Teleoperation Tools for Bench-scale Shake Tables for Instruction in Earthquake Engineering

Shirley Dyke¹, Richard Christenson², Zhaoshuo Jiang,² Xiuyu Gao¹ and Zach Feinstein¹

¹Washington University in St. Louis, St. Louis, Missouri, 63130 USA
²University of Connecticut, Storrs, CT 06269 USA

Bench-scale shake tables are an engaging tool for educating students at all levels about the importance of earthquake engineering. Shake tables allow for classroom demonstrations and hands-on experimentation regarding how structures respond to earthquake ground motions. 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. 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 (see: http://ucist.cive.wustl.edu/). 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 plentiful.

UCIST has recently partnered with the George E. Brown Network for Earthquake Engineering Simulation (NEES), 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 impacted by UCIST educational exercises, and to develop a collaboratory in earthquake engineering education. In partnership with the NEES Consortium, Inc. (NEESInc) we will leverage the geographically-distributed network of world-class experimental facilities, its connecting cyberinfrastructure, and its extended community of engineering and cross-disciplinary faculty from academic programs across the nation to provide undergraduates with exceptional learning opportunities. We plan to employ the extensive array of cyberinfrastructure tools developed for NEES research to enhance the learning process at the undergraduate level. Most of these tools are opensource and are being continually updated and improved.
Our vision is to develop a national collaboratory of bench-scale earthquake engineering facilities that will engage a broad range of students by creating a series of shared laboratory exercises available for remote operation via the internet. This educational collaboratory will leverage the cyberinfrastructure, coordination capabilities and educational goals of the NSF-sponsored NEES initiative. Existing state-of-the-art cyberinfrastructure tools developed by NEESit (NEES Information Technology, it.nees.org), the technical support and development component of NEES, for NEES research activities will be utilized for tele-operation, tele-participation. Tools have been developed recently for the remote control (tele-operation) and the viewing and analysis of streaming data and video (tele-participation) for the instructional shake tables over the internet. These capabilities have been incorporated 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 capabilities will also be developed. Information on how to join this collaboratory is available at the end of this article.

**Instructional Materials Developed**

The equipment used for these instructional materials 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 frequency of 0-20Hz, a +/-7.6cm stroke and a peak acceleration +/-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 motions. 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 (available for $10,000-$25,000 depending on the components needed) 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 universities nationwide.

Several 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.

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. 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.

**Teleoperation Capabilities and Current Directions**

NEES cyberinfrastructure tools make it possible for earthquake engineering researchers to conduct hybrid experiments, involving distributed testing various components of a single structural system. Video and data can be transferred in real time to laboratories and users around the country for analysis and simulation. These teleparticipation capabilities are being employed here for educational uses by UCIST as well for 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.

Tele-operation, 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 cyberinfrastructure tools. The Shaker IV control PC (connected to the shake table) is configured as a server to receive commands. Commands to the shake table originate by the user though 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. Figure 2 is a snapshot of the streaming video and data from the STII shake table displayed through RDV. Instructions for configuring and implementing these tools will be available on the UCIST website by the fall of 2007.

To date, one formal 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. 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

![Fig. 2 Tele-presence tool (RDV).](image-url)
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 (see Fig. 3). An accelerometer 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 module culminates with the preparation of a laboratory report. 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.

![Fig. 3 Student (Zach Feinstein) running experiment using single story structure.](image)

A second teleoperation experiment for senior level undergraduates is in development and will be made implemented 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.

**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.

Acknowledgements
Partial support for this project is provided by the National Science Foundation, DUE 0618605. Support for development of the UCIST was provided by the NSF, DUE 9950340. Undergraduate research assistants involved in the development of these activities have been supported in part by the National Science Foundation Research Experiences for Undergraduates Program at Washington University (NSF Grant No. EEC–9820506). All of this support is gratefully acknowledged. Funding for the development of the Earthquake Engineering Module for K-12 Education has been provided in part by the NSF under Grant Nos. DGE-0138624, DGE-0538541 and CMS-0530737. Special thanks is also given to the teachers in the St. Louis area that have contributed.