Using Educational ”Hands-On” Experiential Tools to Introduce Math, Science and Engineering Concepts to K-16 Students (Research to Practice)

Ms. Kelly Doyle P.E., University of Nevada, Reno

Kelly Doyle is a licensed professional engineer and has B.S. and M.S. degrees in Civil Engineering from University of Nevada, Reno. She currently works as Administrative Faculty at the University where she recently managed a large research project on curved bridges in the Large-Scale Structures Laboratory. In addition to her research and management capacity, Doyle handles educational outreach for the Center for Civil Engineering Earthquake Research. She conducts and schedules tours for visitors, directs an undergraduate research program, and helps organize Civil Engineering summer camps. On this project she served as lead author and developed the K-12 Seismic Design Competition activity. Doyle has been active with ASCE for many years and serves as Treasurer for the Truckee Meadows Branch (TMB) Board of Directors and President of the TMB Younger Member Group. She also serves as an adviser to the student chapter and was awarded the Practitioner Adviser of the Year for Region 8 in from 2011 to 2013. Recently, she was awarded 2013 Young Engineer of the Year by the ASCE TMB. She also serves on the Nevada Chapter AGC Education Committee.

Dr. Lelli Van Den Einde, University of California, San Diego

Lelli Van Den Einde is a faculty lecturer (LPSOE) in the Department of Structural Engineering at UC San Diego’s Jacobs School of Engineering. Dr. Van Den Einde’s interest in teaching has influenced her current research efforts towards improving engineering education pedagogy through the use of technology in the classroom. She is involved in promoting academic integrity as a way to prepare our students to be ethical practicing engineers, and is the chair of the External Advisory Committee for the IDEA center, which promotes inclusion, diversity, excellence and advancement in engineering. She has conducted research in performance-based earthquake engineering and large-scale experimentation of reinforced concrete, FRP composite, and hybrid bridges.

Prof. Catherine W. French, University of Minnesota, Twin Cities

Catherine French is College of Science and Engineering Distinguished Professor in the Department of Civil Engineering at the University of Minnesota. She received her B. C.E. from the University of Minnesota in 1979. She received her M.S. and Ph.D. degrees from the University of Illinois at Urbana-Champaign in 1980 and 1984, respectively. She has been a member of the faculty of the University of Minnesota since 1984. Her research addresses the behavior of reinforced and prestressed concrete structural systems, field monitoring of bridges, numerical and experimental investigations of structural systems including the effects of earthquakes, evaluation and repair of damaged structures, and development and application of new materials. She is also actively involved in education and outreach activities with the Department of Civil Engineering and the NSF Network for Earthquake Engineering Simulation (NEES) Multi-Axial Subassemblage Testing (MAST) Laboratory. She is a Fellow of the American Concrete Institute (ACI) and the Precast/Prestressed Concrete Institute, and recipient of the National Science Foundation (NSF) Presidential Young Investigator Award, ACI Henry L. Kennedy Award, ACI Reinforced Concrete Research Council Arthur J. Boase Award, and American Society of Civil Engineers (ASCE) Raymond C. Reese Research Prize. She is involved in a number of professional activities including serving as a member of the ACI 318 Structural Concrete Building Code Committee for which she chairs the subcommittee on Bond and Development. She is a past president of the MN-IA ACI Section and the MN Section of ASCE.

Ms. Heidi A Tremayne, Pacific Earthquake Engineering Research Center

Heidi Tremayne is the outreach director for the Pacific Earthquake Engineering Research Center (PEER) with headquarters at UC Berkeley. PEER’s research is conducted in many fields including structural and geotechnical engineering, lifelines, transportation, earthquake hazard, and public policy. Tremayne
disseminates research results and conclusions to various users including professional engineers, students and faculty, funding agencies, news media, and other interested groups. In this effort, she utilizes both her engineering skills (she is a licensed California Civil Engineer) and communication skills to bridge the gap between academia and engineering practice so that new research findings are used to design safer infrastructure that can withstand future earthquakes. She also manages PEER’s educational programs including PEER’s undergraduate internship Program, a K-12 outreach program for local schools that teaches students about earthquakes and engineering, and various activities for graduate students including conference poster sessions and international workshops.

Dr. Sean P Brophy, Purdue University, West Lafayette

Dr. Sean Brophy is the Co-Leader of the Educational, Outreach and Training them for the George E. Brown Network for Earthquake Engineering Simulation (NEES). His research in engineering education and learning sciences explores how children learn through interactions with technologies ranging from manual manipulative like structures students design build and test with shake tables to digital manipulative with mobile devices. He continues to explore new methods to enhance informal and formal learning experiences.
1.0 Abstract

Experiential hands-on tools (instructional table-top earthquake simulators, or “shaking tables”) can be used to teach learners about fundamental physics principles and can stimulate their interest in physical science, engineering, mathematics and technology (STEM) careers. This paper describes a collection of learning experiences developed by researchers from various facilities in the Network for Earthquake Engineering Simulation (NEES) that are scalable for K-16 learners. Assessments targeting the instructors of the outreach activities, the participating K-12 teachers, and the student participants are described, and results are presented that illustrate the effectiveness of the lessons in enhancing the students’ understanding of engineering principles and in generating interest in STEM careers.

2.0 Introduction

Earthquake engineers protect lives by understanding the effects of earthquakes on structures and designing structures to withstand the forces imposed on them during an earthquake. The damage from recent earthquakes has demonstrated the need for improved earthquake engineering design, showing room for growth and the demand for the recruitment and retention of promising future engineers. The problem solving skills required for this field provide interesting applications and context for students as they learn about natural and physical sciences associated with the Next Generation Science Standards1.

To educate prospective students about earthquake engineering and the various methods to mitigate the effects of earthquakes, collaborators from the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) have developed educational activities utilizing hands-on tools (instructional table-top earthquake simulators, or “shaking tables”) to engage and excite students about STEM. NEES consists of 14 large-scale test facilities that support research to better understand the problems and opportunities for designing earthquake-resistant communities. Each facility has a person or team supporting a mission of Education, Outreach and Training (EOT). Their primary objectives include generating interest in STEM careers, teaching students about earthquake engineering, and creating public awareness of NEES and its accomplishments. To address this mission, some of the NEES EOT coordinators have developed and tested learning experiences like the ones described in this paper. When complete, the activities are shared with other NEES sites and the public through the NEESacademy2, which is a website that provides K-16 educators with a large assortment of learning resources, learning objects, and learning modules.

The activities involving shaking tables are used to introduce complicated topics such as seismology, vibration response, and structural performance and design to students, even at the kindergarten level. Younger students are able to develop and test hypotheses, as well as to build and test engineering solutions. More advanced students can predict the behavior of structural systems by applying concepts of math and physics to develop analytical solutions that can be
compared with experiments. The beauty of the activities is that they can utilize shaking tables that range from expensive, higher technology simulators to low cost, low technology solutions.

The educational research described in this paper provides an excellent framework for learning about physical science, engineering, mathematics, and technology (i.e., STEM education). A number of activities built around the shaking table are presented and the effectiveness of using the experiential tool is described. The ultimate goal is to teach K-16 learners about fundamental physics principles that can define the behavior of a structural system in motion. The lessons presented herein engage students in performing interesting engineering activities requiring design, conducting science experiments to test their designs, and analyzing the results to explain the structural behavior.

This paper also presents several multiple purpose assessments used to gage the effectiveness of the shaking table lessons in generating interest in STEM careers. The assessments are used to evaluate the ability of the learners to predict and explain the dynamic behavior of a system subjected to earthquakes. The general research questions guiding the assessments include: 1) How can shaking table activities developed initially for higher education be used to advance K-12 students’ understanding of complex topics like structural dynamics? 2) How well do these activities motivate K-12 students to consider academic and career paths in STEM? 3) How can the activities be effectively scaled up or down to achieve different levels of conceptual understanding defined by K-16 standards?

3.0 The Need for K-16 Engineering Learning Experiences

Recently, there has been a push to improve K-12 STEM education because of the observation that many students, especially at the middle school age, lose interest in math and science. A report by the National Academy of Engineering in 2010\textsuperscript{3} states that engineering is a critical component to developing a community and workforce that understands the technical nature of the manmade world. The lack of interest in STEM is often attributed to low quality of teaching and preparation, but may be more likely due to the disconnectedness of the K-12 science curriculum from topics and content relevant to students’ daily lives and interests\textsuperscript{4}. Although K-12 engineering curricula and research on how students learn is required to develop successful K-12 engineering programs, researchers also believe that engineering education will be greatly enhanced when engineering literacy is clearly defined, informal engineering education programs are integrated into the K-12 curriculum, and engineering-focused schools are supported\textsuperscript{5}. Informal programs, such as those developed by local museums and universities, currently engage a small percentage of the total number of K-12 students in the United States. But the number is quickly increasing, enhancing the opportunity to significantly improve engineering literacy\textsuperscript{6}. Because of technological developments in society and the realization that engineering promotes problem-solving and project-based learning, recent steps have been taken to integrate engineering and technology into the K-12 classroom\textsuperscript{4}.

A key aspect of constructing knowledge and increasing interest in engineering is engaging learners in authentic scientific and engineering activities. Smith, et al. believe that engaging students in formal learning is the primary responsibility of the teacher, who becomes more of a designer or facilitator of the learning experience rather than just an imparter of knowledge\textsuperscript{6}. 
Engineering education research focused on young learners raises questions such as how engineering experiences can be integrated into existing school curricula, and which engineering frameworks are significant, engaging, and inspiring to students. There are many different theories of how to engage students in what they are learning. One of these is Experiential Learning Theory (ELT), which was developed by educational theorist David Kolb and his colleagues. In ELT, “knowledge is created through the transformation of experience,” and ultimately provides students with the opportunity to directly involve themselves in a learning experience, reflect on their experiences using analytic skills, and eventually gain a better understanding of the new knowledge and retain the information longer. Another approach is “interactive engagement” as defined for physics, which has demonstrated a significant enhancement in conceptual learning. According to Hake, interactive engagement promotes conceptual understanding usually through hands-on activities, which generate immediate feedback through discussion with peers and/or instructors. Finally, the theory of constructivism is the idea that development of understanding requires the learner to actively engage in meaning-making. Constructing an understanding requires that students have opportunities to articulate their ideas, test those ideas through experimentation and conversation, and consider connections between the phenomena that they are examining and other aspects of their lives. The central pedagogical approach to instructional activities is to engage learners with what they know and give them opportunities to refine their understanding with multiple learning experiences.

A central conjecture is these experiences can be tailored to promote learning of similar science and engineering associated with the three dimensions framing the Next Generation Science Standards: 1) scientific and engineering practices, 2) crosscutting concepts, and 3) disciplinary core ideas. The context of earthquake engineering and the practice associated with research at the NEES test facilities align well with the major topics associated with these dimensions.

Several education and outreach efforts have introduced the use of instructional shaking tables to K-16 students. In 1999, 23 universities affiliated with the three national earthquake centers in the United States acquired shake table laboratory stations and developed the University Consortium on Instructional Shake Tables (UCIST). A series of hands-on activities were developed and implemented mostly for undergraduate education. One K-12 module asked students to investigate the seismic behavior of two types of buildings by designing and constructing K’Nex and Lego structures and testing them on bench-scale shaking tables. Comments received from third grade participants were extremely enthusiastic about the program and indicated that the students learned a lot of difficult concepts. One student stated, “I really liked the earthquake simulation. I liked watching the buildings and seeing how long each building stayed. I never knew about the Kobe earthquake. I think it is interesting that you can put shock absorbers on a building. It is also interesting to me about the apartment buildings and how they fell and stuff. It was fun and interesting!”

Other similar efforts such as the Webshaker education/research project at UC San Diego provided a convenient learning experimental framework for applications in dynamics including introductory physics, mechanics, structural dynamics, and earthquake engineering courses. An instructional shaking table was made available online allowing undergraduate students and the public to remotely access it. The framework actively engaged students in a stimulating and informative “fun” educational environment. Although the material primarily focused on
educating undergraduate students, the shaking table was also utilized in K-12 outreach and specifically targeted sixth graders to align with California state teaching standards. While these efforts were deemed successful, limited assessments validating the impact of the shaking table activities were conducted.

The activities presented in this paper leverage the experiences of the initial efforts described above. They focus on introducing K-16 students to engineering and encouraging them to pursue careers in STEM through the use of hands-on activities based loosely on experiential learning theory. The shaking tables used in these activities simulate earthquake ground motions in one direction that vary in frequency and amplitude. They can range from expensive computer controlled systems that have highly repeatable events to low cost manually operated tables for basic demonstrations of concepts. A high-end research grade table, shown in Figure 1, is often used to teach undergraduate and graduate engineering students about the behavior of structural systems subjected to dynamic loadings, how structures can be designed to withstand different dynamic conditions, and how to model and test these systems.

![Figure 1: Table-top shaking table.](image)

The following sections summarize several adaptations of learning experiences developed and tested as part of outreach efforts of large-scale test facilities affiliated with NEES. The materials were implemented by instructors at the various facilities and coordinated with participating teachers interested in bringing earthquake engineering concepts into their classrooms. These activities have been implemented many times and various levels of assessments have been used to evaluate their potential in student retention of knowledge and student motivation to pursue STEM careers.
4.0 Descriptions of Shaking Table Activities

4.1 Masses on Rods

A building’s response to the ground motion created by an earthquake depends on the mass of the structure (typically modeled as a concentrated mass at each floor level) and the stiffness of the structure (which depends on cross-sectional properties, material properties, and connection details). Masses on rods (sometimes called lollipop models) provide a simple physical model of large-scale structures, such as buildings, windmills and cell towers. These models can be used to demonstrate the idealized response of a building subjected to an earthquake motion. The demonstration provides a strong visualization of how a building might move by providing a highly exaggerated movement in the smaller scale lollipop model.

In this activity, masses and rods are used to simulate one- and two-story buildings. A one-story building is represented by a mass at a single point on the rod and a two-story building is modeled by masses at two points on the rod. The model includes four rods: a short rod with mass M, two medium rods (one with mass M and one with mass 2M) and a long rod with two separate masses (each equal to M, but located at different points, or lengths, along the rod). The test setup is shown in Figure 2 and features three one-story buildings and one two-story building.

![Figure 2: Masses on rods demonstration.](image)

The model also allows users to simply change various parameters (e.g., length of rods [height of building], number of masses [number of building stories], and size of masses [mass of each story]) to better compare and contrast the differences in behavior. Ultimately students learn that these are important parameters engineers must understand in design to make a building resilient to an earthquake. The manipulation of these parameters also helps to model controlled experiences used in scientific inquiry.

During the demonstration, the masses are pulled and then released, and students are asked a series of questions about the vibration frequencies of the different rods. They are asked to draw
conclusions about the effects that mass and stiffness have on the response. When the rods are pulled and released, the shortest (and stiffest) rod vibrates the fastest. In addition, the medium rod with less mass (M) vibrates faster than the rod with mass 2M. Finally, the longest rod with two masses vibrates the slowest.

The next step of the demonstration is to place the experiment on an educational shaking table. Rather than introducing an earthquake motion at this stage of the demonstration, the concept of a “sine wave” is introduced, where the shaking table is programmed to move back and forth at a specific frequency and amplitude creating a symmetric back and forth motion in one direction. The table frequency is increased until the natural vibration frequency of each individual rod is found. Students can easily identify each natural frequency because at that frequency one rod will be swaying significantly while the others remain nearly stationary. This concept is then identified as resonance of a structure, and the negative effects that a building experiences at resonance are discussed.

Most earthquakes excite a broad spectrum of frequencies. The demonstration shows that when there is significant frequency content near the natural frequency of the structure, a lot of damage can result. In addition, buildings that are adjacent to each other can experience pounding, so they should either be tied together to avoid damage or spaced far enough apart so they do not hit the adjacent structures.

This activity is scalable for all age levels and can demonstrate the most basic concepts of vibration. Elementary students learn about modeling structures, effects of mass and stiffness on frequency, sine waves, and resonance. Older students can use equations to calculate the natural frequencies of the structures and compare their predictions to the experimental results. The activity is also useful for identifying and determining errors between predicted and observed values.

4.2 Plexiglas Houses

A model of a house made from Plexiglas can be used to illustrate the effects of bracing on the structural response of a building. Bracing is a method that can help increase the stiffness of a building. Braces help keep a structure “square” so that nonstructural elements—such as windows and walls—are less likely to be cracked and damaged in an earthquake. The damaged materials are not only costly to repair but they may also strike people if the materials fall from buildings. The types of damage that are observed from building displacement are illustrated in Figure 3. In this activity, a house made of Plexiglas is split in the middle, with one half of it braced and the other half unbraced. Tissue paper is attached to the house to simulate windows and walls in the structure. The tissue paper is dampened slightly to facilitate tearing, which demonstrates cracking of the wall. The house is placed on an educational shaking table and subjected to an earthquake motion. During the earthquake, students observe that the unbraced side undergoes distortion and the tissue paper rips (i.e., the wall “cracks”). The braced side, however, distorts much less and therefore remains intact.
Another important topic discussed during this activity is the importance of securing contents in the building. The house is filled with doll furniture (shown in Figure 4), which is tossed about during the earthquake. After the simulation, students are asked to identify the items that should be tied down during an earthquake to prevent injury (e.g., bookshelves, gas stoves, water heaters).

This activity can be used for all ages (K-16) to demonstrate the effects of bracing and the importance of securing contents to prevent injury. Elementary age children can easily identify with the everyday items they see at home. Older students can relate bracing to structural stiffness and the effects on the dynamic properties of a structure. Undergraduates can even quantify these dynamic properties, and recommendations can be made to improve the building response.
4.3 Earthquake Resistant K’Nex Structures

Building earthquake resistant K’Nex structures is an activity that has been used with a number of different audiences. This section will focus on a project designed for fourth and sixth grade students, which are targeted grade levels with learning outcomes related to earthquakes in their state earth science curriculum. The activities are designed to introduce the students to earthquakes, have the students explore earthquake-resistant design through building structures using K’Nex, and show how these topics are researched through a visit to an engineering laboratory where innovative engineering designs are tested. Goals are to foster enthusiasm in the science of earthquakes and earthquake engineering, expose the students to earthquakes in a hands-on, interactive, exciting environment, and activate student interest in STEM while engaging curiosity and creativity. Additional description and resources related to this K’Nex structures activity can be found in the educational resources in NEESacademy on the NEES website17.

In this project, the curriculum consists of a four-part activity. The first segment of the activity is a lecture tailored specifically for the targeted grade level. The presentation includes videos, hands-on demonstrations, and interactions between the lecturer and the students. Topics discussed consist of: (1) an introduction to basic earthquake science, (2) an explanation of why earthquakes happen, (3) a discussion of professions (such as engineering) that address the effects of earthquakes on our communities and buildings, (4) an introduction to key building systems and components that help buildings to safely resist earthquake shaking, and (5) instruction and background for the hands-on building activity.

During the second segment of the project, teachers are given materials for a hands-on activity to follow up on the topics covered in the lecture. The students (working in groups of four to six) are given a kit that contains K’Nex. Each group is asked to design and construct an earthquake-resistant building model using the information given in the presentation. The class is given a hand powered shake table to practice testing their models (shown in Figure 5). Instructions on how to make this table can be found at on the NEES website’s educational resources18. This portion of the activity gives students the opportunity to participate in a hands-on engineering activity and develop team-building skills.
The next segment of the project consists of teachers and students taking a field trip to a local engineering laboratory such as the NEES@Berkeley lab. They are given a tour of the lab and a video presentation about earthquake testing done there. This portion of the project exposes students to large-scale modern earthquake engineering facilities and shows them the importance of engineering in their everyday lives. It also gives them an opportunity to observe a “lab” that is very different from a traditional chemistry or biology laboratory and broaden their experience to a more diverse definition of laboratory science and research.

During the final portion of the project, teachers go back to their classrooms and are provided with a high-end research grade shaking table to formally test the students’ K’Nex models (shown in Figure 6). The idea is to engage students in similar experimental design procedures that they learned about at the university research facilities. Student design teams observe the performance of their structures when subjected to various levels of earthquake shaking. Students use “damage report” worksheets to record damage to their structure, calculate the hypothetical “cost” of the damage, and draw conclusions about how they would improve future designs to ensure better earthquake performance. Teachers can easily integrate supplemental writing, measuring, drawing, vocabulary or other student assignments with this program as well.
Although this particular activity is targeted for a narrow grade range, it is easily expanded for all K-16 levels. Several universities have already led similar activities with different age groups.

4.4 K-12 Seismic Design Competition

This competition is a hands-on activity for grades K-12 that focuses on constructing earthquake resistant buildings and testing them on instructional shaking tables. The competition is divided into four age ranges with targeted curriculum standards for each group. The age ranges are: K-3, 4-6, 7-8, and 9-12. The two younger age groups construct buildings from gumdrops and toothpicks, while the older groups build structures using balsa wood.

The youngest students (grades K-3) are grouped with a parent or volunteer and construct small towers from gumdrops and toothpicks. The students are given a brief explanation of earthquakes and shown the advantages of using bracing (i.e., triangles) in their design. This is done by allowing the kids to push on a K’Nex tower that was braced in only one direction (shown in Figure 7). Students fill in an observation sheet with descriptions of their towers using words, numbers, and drawings. Although some of the younger kids enjoy observing the structures on a shaking table, the short attention span of this age group does not warrant seismic testing; rather, each tower is loaded with mass until it collapses.
A short presentation to 4-6 grade introduces the basics of how earthquakes are caused and the important building design concepts used to resist the large amount of energy they produce. The students are then divided into small groups to construct buildings using gumdrops and toothpicks. The sample K’Nex tower is used again to show how the use of bracing increases the stiffness of the building and to serve as inspiration for ideas they could try with their designs. The completed gumdrop structures are approximately 5” x 5” x 30” and are loaded with a 2.2 lb weight prior to placing them on the shaking table, as shown in Figure 8. A sample building with minimal bracing is constructed prior to the activity and tested on the shaking table as well. Students record their data on an observation sheet and draw conclusions about the performance of their building by comparing their structure to the sample building.
The older grade levels (7-8 and 9-12) work in groups of two to three constructing buildings from balsa wood. Prior to construction, both age levels listen to a presentation that reviews plate tectonics, describes the importance of seismic design in buildings, and explains how the competition will be scored. The 7-8 grade students build structures that are 8” x 8” x 24”, while the older students construct 12” x 12” x 36” buildings. Each structure is loaded with 0.85 lb on each floor to illustrate the gravity loads that result from the contents and people living in the building. Then a gravity load of 2.2 lb is placed on the roof level to simulate typical utilities and equipment located on roofs. After this static testing, the prototype structures are placed on the shaking table and subjected to dynamic loading. Students record their observations and then calculate building cost (based on weight of materials used) and income (based on usable floor area by the occupants). The net revenue is calculated as the difference between the two and reduced if the structure does not survive the full earthquake (i.e., if the building only withstands 75 percent of the applied earthquake then the team only receives 75 percent of the revenue earned).

All competition materials (including rules, teaching standards, instructor guidelines, classroom presentations, materials lists, and assessment questionnaires) are available for download online20.

This competition can easily be scaled up for undergraduate students by incorporating measurements such as acceleration and/or building displacement into the final score. The Earthquake Engineering Research Institute (EERI) currently holds an annual competition like this for undergraduate students, and details can be found on their website21.

4.5 Energy Dissipation and Seismic Isolation

All of the previously described activities can also be supplemented to illustrate the advanced concept of energy dissipation, or absorption. The design techniques in some of the previous activities focused on increasing the stiffness of structures to resist the effects of the earthquake. Engineers can use various energy dissipating devices to help to “eat up”, or absorb, the energy introduced into the structure by the earthquake. An example is to use friction to dissipate energy through scraping of elements that rub against each other during the ground motion. This can be accommodated through the structural bracing. Another energy dissipation approach is to add tuned mass dampers to a structure. The dampers are masses located high in the structure that are displaced to offset the motion of the structure. These dampers change the building’s frequency so that the earthquake is unlikely to achieve damaging resonant vibration explored in the Masses Rods activity (section 4.1).

These concepts can be illustrated using educational shaking tables by placing some of the structures already described (masses on rods, K’Nex buildings, etc.) on sliders (e.g., rollers like a skateboard). Another technique is to place two jugs of water on a shaking table (one with isolation sliders and one without) and shake them with an earthquake motion. In any case, the isolated systems experience much less vibration and students can easily identify this phenomenon. This activity is applicable for all grade levels; it introduces the concept of energy dissipation for young students and serves as a complex seismic design problem for undergraduate and graduate level students.
5.0 Activity Culmination with COSMOS Summer Program

Many of the concepts and activities described in the previous section have been combined in longer summer programs on university campuses. An example is the California State Summer School for Mathematics and Science (COSMOS), which is a four-week educational summer program for gifted and talented high school students. In this program, engineering topics are presented via a variety of “clusters” located at four of the University of California campuses. The “Earthquakes in Action” cluster (Cluster 4) at the University of California, San Diego (UCSD) has successfully employed experiential education methods in order to present structural engineering and geophysics topics. Lecture material on seismology and earthquake engineering has been integrated with activities, field trips, and group projects in order to enhance the students’ understanding of the material. Two of the group projects using shaking tables are described below.

The goals of the program are to present earthquake engineering and geophysics topics at a high level, meet national math and science program standards for high school students, and to encourage the students to pursue math- and science-based majors at public, in-state universities. A longitudinal survey was conducted to assess whether the program, and more specifically the use of the table top shaking table, engaged the students to learn topics about earthquake engineering and vibrations and promoted learning of the material. Results from this survey are described in the Assessments section.

5.1 Seismic Behavior of Masonry Structures

In seismically active regions, the use of masonry can pose a challenge to engineers. Walls made of only masonry units and mortar in building systems typically behave in a brittle fashion, and the material itself is very heavy; these two characteristics can cause regular masonry structures to perform poorly during an earthquake. Certain things can be done, however, to enhance the performance of masonry walls when they are acted on by forces other than compression. One way to improve the behavior of such systems is to use steel reinforcement, either as reinforcing bars within the walls or a mesh-like material that covers the wall face, in order to increase the deformation capacity of the structure during an earthquake.

One of the group projects in the UCSD COSMOS Cluster 4 (Earthquakes in Action), asks teams of three students to research and report on the structural aspects of unreinforced and reinforced masonry construction. They are required to follow specific guideline questions and then design, construct, and test a pair of masonry structures to observe how they behave under earthquake loading.

The research portion includes answering questions such as: 1) What are some of the advantages and disadvantages of masonry construction? 2) How have masonry structures performed in past earthquakes? 3) What was learned from the failures that occurred? 4) Define ductility (i.e., deformation capacity) as it relates to structures and hypothesize whether unreinforced masonry structures are adequately ductile. Students are also asked to research structural design principles such as: 1) What areas in masonry structures are especially susceptible to seismic damage? 2) What kinds of engineering solutions have been employed to improve the seismic safety of
masonry structures? 3) What are the different ways that masonry structures can be reinforced with steel or other materials? 4) What are some of the advantages and disadvantages of each method? Finally, advanced seismic design techniques are investigated such as: 1) How is seismic energy dissipated in reinforced masonry structures? 2) What kinds of special materials can be used to strengthen masonry walls, and how? 3) Are these materials practical for use in everyday structures? 4) What things are currently being studied on the seismic safety of masonry structures? 5) What are some areas where future research is needed?

The teams then construct two different masonry structures using sugar cubes (simulating the masonry units) and cake frosting (simulating the mortar). The structures are identically designed within the constraints described below, except that one structure is unreinforced and the other contains some sort of reinforcement. Design specifications consist of:

- The structures will be three stories tall
- Each story will be at least 5” in height
- Each story will have an approximate footprint of 6” x 12”
- The structures will be tested on the shaking table with their long dimension (12”) oriented in the direction of motion
- The 5” x 12” walls on the first story must each contain a door that is approximately ¼ of the wall area in size
- The 5” x 12” walls on the second and third stories must each contain two windows that are, jointly, approximately ¼ of the wall area in size
- Additional openings (i.e., on side walls) may be included as desired
- The walls of the structures must only be constructed using sugar cubes and icing; each floor of the structure will be made with rigid foam poster board that is approximately 1” larger in both dimensions than the footprint of the structures.
- The structures will be affixed to base pieces of the same rigid foam poster board that are approximately 4” larger in both dimensions than the footprint of the structures.

Figure 9 shows a schematic of the masonry design specifications. A sample structure with retrofitted measures (such as reinforced windows, better connection between stories, and fiber reinforced walls) is shown in Figure 10.
The structures are loaded with auxiliary mass, instrumented with an accelerometer, and then tested under simulated earthquakes using an educational shaking table. The initial unreinforced structure is tested until failure or other significant damage occurs. Based on these results, teams brainstorm ways to improve the behavior of the same structure by incorporating some sort of reinforcement. The reinforced structures are then tested using the same experimental protocol, and students observe differences in the behavior of the retrofitted structures relative to the unreinforced ones. Students process the data gathered from the accelerometers and make recommendations for future study.

In addition to the preliminary research questions described above, students are asked to compare and contrast the performance of their unreinforced and reinforced masonry structures. Other discussion questions include: 1) How do you think pre-existing unreinforced masonry structures can be strengthened against earthquakes? 2) What are some of the challenges? 3) Can you imagine a hybrid building system that includes both reinforced masonry with another material that would perhaps improve the overall seismic behavior? 4) What types of hybrid systems are constructed in full-scale situations? The projects culminate in preparing a 10-15 minute presentation and a digital poster of their research and experiments, which they present to other COSMOS groups.

5.2 Base Isolation

Base isolation devices (a type of energy dissipation device, as described in Energy Dissipation and Seismic Isolation activity in section 4.5) are used in structures or mechanical devices in order to minimize the amount of damage that they experience due to vibrations of their bases. By separating a structure from its foundation, engineers are able to limit the amount of seismic energy that enters the building during an earthquake. Such a structure will experience lower amounts of total acceleration, and will generally move mostly as a rigid body (i.e. the structure will not experience much relative displacement between its components). However, the total displacements occurring relative to the ground at the base isolation device will be large and must be considered in design.
In the UCSD COSMOS Cluster 4, one team is asked to conduct a base isolation project with the goal of researching and reporting on seismic isolation methods for structures, and then designing, constructing, and testing an isolation system for a single-story structure on an instructional shaking table.

As with the masonry project, students are asked to research into the structural principles behind base isolation systems. Some basic structural concepts explored include: 1) Why are base isolation systems used? 2) Define the terms total acceleration and relative displacement for a structure. 3) Why are they important with regard to what happens to buildings during an earthquake? Questions targeting other structural design principles that the students are asked to research include: 1) Compare and contrast the behavior of a base-isolated building with a building having a traditional, fixed foundation. 2) Find examples of base-isolated bridges and buildings. 3) Have any been proven to be effective during an actual earthquake? 4) What are the different types of base isolation systems available? 5) What are their advantages and disadvantages? Finally, the students research advanced seismic design techniques through questions such as: 1) Why is it important to dissipate or dampen energy at a specific location within a structure during an earthquake, and how can base isolation help to accomplish this? 2) What is an energy absorber and how can it be used along with a base isolation system? 3) When would it not be effective to use a base isolation system for a structure?

Students are provided with a single degree-of-freedom (SDOF) structure that is initially tested on the shaking table to determine its natural frequency (much like the “Masses on Rods” activity in section 4.1). Each group is then asked to design a mechanism to isolate their structure to avoid resonant vibrations near its natural frequency. In their design, they must determine how to attach their isolation systems to the shaking table and how to avoid potential overturning of their structure. This project involves a lot of trial and error as students develop several design ideas using a variety of materials. After each modification to their base isolation system, students test the system on the shaking table to improve their designs. Figure 11a shows the fixed-based SDOF building being tested on the shake table to determine its natural frequency, and Figure 11b shows the SDOF on a base isolation system during testing. Acceleration data for both the fixed and isolated structures are collected at the same amplitude and frequency so groups can fine tune their base isolation systems.

Figure 11: SDOF structures on the shaking table.
Similar to the masonry project, students are asked to compare results from each of the tests and make recommendations for future study or improving the design. The projects culminate with a final presentation and a digital poster describing results from the shaking table activity, addressing both traditional structures and retrofitted designs. Some questions they are asked to discuss in their final presentations and digital posters include: 1) What method of base isolation worked the best for your structure? 2) Use the data you acquired to justify your conclusion. 3) What issues, if any, continued to exist with your base isolation systems? 4) How might they have been improved? 5) What materials could be used in real life (full-scale) to build your base isolation systems?

The above two projects (Seismic Behavior of Masonry Structures and Base Isolation) are part of seven team projects that students can conduct during their four week summer program. While only five of these projects currently utilize the shaking table, efforts are in place to increase this number. The other team projects include the design and retrofit of flexural reinforced bridge columns, the design, repair and/or retrofit of timber building structures, resonance control using a tuned mass damper, foundation design in liquefiable soils, and the development of a sustainable concrete mix design. Teacher and student guidelines for most of the activities conducted during the UCSD COSMOS Cluster 4 program are available for download from the NEESacademy repository.

6.0 Connecting with Participants

The keys to the success of these programs are the connections and relationships established between the researchers and participants, which have developed in several ways. Most of the universities have collegiate outreach coordinators who can facilitate the connection with local schools. In addition, the researchers seek out opportunities to develop partnerships with schools through already established contacts with research centers, advertising through web pages, communication through legacy e-mail lists, and newsletter and e-mail lists maintained by local science education non-profit resources. Often, schools will make annual visits to outreach events sponsored by the universities. In some circumstances, the school teachers have been funded through the educational outreach programs to translate the shaking table curriculum into lesson plans to meet the educational standards they are required to deliver. The teachers then have the opportunity to deliver the curriculum within their own classrooms. The developed curriculum has been posted on the NEESacademy website, described above, for use by other interested teachers.

7.0 Assessments

Most of the activities described above have been formally assessed for feasibility for learning, meeting curriculum standards, and increasing interest in STEM careers. Depending on the activity, assessments were given to: 1) the instructors who deliver the material, 2) to the participating K-12 teachers, and 3) to the participants (learners) involved in the activity. These assessments provide the current benefits of the activity and formative feedback for continuous improvement.
The purpose of giving assessments to the instructors is to determine whether or not the instructors have recommendations for the content of the activity or suggested changes. These assessments may consist of a debriefing at the end of an outreach activity to review the effectiveness of any materials and demonstrations, identifying successes and areas for improvement, discussing if the activity documentation was useful for the instructor, and determining if the instructor was provided enough background information. The data obtained from these assessments are used to train future activity instructors and improve the delivery of current activity instructors.

The assessments given to the K-12 teachers of the student participants are used to improve the activities for future participants, to enhance each activity’s integration with the K-12 curriculum standards, and to provide new resources that supplement each activity for teachers.

Assessments given to the participants are used to determine if the activities are engaging students, if students are retaining the concepts immediately following the activity so the knowledge can be used as they learn more complicated topics, and whether or not the activities are meeting the learning objectives. In addition, the results of some of the survey assessments are used to determine whether the activities motivate the K-12 students to consider educational and career paths in STEM.

Several different types of assessments have been used to collect data from the participants. The most direct assessment method is “clicker technology” used to poll the students during the demonstrations. Demographic information can be collected as well as knowledge acquisition using pre- and post-activity questions. For younger audiences informal vocabulary recall can be used to have the students retain key concepts. Additional activities for younger participants include word searches that may be given to teachers to reinforce vocabulary when students return to the classroom.

In some cases, formal surveys are administered to student participants and/or teachers to get feedback about the effectiveness of the learning experience toward developing skills, knowledge or attitudes related to STEM. Questions in the surveys include both formative evaluations to find areas of improvement and summative assessments to estimate the learning outcomes achieved during the activity. For example, teachers participating in the Earthquake Resistant K’Nex Structures activity (section 4.3) complete an evaluation form that asks them to estimate what percentage of their students retained each of the activity’s learning objectives. Teachers typically complete this evaluation form within three months of the activity, without a specifically defined retention time frame identified in the evaluation form. A sample of these results is summarized in Table 1. In addition, they rate each of the program elements so the program’s coordinator and instructors know which elements need future development work and improvement. Samples of this data are shown in Table 2. The assessment sheets sent to the teachers can be found online. For this particular activity, anecdotal information including repeated participation of teachers over many years, as well as a regular yearly increase of participation requests from new teachers, shows that the teachers find this program to be a useful learning activity.
Table 1: Average percentage of students achieving each learning objective according to the teacher’s interpretation gathered from teacher evaluation forms in the 2010-2012 school years.

<table>
<thead>
<tr>
<th>Learning Objectives</th>
<th>Average percentage of students retaining info (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Teach students what engineering is, what types of engineers exist, and what engineers do.</td>
<td>71</td>
</tr>
<tr>
<td>Increase student's understanding of earthquakes, including plate tectonics, earthquake faults, and how earthquakes are measured.</td>
<td>78</td>
</tr>
<tr>
<td>Explore how earthquake shaking affects buildings and geologic features.</td>
<td>87</td>
</tr>
<tr>
<td>Explore how buildings are constructed and what materials are used in buildings.</td>
<td>82</td>
</tr>
<tr>
<td>Describe what building elements affect building stability and help them resist earthquake shaking.</td>
<td>84</td>
</tr>
<tr>
<td>Engineer a model building to withstand earthquake shaking or an earthquake simulator.</td>
<td>88</td>
</tr>
<tr>
<td>Learn what to do during an earthquake and how to prepare in advance for an earthquake.</td>
<td>88</td>
</tr>
<tr>
<td>Involve students in projects that require them to think critically, use math, be creative, work together, and develop their problem solving skills.</td>
<td>75</td>
</tr>
</tbody>
</table>

Table 2: Average teacher rating (from 30 participating teachers) of each element in the Earthquake Resistant K’Nex Structures Activity from the 2010-2012 school years.

<table>
<thead>
<tr>
<th>Element</th>
<th>Average Rating (scale of 1 – 5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall Experience</td>
<td>4.7</td>
</tr>
<tr>
<td>Lecture</td>
<td>4.6</td>
</tr>
<tr>
<td>Lab Tour</td>
<td>4.4</td>
</tr>
<tr>
<td>K’NEX Activity</td>
<td>5.0</td>
</tr>
</tbody>
</table>

During some of the activities, technical worksheets are given to the students so that learning objectives may be assessed. For example, during the Earthquake Resistant K’Nex Structures activity (section 4.3) students are given various worksheets that reinforce the new engineering vocabulary introduced during the presentation, calculate building volume, generate cost
estimates for the student structures, record observations of building damage during the testing of their structures, and graph the natural frequency of each student’s structure determined from shaking table testing. During the K-12 Seismic Design Competition activity (section 4.4) data sheets are also used to assess learning objectives. Students are asked to fill out the data sheets as they build their structures. Depending on the age level, students describe their buildings using words, shapes, tables, and quantitative data. Samples of these data sheets may be downloaded online. These data are collected and analyzed to determine if the learning objectives of the activity were met.

For the COSMOS high school summer program at UCSD (section 5.0), several assessments are conducted throughout the program. Students are asked questions on the first day about their interest in STEM and field they plan to pursue in college. Students are asked similar questions on the final day to determine if the program influenced their interest and career choices. They are also asked to evaluate each activity (e.g., lectures, assignments, projects, field trips) as a summative assessment to improve the program for future years.

In fall 2012, an additional longitudinal assessment of past participants of the COSMOS program was conducted. Students who participated in the program over the past five years (2007 through 2012) were asked what their current education status was (i.e., still in high school, in college, graduated, working) and what they planned on studying (or previously studied) in college. From the 130 students polled, 23 responded to the survey. Participants were asked if they planned to pursue a career in STEM prior to attending COSMOS or if the summer program influenced their decision to pursue a career in that field. More specifically, students were asked if they were interested in structural engineering before and/or after participating in the program and whether their experiences in the program changed their inclination towards a specific major. Additionally, participants were polled to see if their experience in the summer program influenced which college/university they wanted to attend. Finally, students self-evaluated the use of the shaking table during instruction of the program; they were asked whether they enjoyed using it, if it made difficult concepts (e.g. force, acceleration, motion and modeling) easier to understand, if it engaged them to ask scientific questions and help them become a better problem solver, and whether their knowledge and interest in STEM concepts increased as a result of hands-on activities with the shaking table. The survey was implemented using a 5-point Likert scale with five being strongly agree, and one being strongly disagree. Sample results, shown in Figure 12, indicate that most of the students strongly agreed that they enjoyed the shaking table activities (average response of 4.91) and the shaking table made the difficult concepts easier to understand (average response of 4.61).
Although not all respondents used the shaking table extensively for their projects (only 20 out of the 23 did), most of them said that the shaking table activities engaged them to ask scientific questions (average response of 4.52). The students were slightly more mixed about whether the shaking table activities helped them become a better problem solver (average response of 4.17). These results are summarized in Figure 13.

One of the most encouraging results was the average score of the respondents regarding whether their knowledge and interest in STEM concepts increased as a result of hands-on activities with the shaking table (average response of 4.3), shown in Figure 14. Overall, this demonstrates the effectiveness of the use of the hands-on shaking table in promoting understanding of difficult structural engineering concepts.
Figure 14: Survey results demonstrating whether their knowledge and interest in STEM concepts increased as a result of hands on activities with the shaking table.

The comments about the program and the use of the shaking table from the students were very enthusiastic, and the program seemed to have a large impact on the careers of these students. Some comments are as follows:

“I had so much fun and learn[ed] a lot using the table-top shake tables! I was able to learn many concepts thoroughly after using the shake tables.”

“Before I attended COSMOS, I want[ed] to pursue a career where I could be able to create different structures. I have always been a fan of building different structures, but now that I experienced COSMOS, I realized that there is a lot more to structures than what I originally thought. It is amazing that so much is done to one structure to keep it standing. … the projects and everything was amazing. We had the opportunity to actually build things and test them, which were amazing for me to watch. More building projects would be nice to incorporate because we learn from the flaws to make a better one. What better way than the shake table; which helped me visualize what was actually going on.”

These assessments illustrate the potential of the learning experiences developed by EOT personnel at the NEES research facilities. The results have been primarily used as formative assessments to increase the quality of the materials. These materials are now on the NEESacademy and other sites and schools are adopting them into their outreach or science curriculum. Therefore, as part of the dissemination of these materials the NEES EOT is developing standardized assessments to accompany the learning experiences. These will be offered to help educators assess the learning outcomes of their students and for the NEES EOT community to evaluate the effectiveness of the experiences to inform continuous improvement.

8.0 Conclusions

Instructional shaking tables have been shown to be an effective tool in teaching earthquake engineering concepts to a broad range of students of different ages. The collection of activities
described in this paper illustrates a range of STEM concepts that can be achieved through engineering contexts. Linking the activities to what engineers do at large-scale test facilities—such as those belonging to NEES—provide an authentic condition where this knowledge applies. Also, these projects engage learners in realistic problem solving used by experts in STEM careers. Therefore, these learning activities are well suited to meeting the Next Generation Science Standards by illustrating the practice of engineers to design, build and test structures and devices using experimental and numerical methods. As a result, there is a high potential to increase both the learning and retention of the information and concepts explored during the activities.

Although these projects primarily represent outreach activities implemented by educational professionals at engineering facilities, work also includes supporting teachers’ replication of these learning activities in their own classrooms using low cost shaking tables that can be borrowed from the facilities or built using their own resources. Most of these activities may be easily scaled up or down by teachers through modifying the types of data collected, mathematical difficulty, and difficulty of construction.

Initial assessments have been successfully used to investigate the effectiveness of the learning activities from three different groups: instructors, participants’ classroom teachers, and the participants themselves. These data indicate that the hands-on activities using educational shaking tables are effective in developing K-12 students’ understanding of complex topics like vibration, resonance, bracing, energy dissipation, and seismic retrofitting. Furthermore, results indicate that participation in these programs motivates K-12 students to consider career paths in STEM.

9.0 Acknowledgements

This work was funded by the National Science Foundation (NSF) through the George E. Brown, Jr. Network for Earthquake Engineering Simulation program (CMMI-0927178). The findings, statements and opinions presented in this paper are those of the authors and do not necessarily represent those of the NSF.


