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UNIVERSITY CONSORTIUM OF INSTRUCTIONAL SHAKE TABLES: ENHANCING EDUCATION IN EARTHQUAKE ENGINEERING

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Abstract

This paper focuses on the development, implementation, and impact of a unique cooperative educational effort including over fifty universities in the US and abroad. The University Consortium on Instructional Shake Tables (UCIST) was developed in 1999 to foster collaborative teaching and learning at the university level. This consortium, headquartered at Washington University in St. Louis, originally consisting of 23 universities associated with the three US national earthquake centers, has expanded to more than two times its original size. UCIST has endeavored to enhance the education of civil engineering undergraduates through the procurement of instructional shake tables and the development of curricula to be used at the undergraduate level and shared among member institutions. Additionally, outreach activities and undergraduate research opportunities are encouraged.

1. Introduction

One of the most important challenges facing civil engineers of today is the mitigation of the human and economic consequences of severe dynamic loads (*i.e.*, earthquakes, hurricanes, blasts). Civil engineers must have an understanding of the dynamic response of structures such as buildings, bridges, towers and dams to ground motion created by natural disasters such as earthquakes, as well as man made disasters such as blast loads. Considering this dynamic behavior, and the implications of this behavior, is of fundamental importance in modern structural design worldwide. However, too few engineering students are exposed to structural dynamics at the undergraduate level. Furthermore, the tragic events of September 11, 2001, have heightened our consciousness, nationally and internationally, of the need for careful consideration of such issues for our infrastructure. There is a need to integrate this important topic into the undergraduate civil engineering curriculum.

Experiments are quite effective for demonstrating basic concepts in structural dynamics and earthquake engineering.[1] Earthquake simulator tables, or shake tables, are traditionally used for experimental research in earthquake engineering. These instruments are capable of reproducing the motion of the ground during an earthquake, or simulating other acceleration records of interest, allowing for controlled testing of structures subjected to earthquakes. New concepts and techniques are often tested on scaled structures using shake tables before imple-

mentation on actual structures. Shake tables have been used at several universities for educating students about earthquake engineering and structural dynamics. However, only a handful of universities have shake tables, and due to testing schedules only a few of these universtities have the freedom to provide students with access to these instruments. Moreover, "hands-on" experiments are not feasible due to the size of the equipment and the specialized training required to operate such systems safely.

Bench-scale shake tables are an ideal alternative to provide students access to such "hands-on" experiments. At this scale, students can observe the dynamic behavior of structures and vary structural designs to perform experimental evaluations. Further, bench-scale tables are mobile enough to bring into the classroom or even to local grade schools for demonstrations. This concept was the basis of the formation of UCIST, and continues to be the motivation for its expansion.[2–4] Students at UCIST member institutions are able to engage in testing of structural responses, develop familiarity with testing procedures and equipment, gain an understanding of the consequences of seismic inputs on structures, and evaluate innovative concepts in seismic resistant design.

UCIST serves as a national, and international, model for integrating structural dynamics and earthquake engineering into the undergraduate curriculum, a recognized need within civil engineering. Additionally, this program may be an attractive model for other engineering disciplines interested in sharing resources and expertise for the mutual benefit of their students. The website (*http://ucist.cive.wustl.edu/*), which provides information on the program and is also a repository for the tools and exercises developed, is averaging approximately 10,000 hits per month, an exciting amount of activity. New members are always welcome and the program has experienced a 116% increase in membership in only two years. There are now 52 UCIST member universities in the United States, Italy, China, Japan, England, Canada, Israel and Portugal. Membership in UCIST requires new member institutions obtain an instructional shake table, use at least one experiment from the web page, and submit surveys online when they are requested. All members are encouraged to submit newly developed projects to the web page.

This paper will focus on the development, implementation, and impact of this cooperative educational effort that is based on the widespread sharing of resources to impact the civil engineering curriculum. The basic strategy behind the program described herein is to work collaboratively to achieve the project objectives, resulting in a well-rounded series of experiments that are geared for students at all levels. The paper will discuss the equipment selected for this program, the exercises developed and distributed through the web site, the educational tools developed within the program, and the impact of the program as measured through surveys and statistical measures. Additionally, we will provide information on outreach activities and undergraduate research opportunities that have been facilitated through the development of UCIST and the acquisition of the associated equipment.

2. Experimental Equipment

Exercises are based on a bench-scale shake table. To ensure that the shake table would be flexible for several experimental scenarios, a task force was formed to develop design specifications. Specifications for the shake table include a peak acceleration of 1g with a 25lb payload,

as well as a bandwidth of 20 Hz, a peak velocity of 20 in/sec, and a stroke of 6 in. Specifications also required that the shake table require little maintenance, be computer-controlled with a simple interface, be portable for off-site demonstrations, be "student–proof" to prevent injury or damage, and be reasonably priced. Further, the goal was to obtain an instrument that can be easily assembled and requires minimal start-up time before experimentation can begin.

Three vendors participated in developing prototype units and bidding on the project. The task force selected a bench scale shaking table produced by Quanser Consulting, Inc. This instrument, shown in Figure 1 has a 18"x18" plate, which slides on high precision linear bearings and is driven by a Kollmorgan Silverline Model H-344-H-0600 motor fitted with a 1000 LPR IP 40 encoder. The earthquake simulator uses unit gain displacement feedback, and control is achieved using a MultiQ board, a general purpose data acquisition and control board. The system is controlled by a Pentium computer using Wincon software. The lab station comes with several historical earthquake records. In addition to the shake table, the laboratory package purchased includes a two-story test structure and three accelerometers to measure the excitation and system responses. The package also includes a stand-alone function generator for off-site demonstrations. Thus, the complete package allows students to reproduce earthquakes, observe structural behavior, measure structural responses, and utilize sensors and modern computer control systems.

Additionally, several institutions opted to acquire an active mass driver (AMD), a moving mass that is driven horizontally at the top of the structure to reduce structural vibrations. This equipments allows educators to introduce the concept of active controllers for buildings. A typical project on this research that can be performed with the UCIST equipment has been proposed by Battaini *et al*.[5]

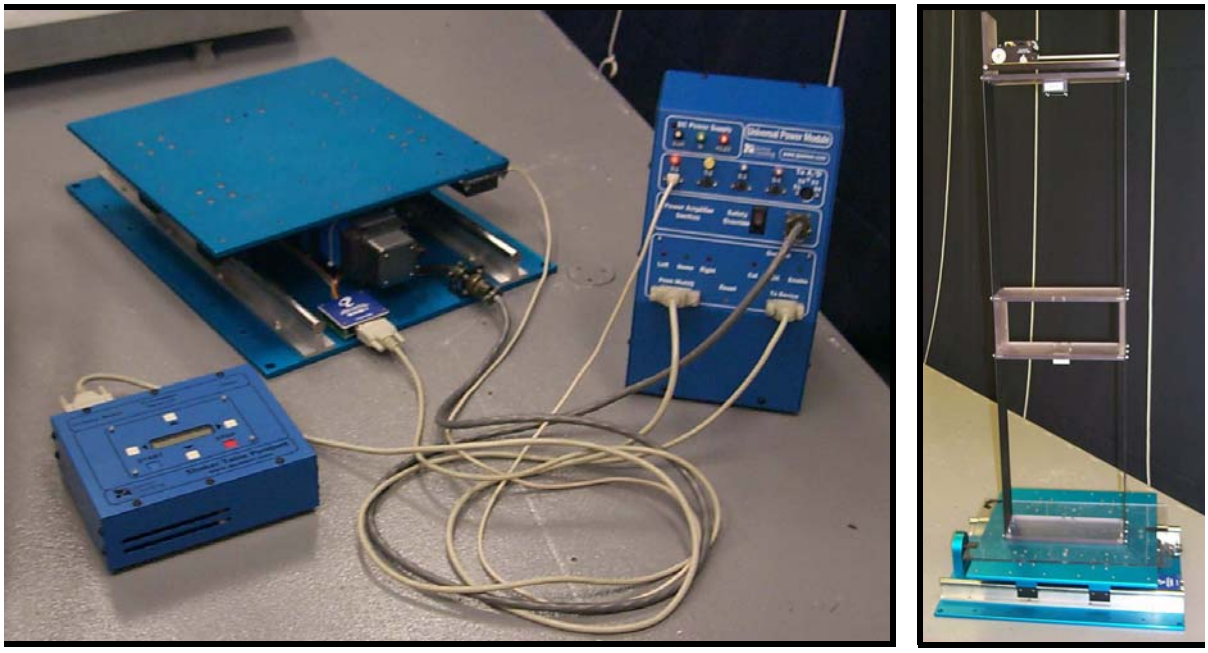

Figure 1. Instructional Shake Table Lab Station.

3. Outcomes and Products

The overall goal of the UCIST program is to instruct students in concepts in structural dynamics, earthquake resistant design, geotechnical engineering, and more generally, in topics related to earthquake engineering. This goal is being achieved primarily through the introduction of experiments in earthquake engineering throughout the civil engineering undergraduate curriculum. The experiments focus on the use of "hands-on" seismic simulation experiments which offer students opportunities to operate the shake table, excite scaled models of various civil engineering structures (e.g., buildings, bridges, towers, etc.) with typical earthquake loads, learn basic concepts in structural dynamics, and utilize sensors to measure responses of the structures. Experiments are being developed for students at all levels – from freshman level introductory courses through senior/graduate level courses. The specific objectives of these activities are: i) to develop an understanding and an intuition regarding the dynamic nature of structures; ii) to reinforce theoretical concepts through the use of "hands-on" laboratory experiments; iii) to provide experience in the use of modern engineering tools including sensors, actuators, and data acquisition/analysis equipment; iv) to provide non-engineering students with exposure to the potential consequences of earthquakes and the dynamic behavior of civil engineering structures; v) to provide exposure to emerging technologies and modern methods in seismic resistant design; and vi) to improve technical communication abilities through written reports and oral presentations. Each of the original 23 member institutions has implemented at least three of the exercisees developed within their curriculum. Additional activities include plans for developing nationwide competitions in earthquake resistant design as well as research opportunities for undergraduate and graduate students. Furthermore, experiments are being developed for non-engineering students that will benefit from such exposure (e.g. architects, geo-scientists, risk-managers).

Several tutorials and sample experiments have been developed to help familiarize users with the capabilities and operation of the equipment. Additionally, many of the individual experiments have been completed and submitted to the web site. These are available for downloading to interested parties, and are discussed in the following sections.

3.1 Learning Tools and Resources

To accelerate the learning curve associated with using this equipment, several projects and manuals were developed to provide guidance for conducting the experiments that were produced and to allow the user to extend their knowledge of the functions and capabilities of the shake table. Since this type of equipment is new to many of the member institutions, the implementation of the equipment by faculty, graduates, and undergraduates has been greatly accelerated by the sharing of these outcomes.

Table 1 provides a summary of the learning tools and manuals that have been developed within UCIST. All of these are available for downloading on the web site. The first item listed is an experiment intended for undergraduate use, and is the most widely used of the experiments developed at this time. This experiment fully utilizes the capabilities of the shake table, and was developed at Washington University, in part, to serve as an example for other investigators. The second item listed is a sample outreach activity developed at the University of Notre Dame. This experiment has been successfully implemented in several K-12 classrooms (see: *http://www.nd.edu/~eeriund/ucist.html*). The next items are manuals that describe the

proper procedure for running the shake table and for developing customized programs to operate the shake table through Simulink and Wincon. Finally, the interactive manual is provided to describe the steps required to properly set up the table, and introduce the user to the shake table operation with the pendant controller.

Table 1. Samples and tutorials developed for UCIST.

Title of Project	Attributes	Project Summary
Sample Experiments and Projects		
Introduction to Dynamics of Structures **Institution:** Washington University	**Authors:** Juan Caicedo[a], Sinique Betancourt[a], & Shirley Dyke	The purpose of this experiment is to introduce students to principles in structural dynamics. Natural frequencies, mode shapes and damping ratios for a small scale structure will be obtained experimentally through a series of tests. Students will use a Matlab GUI program to obtain experimental data of the structure and analyze the data.
K-12 Outreach Activities in Earthquake Engineering **Institution:** University of Notre Dame	**Authors:** Bill Spencer	K-12 students will investigate the seismic behavior of buildings to better understand the way in which civil engineering structures respond to earthquakes. The students will design and construct model buildings for testing during class visits. K'Nex and Lego buildings are used.
Relevant Supporting Documents and Media		
Shake Table Interactive Manual	**Author:** Keenan Bull[b]	This manual was created as a tool to learn to operate the shake table. It is an interactive, web based manual that guides the reader through table setup and operation.
Guide to Creating Simulink Models for the UCIST Table	**Author:** Scott Johnson[b]	This is a manual that was created as a tool for creating Simulink models to use on the shake table. It contains basic procedures for composing and building Simulink models.
Kobe Earthquake Video & Sine Function Video Demonstrations	**Authors:** Tyler Ranf[b] & Euridice Oware[b]	These videos provide demonstrations of the shake table in operation.
Virtual Structural Dynamics Lab	**Authors:** Manolo Soto-Fournier[b] & Juan Caicedo[a]	This is a web-based program that serves as a tutorial on experimental methods, data acquisition, and sensors for typical dynamic testing.
Implementation of Transfer Function Iteration Program	**Author:** Tyler Ranf [b]	This program runs the transfer function iteration algorithm to reproduce historical earthquakes. This program is based on one by Yang & Spencer[7], and revised by Nepote, *et al*[6].

a. Graduate Research Assistant at time work was performed.
b. Undergraduate Research Assistant at time work was performed.

The Virtual Structural Dynamics Laboratory (VSDL) was developed as a stand-alone tool to give students an opportunity to learn about experimental procedures and phenomena in dynamic testing. However, this tool can also be used in conjunction with shake table experiments. Users are able to vary several parameters of a multi-story building model and visualize the behavior. User-defined variables (such as type of sensors, number of floors, floor properties, input gains, *etc*) are varied to allow users to investigate phenomena such as aliasing in data acquisition, the need for appropriate sensor selection, quantization errors. The VSDL

(a) Main page **(b) Mode shape page**

Figure 2. Virtual structural dynamics lab – interactive web-based instructional tool.

uses a Macromedia Shockwave interface coupled with MATLAB to offer an engaging, interactive tutorial based on experiments that could be performed with the instructional shake table. The main interface page, as well as the page displaying the mode shapes is shown in Fig. 2.

The transfer function iteration utility is the most recent tool, facilitating the accurate reproduction of scaled earthquakes, or other time history records, with the instructional shake table. This program is implemented in MATLAB and adapted for the instructional shake table from previous versions of the code.[6,7] Details on the algorithm and its implementation on actual shake tables can be found in these references.

3.2 Exercises and Experiments

Many experiments for have been developed by the original 23 members of the consortium. These exercises can be downloaded from the UCIST web site and used with the equipment. Each exercises has a student manual and instructor manual, drawings (when necessary), visual aids or videos when appropriate, and typical data/observations. A complete list is provided in table 2. Note that these projects span a wide range of disciplines within earthquake engineering, including structural, geotech, and social science. Newly developed projects are being posted on the UCIST web site as they are developed.

Table 2. Projects Currently Available on the Web Site.

Title & Attributes	Project Summary
Demonstration of Non-Structural Seismic Hazards in the Home **Institution:** University of Nevada, Las Vegas	A cutaway and see-through model of a home was created for the shake table to demonstrate non-structural seismic hazards. The demonstration will be set up so that heavy objects fall from high shelves, bookcases tip over, pictures fall off walls, and a water heater topples. The purpose of the demonstration is to educate the general public about nonstructural hazards and some simple things they can do to make their homes safer during an earthquake.
Liquefaction Demo **Institution:** Southern Illinois University, Edwardsville	This experiment demonstrates to a wide audience the effects of soil liquefaction on structures. The experiment is designed to be inexpensive and portable to allow easy transportation for demonstrations at schools and museums.
K-12 Outreach Activities in Earthquake Engineering **Institution:** University of Notre Dame	Students will investigate the seismic behavior of buildings made from masonry and steel to better understand the way in which civil engineering structures respond to severe earthquakes. The students will design and construct model buildings that will be tested on the bench-scale shaking tables during class visits. Both K'Nex and Lego building systems will be provided.
Tuning of a Vibration Absorber on UCIST Shake Table **Institution:** University of California, San Diego	Vibration absorbers are relatively small mass-spring systems that are calibrated to be in resonance with the structure on which they are installed. These systems, usually installed on the roof of buildings, have been proven effective to reduce wind-induced vibrations in high-rise buildings, floor vibrations induced by occupant activity, and the seismic response of buildings. The purpose of this project is to demonstrate the effectiveness of vibrations absorbers in reducing the seismic response of structures.
Determination of Natural Frequencies & Mode Shapes of Multi-Degree of Freedom Structures **Institution:** Florida A&M	The effect of control devices will be demonstrated on a two story structure. The students will calculate the natural frequency of the structure and design and construct a suitable passive tuned mass damper. The results from this passive system will be compared to the uncontrolled building model and a building model with an active mass driver. The demonstrations will benefit the First Year Engineering course and the Civil Engineering Mechanics course, or to complement instruction in the advanced senior and graduate level Structural Dynamics course.
Earthquake-Resistant Bridge Competition for Introductory Engineering Students **Institution:** San Jose State University	This project is intended for entry level engineering students at either the freshman or sophomore level. Student teams design a small truss bridge from balsa wood and the competition is based upon the ability to support a given gravity load while exposed to a transverse lateral motion generated by the shake table. The winning bridge is the entry that supports the highest mass while being shaken by the most severe earthquake motion.
Small Shake Table Experiments and Comparison to Analytical Predictions **Institution:** Oregon State University	This project describes the necessary steps to run an earthquake simulation on the UCIST Shake Table and to create the corresponding SAP 2000 model. The manual starts with some basic information about the UCIST equipment and explains how to build a 3D model. It goes on to explain how to determine properties of the 3D model, including stiffness and damping. The manual ends with the steps for developing the SAP 2000 model.
Experimental Identification of Dynamic Properties of Small-Scale Model Frames **Institution:** Penn State University	Researchers have designed an experiment to be conducted on the instructional shaking table to introduce some basic concepts of seismic response of structures. Using the shake table, students can observe how the dynamic response of a simple portal frame changes by doubling the mass and by doubling the stiffness. Students will have the opportunity to compare calculated periods with actual measured periods. Moreover, the experiment allows students to realize how the stiffness of a frame is dependent on the assumption for boundary conditions of the members and how close these assumption are relative to the actual stiffness of a built model.

4. Nationwide Impact of the Project

4.1 Impact on Undergraduate Education and Research

To assess the impact of the program, all member institutions were asked to complete a survey on their experiences with the exercises and the equipment. Surveys were completed by course instructors using the equipment as well as by students enrolled in those courses. The surveys were made available online, and password access was provided to members. Thousands of undergraduate students, graduate students, and K-12 students have been exposed to concepts in structural dynamics through the development of UCIST and the associated exercises and learning tools. A public survey was also provided on the web site to collect information about the information that potential users are accessing. The results of the surveys from faculty and students are summarized as follows:

- All faculty surveyed indicated that this equipment was a valueable addition to the teaching and research capabilities of their department;
- Most universities are using the equipment to initiate new research directions as well as for educational uses (*e.g.*, health monitoring, sensor development, tank design and masonry studies);
- With few exceptions, most faculty surveyed are using the equipment for courses dedicated to junior through graduate level students; and
- Students surveyed indicated that the equipment enhanced their understanding of the concepts through the exercises.

4.2 Outreach Successes

A secondary objective of UCIST is to improve public awareness of earthquake hazards and to inform the public of a safe way to reduce losses from these possible hazards by proper mitigation strategies. Across the country, UCIST has increased our ability to fulfill this role. The equipment has been used extensively for demonstrations to school children and public groups. Guests at the St. Louis Science Center during Earthquake Engineering Weekend have viewed demonstrations on the instructional shake tables for three years (see Fig. 3a). The shake table has also been used by GK12 Fellows at Washington University in St. Louis schools to introduce 6th and 8th graders to earthquake engineering. The student chapter of the Earthquake Engineering Research Institute at Notre Dame used the shake tables to support Shakes and Quakes, an outreach event to schools in South Bend, Indiana using K'Nex (see Fig. 3b). The University of California at Irvine hosted Learning with Legos, and used the UCIST shake table to teach schoolage students about seismic design (see Fig. 3c). The shake table has been used at the Illinois State Fair to demonstrate earthquake engineering principles to the general public. Several additional outreach activities are listed in Table 3.

5. Summary

Since its inception in 1999, the University Consortium of Instructional Shake Tables has endeavored to develop tools and exercises to provide undergraduate students with hands-on experiences in structural dynamics and earthquake hazard mitigation. This collaborative and systematic approach to earthquake engineering education has been realized through the development of classroom experiments and online resources for educators and students, and the integration of these experiments in the undergraduate civil engineering curriculum. Member institutions have developed these exercises that are freely available on the internet. Further

Table 3. Recent outreach activities with instructional shake tables.

• Earthquake Awareness Weekend at the St. Louis Science Center (1999–2003, see Fig. 3a)
• Women-in-Engineering Day at Washington University in St. Louis (1999–2000 sponsored by SWE)
• Take-Your-Daughter-to-Work Day at Washington University in St. Louis (1999)
• Illinois State Fair, Springfield, Illinois (2000 sponsored by MAE)
• April Welcome at Washington University in St. Louis (1999–2000)
• Stanley Clark Elementary School Lego competition in 3rd grade, South Bend, Indiana (1998)
• Brown and Merit Scholar Tours, Washington University in St. Louis (1999, 2000)
• Stanley Clark Elementary School Lego competition in 5th grade, South Bend, Indiana (1999–2002)
• Andrew Jackson Middle School Lego competition in 7th grade, South Bend, Indiana (2001)
• Dickinson Middle School Lego competition in 7th grade, South Bend, Indiana (2002)
• Gifted Resource Council Introduction to Engineering Program (Fall 2001, 2002)
• Steger Sixth Grade Center, GK-12 Program in engineering, Washington University (2002–2003)
• Learning with Legos, University of California at Irvine (2000–2002, see Fig. 3b)

educational opportunities are encouraged by UCIST, including undergraduate research experiences and outreach activities.

Several additional universities have obtained instructional shake tables and joined UCIST, resulting in a 116% increase in membership. This consortium welcomes all interested institutions. For further information on the UCIST program, contact Dr. S.J. Dyke at *sdyke@seas.wustl.edu*, or see the web page: *http://ucist.cive.wustl.edu/*. Further evaluation of the impact of these ongoing activities will be performed over the next several years.

Figure 3. Recent outreach activities: (a) St. Louis Science Center Earthquake Awareness Weekend, (b) Notre Dame EERI Chapter, Stanley Clark Middle School, and (c) Learning with Legos at University of California at Irvine.

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