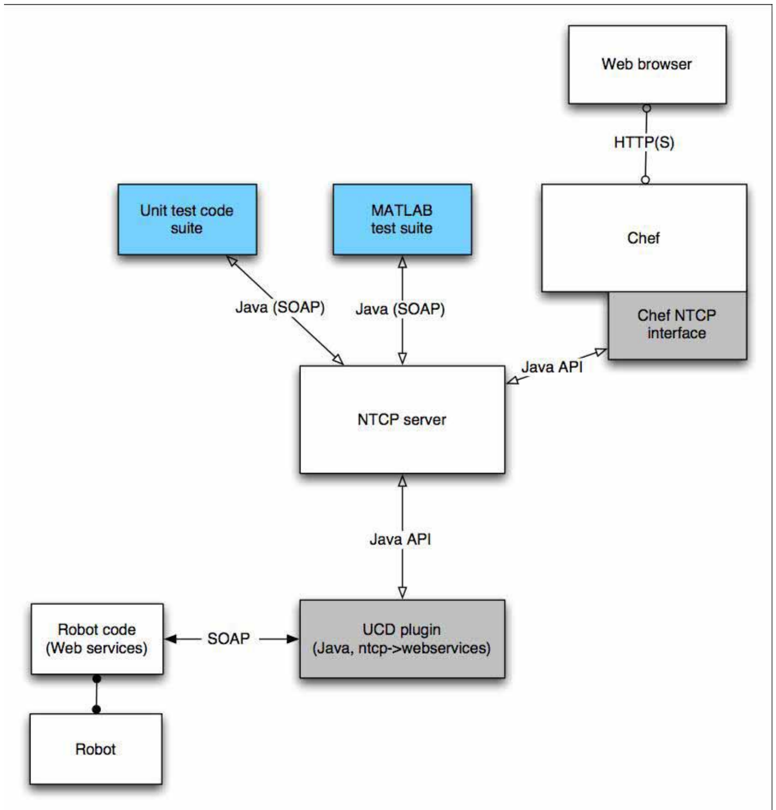


Fig. 8: Architecture for interfacing a Java-based client to the Linux-based robot control computer using the NEESgrid NTCP server. NTCP will ensure only qualified users can gain access to the robot control server. (Figure courtesy of Paul Hubbard from the NEESgrid team).

CONCLUSIONS

The NEES centrifuge at UC Davis, with its large size and versatile data acquisition network, provides a new opportunity to produce comprehensive data sets that enable description of model behavior as opposed to sparse sampling of data at selected points. Hundreds of sensors can be used at the NEES centrifuge to enable significantly improved resolution of the behavior and mechanisms that occur during shaking. Geophysical tools are being developed to enable researchers to measure internal deformations and strains. A robot is being constructed that will enable much improved simulation of stress paths due to construction and testing.

A large centrifuge model experiment using all of the resources described herein will be more than simply a “test”. With the advanced instrumentation and large size of the experiments, we believe that experiments will be viewed as “repeatable” case histories. Due to the large quantity of information to be captured from one model test sequence, we anticipate that new findings, theories, and design procedures can be improved and tested. We are taking the responsibility to train the profession to fully appreciate and to understand what may be learned from the large-scale centrifuge model tests. For example, to improve the understanding and increase the comprehension of the measured data, we are developing methods to rapidly visualize experimental data in new and intuitive ways.

The Center for Geotechnical Modeling facilities are intended for use by researchers from academia and industry, from both the US and abroad. The UC Davis NEES facility upgrades will soon be complete and the centrifuge at UC Davis will be operated as a national shared-use resource. We have an "all hands on deck" philosophy; one person cannot quickly operate a shaking table, all the sensors, tomography tools, as well as the sequence of events being tested. Future experiments will be performed by teams of researchers; with remote researchers able to control their experiments at UC Davis as easily as local researchers.

ACKNOWLEDGEMENTS

Development of the NEES Geotechnical Centrifuge at UC Davis is supported by the NSF Network for Earthquake Engineering Simulation Program award number CMS-0086566. The University of California at Davis and the Department of Civil and Environmental Engineering supported the construction of the Geotechnical Modeling Facility building. The Center for Geotechnical Modeling staff of Lars Pedersen, Stephanie Dempsey, Tom Kohnke, Tom Coker, Chad Justice, and Penny Walgenbach have been instrumental in upgrading the NEES centrifuge at UC Davis and in preparing material for this paper. Tom Slankard wrote much of the Shaker source code. Zhihua Li, Seokhyeon Choi, and Jong-Sub Lee played major roles in the development of geophysical testing tools for the centrifuge. Paul Hubbard and Charles Severance from the NEESgrid System Integrator team are working with the UC Davis team to implement the NEESgrid software at Davis.

REFERENCES

1. Kutter, B.L., Li, X.S., Sluis, W. and Cheney, J.A. Performance and Instrumentation of the Large Centrifuge at Davis. *Proceedings of the International Conference Centrifuge 1991*, pp. 19-26, Boulder, Colorado, June 13-14, 1991.
2. Kutter, B.L., Idriss, I.M., Khonke, T., Lakeland, J., Li, X.S., Sluis, W., Zeng, X., Tauscher, R.C., Goto, Y., and Kubodera, I. Design of a Large Earthquake Simulator at UC Davis. *Proceedings, International Conference, Centrifuge 94*, pp. 169-175, Singapore, August, 1994.
3. Wilson, D.W., Boulanger, R.W., Kutter, B.L. Seismic lateral resistance of liquefying sand, *J. Geotech. Geoenviron. Engr.*, ASCE, 126(10):898-906, 2000.
4. Brandenberg, S.J., Boulanger, R.W., Kutter, B.L., Wilson, D.W., and Chang, D. Load Transfer Between Pile Groups and Laterally Spreading Ground During Earthquakes. *Proc. 13th World Conference on Earthquake Engineering*, Vancouver, B.C., Canada, August, 2004.
5. Balakrishnan, A., Kutter, B.L., Settlement, sliding, and liquefaction remediation of layered soil. *J. Geotech. Geoenviron. Engr.*, 125(11):968-978, 1999.
6. Rosebrook, K., Wilson, D., Jeremic, B., Kutter, B., Smith, A., Humphrey, D., Patenaud, S. Centrifuge characterization and numerical modeling of the dynamic properties of tire shreds for use as bridge abutment backfill. *Proc. 4th International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*, San Diego, CA, 2001.
7. Malvick, E.J., Kulasingam, R., oulanger, R.W.,Kutter, L. Analysis of a void redistribution mechanism in liquefied soil, *Proc., 12th Pan American Conf. Soil Mechanics and Geotechnical Engineering*, Cambridge, MA. (Culligan, Einstein, Whittle, eds.), Verlag Gluckauf, Essen, Germany, pp. 955-961, 2003.
8. McCullough, N.J., Schlechter, S.M., Dickenson, S.E. Centrifuge modeling of pile-supported wharves for seismic hazards, *Proc. 4th International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*, San Diego, CA, 2001.
9. Nova-Roessig, L., Sitar, N. Centrifuge studies of the seismic response of reinforced soil slopes. *Geotechnical Earthquake Engineering and Soil Dynamics III.* Proc, Specialty Conference, Seattle, WA, (Dakoulas, P., Yegian, M., eds.), Geotechnical Special Publication No. 75, Reston, VA: ASCE and Geo-Institute, pp. 458-468, 1998.

10. Siddharthan, R.V., Ganeshwara, V., Kutter, B.L., El-Desouky, M., Whitman, R.V. Seismic deformation of bar mat mechanically stabilized earth walls. I: Centrifuge Tests, *J. Geotech. Geoenviron. Engr.*, 130(1):14-25, 2004.
11. Elgamal, A., Lai, T., Wilson, D., Kutter, B.L. Identification of small strain dynamic properties of dense sand. *Proc. 4th International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*, San Diego, CA, 2001.
12. Gajan, S., Phalen, J.D., Kutter, B.L., Hutchinson, T.C., Martin,G.R. Centrifuge modeling of nonlinear cyclic load-deformation behavior of shallow foundations, *Proc., 11th International Conference on Soil Dynamics & Earthquake Engineering, and 3rd Int. Conf. on Earthquake Geotechnical Engr.* Berkeley, CA, (Doolin, Kammerer, Nogami, Seed, Towhata, eds.), Stallion Press, pp. 742-749, 2004.
13. Stewart, D.P., Settgast, R.R., Kutter, B.L., Kawai, T., Higuchi, S., Ishikawa, H., Takeda, T. Experimental performance of a seawall model under seismic conditions. *Soils and Foundations*, 40(6):77-91, 2000.
14. Wilson, D.W., Kutter, B.L., Dense instrumentation arrays, *Proc. Int. Conf. on Physical Modelling in Geotechnics*, St. Johns, Canada, (Phillips, Guo, Popescu, eds.), Balkema, Lisse, Netherlands, 131-137, 2002
15. Weber, G.H., Schneider, M., Wilson, D.W., Hagan, H., Hamann, B., Kutter, B.L. Visualization of earthquake data. *Proc., Visualization and Data Analysis 2003*, (Erbacher, Chen, Roberts, Groehn, Boerner, eds.), SPIE, 5009:268-276, 2003.
16. Velinsky, S.A., Feng, X., Bennett, D.A. Operator controlled vehicle-based crack sealing machine, *Heavy Vehicle Systems*, 10(3):145-166, 2003.
17. Feng, X., Velinsky, S.A. Integrating embedded PC and internet technologies for real-time control and imaging, IEEE/ASME *Transactions on Mechatronics*, 7(1):52-60, 2002.