ABSTRACT: One of the most important challenges facing civil engineers is mitigating severe human and economic consequences of structural dynamic responses to various large-scale excitations and future civil engineers must have an understanding of the dynamic response of structures resulting from these excitations. The recent establishment of the NSF-sponsored Network for Earthquake Engineering Simulation (NEES) provides an excellent opportunity to frame hazard mitigation education in the tangible context of earthquake engineering. The cyberinfrastructure of NEES can provide teleoperation and teleparticipation of bench-scale instructional shake tables to help educate future civil engineers. This paper will discuss the establishment of a collaboratory of bench-scale instructional shake table deployment sites that provide for real-time online laboratory experiments leveraging the unique capabilities of the NEES initiative to offer laboratory experiences previously unavailable to undergraduate students. Here we will describe an initial laboratory exercise developed to educate students in the fundamentals of earthquake engineering as well as introducing them to emerging technology and multidisciplinary tools which promise to revolutionize civil engineering practice and education.

Keywords: Shake tables, Civil engineering education, NEES, UCIST

1 INTRODUCTION

Bench-scale shake tables are an engaging tool for educating students at all levels about fundamental concepts in structural response and earthquake engineering. These tools allow for classroom demonstrations and hands-on experimentation on physical structures using modern instrumentation. Demonstrations for K-12 students allow students to gain an understanding of earthquake motions and how structures can be designed or retrofitted to better withstand seismic motions. At more advanced levels, undergraduate and graduate students can conduct experiments to test their knowledge of fundamental concepts (Christenson et al. 2006). Students may also easily build or modify scaled models of structures to experiment with their own innovations, and may also gain experience with modern sensors. While theoretical and analytical discussions are necessary, hands-on experiments are quite effective for demonstrating basic concepts in structural dynamics and earthquake engineering, supplementing the more traditional methods of delivery.

The University Consortium of Instructional Shake Tables (UCIST) was developed by Prof. Shirley Dyke in 1998 to enhance undergraduate and graduate education in earthquake engineering (Dyke et al. 2002, 2003). This consortium, headquartered at Washington University in St. Louis, was initially a cooperative educational effort between 23 universities associated with the three U.S. national earthquake centers (the Pacific Earthquake Engineering Research Center (PEER), the Multidisciplinary Center for Earthquake Engineering Research (MCEER), and the Mid-America Earthquake Center (MAE)), and has expanded to over 100 institutions around the world. UCIST has endeavored to enhance the education of undergraduates through the procurement of instructional bench-scale shake tables, the development of curricula, and the dissemination of these tools to other institutions. Additionally, outreach activities targeting K-12 students and the general public are encouraged, and undergraduate research opportunities are available.

UCIST has recently partnered with the George E. Brown Network for Earthquake Engineering Simulation (NEES, see Figure 1), a premier cyberenvironment project funded by the NSF. The recent establishment of NEES provides an excellent opportunity to increase the number of students that can be im-
pacted by UCIST educational exercises, and to de-
velop a collaboratory in earthquake engineering edu-
cation. The *NEES Education, Outreach and Train-
ing (EOT) Strategic Plan* was developed in parallel
with establishment of NEESinc, the equipment sites
and the cyberinfrastructure (Grant CMS-0337808).
The plan calls for the development of a Coordination
Framework for all of the EOT activities related to
NEES, encompassing activities at the sites, by the
PIs of research projects, by NEES EOT staff and by
external PIs who have a particular interest in earth-
quake engineering or cyberinfrastructure education
initiatives (Dyke et al. 2006). An Execution Plan, in-
tended to accompany the Strategic Plan, will provide
a detailed roadmap to the NEES community for
helping them to achieve the goals of the NEES EOT
Program. Additionally, a Diversity Strategic Plan
has been developed and is available on the website.
The broad group of users of the NEES collaboratory
and EOT efforts will include all of the following
identified constituents:
• precollege education (teachers and students)
• undergraduate education (faculty and students)
• graduate education (faculty and students)
• researchers & remote NEES collaboratory users
• practitioners and decision makers
• lab staff supporting NEES experiments
• the public-at-large

Our vision is to develop an international collabora-
tory of bench-scale earthquake engineering facili-
ties that will engage a broad range of students by
creating a series of shared laboratory exercises avail-
able for remote operation via the internet. This edu-
cational collaboratory will leverage the cyberinfra-
structure, coordination capabilities and educational
goals of the NSF-sponsored NEES initiative. Exist-

ing state-of-the-art cyberinfrastructure tools devel-
oped by NEESit (NEES Information Technology,
it.nees.org), the technical support and development
component of NEES, for NEES research activities
will be utilized. Tools have been developed recently
for the remote control (teleoperation) and the view-
ing and analysis of streaming data and video
(teleparticipation) for the instructional shake tables
over the internet. These capabilities have been in-
corporated into formal laboratory exercises, and in
the fall of 2007 we will be deploying these exercises
to several universities within the US. Over the next
couple years, several new exercises using these ca-
pabilities will also be developed. Information on
how to join this collaboratory is available at the end
of this paper.

2 LABORATORY STATION COMPONENTS

The equipment used for these instructional mate-
rials consists of a Shaker IV system from Quanser
Consulting (www.quanser.com). The bench-scale
seismic simulator has a 46x46 cm slip-table driven
by a ball-screw mechanism with an operating fre-
quency of 0-20Hz, a +/-7.6cm stroke and a peak ac-
celeration +/-1g with an 11.3kg payload. The Shaker
IV interfaces with a PC through the Quanser Q8
board and is controlled using WinCon real-time
software. This shake table is a powerful tool for high
fidelity and controllable reproduction of seismic mo-
tions. Accelerometers are available for measuring
the responses of the structure and recording the
measurements. Data can also be streamed in real
time to remote users for plotting and analysis. This
equipment is ideal for educational uses, and has also
been used widely for K-12 outreach, demonstrations,
and small scale research projects. A prior NSF-
funded cooperative project to establish these shake
tables at universities across the country facilitated
the dissemination of the proposed project to univer-
sities nationwide.

NEES cyberinfrastructure tools now make it pos-
sible for earthquake engineering researchers to re-
motely participate and control experiments, facilitat-
ing new testing methods such as distributed hybrid
testing where various components of a single struc-
tural system are tested at geographically distributed
sites. Video and data can be transferred in real time
to laboratories and users around the country for
analysis and simulation. These teleparticipation ca-
pabilities are being employed here for educational uses by UCIST through the development of a series of new educational exercises. These exercises will allow a broader set of students and institutions access to use the shake tables for education and training, and will facilitate national dissemination of real-time online laboratory experiments to offer state-of-the-art laboratory experiences previously unavailable to undergraduate students.

Teleoperation, remotely controlling the UCIST shake table using the NEES cyberinfrastructure, was first accomplished by Prof. Richard Christenson in December 2004. More recently, an expansion of this effort has been undertaken involving teleparticipation by adding functionality to stream data and video through existing NEES cyberinfrastructure tools. The UCIST PC is configured as a server to receive commands. Commands to the shake table originate by the remote user through the graphical user interface running at the client (remote) end. The NEES Real-time Data Viewer (RDV) is then used to view the time synchronized streaming video and data from any PC over the internet. The bench-scale instructional shake table deployment site at University of Connecticut is shown in Figure 2.

There are several components that allow for teleoperation and teleparticipation, which are illustrated in the flow chart in Figure 3. In this configuration a Remote PC, any PC with internet access, uses a teleoperation java applet as an NTCP Client. NTCP is the NEESGrid Teleoperations Control Protocol where the NTCP Client is the front end client that provides teleoperation commands. Telepresence is achieved through the Real-time Data Viewer (RDV). The RDV is a NEES tool that allows for viewing of synchronized streaming data and video.

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The Ring Buffered Network Bus (RBNB) program, running on a Data Turbine PC, buffers and streams data and video to the RDV. The PC has three main functions: control of the UCIST shake table through the WinCon real-time software; receiving NTCP commands, through the NTCP Server, for teleoperation; and streaming data to RBNB, through the WebDaemon program, for teleparticipation. An Axis 2130 pan-tile-zoom web camera provides streaming video to the RBNB. A view of the portal seen by a remote user while streaming data and video from the RBNB using the NEES Real-time Data Viewer (RDV), shown in Figure 4. A Java applet serves as the NTCP Client graphical user interface (GUI). This GUI is shown in Figure 5, providing remote users a friendly means to control the experiment by adjusting the frequency and amplitude of the sinusoidal excitation and pressing start.
Detailed instructions on how to set up the RBNB server on a Windows-based PC, and how to enable teleparticipation and teleoperation of the UCIST shake table are available at:
http://cive.seas.wustl.edu/wusceel/ucist/.

3 INSTRUCTIONAL MATERIALS

Several early experiments that use this shake table lab station are available on the UCIST website for downloading and implementation. Experiments consider structural dynamics, soil-structure interaction, bridge design, torsional responses of structures, etc. The website contains laboratory manuals for instructors and students, drawings for building experimental components, and sample data. These experiments have been used at institutions across the US to educate undergraduate and graduate students in earthquake engineering topics. Users who may be interested in posting new experiments to share with the earthquake engineering community are welcome to contact the authors.

More recently a K-12 teaching module has been developed as part of a NSF-funded GK12 site at Washington University. Furthermore, to date, one formal NEES-based telepresence experiment has been conducted in a classroom setting. A freshman level experiment has been developed to introduce earthquake engineering concepts through teleparticipation experiments utilizing the bench-scale shake table.

All of these activities are summarized below, followed by a description of the future activities of the UCIST.

3.1 Overview of K-12 Materials Available

In addition, an Earthquake Engineering Module for K-12 Education has been developed around the use of this shake table lab station. The module contains a series of lessons that have been developed and refined over the course of several years (Truman et al. 2006). In principle, any of the ‘modules’ could be used as a stand alone, one-time lesson to supplement one specific academic area such as forces and vectors or building fundamentals. Alternatively, the full module could be used as a continuous series of lessons over an 8-10 week period. Supplemental worksheets, learning activities and presentations are included to provide opportunities for active learning. The final lesson involves a design project incorporating all of the materials learned within the module. Teams of students design and construct a balsa wood building. A scorecard is provided for students to encourage them to be creative and yet understand practical issues associated with construction and design. Ideally this module, presented as a whole or individually, will satisfy some of the educational requirements and standards of the K-12 classroom in which it is offered.

3.2 Teleparticipation and Teleoperation at the Freshman Level

The module consists of a series of 8 lectures. Students are introduced to structural engineering topics, mathematical modeling of dynamic behavior, MATLAB simulation tools, and NEES capabilities and research through a series of lectures. Then the students use the teleparticipation tools to conduct an experiment using the shake table. A one-story (single-degree-of-freedom) structure with light inherent damping is used (as shown previously in Fig. 2 and 4). A linear voltage differential transducer (LVDT) is used to capture structural response data for a sinusoidal excitation. Video and data are observed and downloaded through RDV for analysis and comparisons to mathematical models. The students are introduced to structural engineering and vibration concepts as they are asked to model the structure and analytically determine the natural frequency and response at various sinusoidal excitations, through a series of three homework assignments. The module culminates with the students conducting experimental tests online to observe the structure’s actual natural frequency and response to various sinusoidal excitations. The students prepare a laboratory report documenting their efforts during the module. This
experiment has been implemented at the University of Connecticut and Washington University. Evaluation of the tools is now underway, and the tools will be disseminated on the UCIST and NEES websites in the Fall of 2007.

3.3 Evaluation Procedures and Outcomes

The evaluation plan for this exercise considered multiple approaches. For the first experiments at the University of Connecticut and Washington University, students completed an online survey at the end of each module. Faculty used the web-based Student Assessment of Learning Gains (http://www.wcer.wisc.edu/salgains/instructor/); this survey instrument was designed by Elaine Seymour, author of Talking about Leaving: Why Undergraduates Leave the Sciences, and is available to all faculty through multiple NSF funded projects and the ExxonMobil Foundation. Eighty-three students from the two institutions have responded; fourteen were female.

Preliminary results indicate that peers are important to student learning and that the shake table experiments are “amazing;” the experiments help them “see the way a structure physically, as opposed to analytically, moved and reacted to vibrations.” Across both institutions and three implementations of the initial module, students ranked working with peers outside class the most important support they had as a learner. When asked about what they liked about the shake table learning experience, students wrote:

- I liked how we actually ran a real experiment and were able to run it from our dorm rooms even though the shake table was someplace else, and actually view it through live streaming video.
- [It] Was very hands on, and many people learn better by doing and seeing than just calculations.
- It was a very interesting experience. The fact that you could manipulate a structure in another building across campus from you room is amazing.
- You go to see live footage of what was actually happening to the structure under vibrations of differing magnitudes and see how your frequency matched up to the real structure

When asked what improvements they would suggest, students wanted more control of the table plus more time and more explanations. They commented:

- Give the students a chance to control the table to find the frequency that produces resonance, rather than just showing pre-formulated simulation.
- More time and more thorough explanation of what we were actually doing. We were thrown head first into the deep end with no help aside from our peers.

On-going formative evaluation will ensure that the project effectively achieves its goals in a timely way. Using outcome measures, the ongoing assessment of the project’s progress will enable the project leaders to make midcourse corrections and improvements. As part of a continuous improvement management model, faculty will use the data to improve the modules for students on the initial two campuses as well as at the other network institutions that will implement the modules in fall, 2007.

3.4 Next Steps in Developing and Deploying Experiments

To deploy the shake tables to other sites within the project, documents have been prepared for distribution and feedback to lead the remote deployment sites through the setup process. Subsequently the updated documents will be posted to the website http://cive.seas.wustl.edu/wusceel/ucist/ and made available through the NEES central site for this project. By the end of the summer of 2007 we anticipate all sites being operational. The Freshman level module will be implemented at most of these deployment sites in the 2007-2008 academic year.

Additionally, this summer we will be developing a second teleoperation experiment for senior level undergraduates is in development and will be made implemented on a trial basis in the fall of 2007 and subsequently disseminated through the website. Furthermore, an undergraduate structural design competition will be implemented with the instructional shake tables to engage students in learning more about earthquake engineering and introduce them to the broader earthquake engineering community. Activities such as the well-recognized Steel Bridge and Concrete Canoe competitions by ASCE have long-proven that these types of team-building exercises promote technical interaction and excitement in civil engineering among undergraduates, while stimulating life-long learning in those students that participate in the events. In this spirit, the networked shake tables provide a unique opportunity to engage civil engineering undergraduates by providing students a challenge to innovatively design model structures to withstand strong ground motions.
4 SUMMARY

Bench-scale shake table lab stations provide a flexible tool on which to base educational exercises for students at all levels. Hands-on experiments and demonstrations provide tangible evidence of the dynamic behavior of structures to improve student understanding and awareness. Training in the use of sensors is also an essential component of such exercises, engaging individuals in the use of modern engineering tools. NEES cyberinfrastructure tools, originally developed for advancing research efforts, are being adopted for developing educational tools. Through a partnership with NEES, the UCIST is extending its reach to impact students across the US, and potentially around the world.

Further information about the UCIST, as well as Educational Modules, Lab Exercises, Teleparticipation and Teleoperation Tools, and all documentation for these activities will be made available at: http://cive.seas.wustl.edu/wusceel/ucist/. For more details on how to participate in or partner with this educational collaboratory please contact Prof. Shirley Dyke at sdyke@seas.wustl.edu.

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6 REFERENCES


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