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DEVELOPMENT OF EARTHQUAKE ENGINEERING CURRICULUM FOR HIGH SCHOOL STUDENTS USING LOW-COST SHAKE TABLES

L. Van Den Einde[1]

ABSTRACT

A report by the National Academy of Engineering in 2010 states that engineering is a critical component to developing a community and workforce that understands the technical nature of the manmade world. Researchers 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. 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. To address this concern, a group of faculty across the Network for Earthquake Engineering Simulation (NEES) initiated an effort to develop, harden and broadly disseminate earthquake engineering curriculum primarily targeting high school students with the overarching objective of exposing and ultimately recruiting students into the engineering field. The vast curriculum available in the earthquake engineering community was inventoried and evaluated based on a rigorous rubric. In coordination with high school teachers as part of Project Lead the Way (PLTW), the faculty reviewed the inventory and selected several activities/projects to implement. The modules selected leverage the Network for Earthquake Engineering Simulation (NEES) low-cost shake table. During the remainder of this year, documentation supporting implementation of the curriculum including student assessment of learning gains will be developed. In Spring 2014, the curriculum will be pilot tested in PLTW high school courses (Civil Engineering and Architecture and Engineering Principles). The ultimate goal is to provide to the K-12 community with an "engineering" package that could be broadly distributed and implemented in high school programs.

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A report by the National Academy of Engineering in 2010 states that engineering is a critical component to developing a community and workforce that understands the technical nature of the manmade world. Researchers 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. 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. To address this concern, a group of faculty across the Network for Earthquake Engineering Simulation (NEES) initiated an effort to develop, harden and broadly disseminate earthquake engineering curriculum primarily targeting high school students with the overarching objective of exposing and ultimately recruiting students into the engineering field. The vast curriculum available in the earthquake engineering community was inventoried and evaluated based on a rigorous rubric. In coordination with high school teachers as part of Project Lead the Way (PLTW), the faculty reviewed the inventory and selected several activities/projects to implement. The modules selected leverage the Network for Earthquake Engineering Simulation (NEES) low-cost shake table. During this year, documentation supporting implementation of the curriculum including student assessment of learning gains will be developed. In Spring 2014, the curriculum will be pilot tested in PLTW high school courses (Civil Engineering and Architecture and Engineering Principles). The ultimate goal is to provide to the K-12 community with an "engineering" package that could be broadly distributed and implemented in high school programs.

Introduction

Recently, there has been a push to improve K-12 STEM education because of the realization that many students, especially at the middle school age, lose interest in math and science [1]. The lack of interest in STEM could be due to poor teaching and preparation, but more likely due to the disconnectedness of the K-12 science curriculum from topics and content relevant to students' daily lives and interests [3]. The National Academy of Engineering issued a report in 2010 [1] that stated that engineering skills are critical in order to develop a workface that understands the technical nature of the manmade world. To enhance engineering education, informal engineering education programs must be integrated into the K-12 curriculum, and engineering-focused schools must be supported [4]. Because of technological developments in

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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 [4].

The George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) has been a leader in education, outreach and training (EOT) for the earthquake engineering community with primary objectives that include generating interest in STEM careers, teaching students about earthquake engineering, and creating public awareness of NEES and its accomplishments [1]. Dedicated EOT staff at each of the 14 large-scale NEES experimental facilities are collaborating to develop educational activities to educate prospective students about earthquake engineering and the various methods to mitigate the effects of earthquakes. Curriculum and outreach activities that are developed are shared with other NEES sites and the public through the NEESacademy [5], a hub providing K-16 educators with an array of learning resources, learning objects, and learning modules.

Experiential tools such as instructional table-top "shaking tables" can be used to teach students about fundamental physics principles and can stimulate their interest in science, engineering, mathematics and technology (STEM) careers. These educational shaking tables can introduce complicated topics such as seismology, vibration response, and structural performance and design to students from K-12 [1].

This paper describes the development of earthquake engineering curriculum for high school students with the overarching objective of exposing and ultimately recruiting students into the engineering field. In collaboration with researchers from various NEES facilities, curriculum is being developed that is easily implemented and more broadly disseminated into K-12 schools. The modules being developed leverage a low-cost shake table being built by NEES. The ultimate goal is to provide to the K-12 community with an "engineering" package that could be broadly distributed and implemented in high school programs. An overarching objective is to increase awareness of how engineering is used to mitigate the impacts of earthquakes and increase interest in STEM fields. Materials being developed include lectures, instructions and a list of materials to build the low-cost shake table, materials to develop the demonstrations and projects that utilize the shake table, and teacher/student documentation including assessment tools. Impact is associated with the availability of documented curriculum that has been vetted with high school teachers and is easy to adopt and integrate into their classes.

The Need for High School Engineering Curriculum

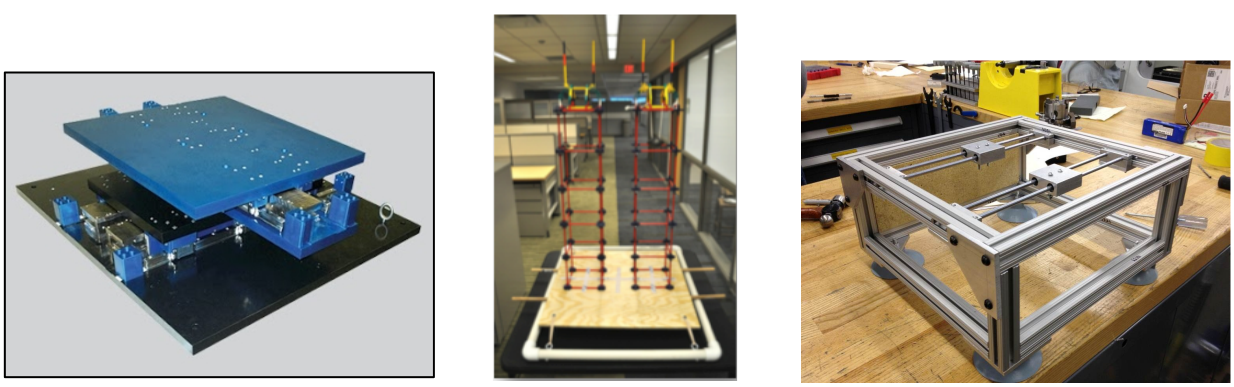
Because engineering is a critical component to developing a community and workforce that understands the technical nature of the manmade world [4] and engineering literacy can only be achieved when informal engineering education programs are integrated into the K-12 curriculum [2], recent steps have been taken to integrate engineering and technology into the K-12 classroom through problem-solving activities.

A primary part of students being able to construct knowledge and increase their interest in engineering is by engaging them in authentic scientific and engineering activities. Extensive engineering education research is focused on how engineering activities and experiences can be integrated into K-12 curricula [9] and [10]. There are many different models for how to engage students in what they are learning. Experiential learning is the process through which knowledge is developed via the use of engaging, hands-on activities and experiences that draw on prior understanding in order to form new connections [11]. Project Based Learning (PBL) allows students to grow through assisted problem solving activities that center on complex problems for which a variety of solutions exist [12]. Another approach defined in Physics by Hake [13] termed “interactive engagement” promotes conceptual understanding usually through hands-on activities. Feedback to the students is generated through discussion with peers and their instructors. The primary pedagogical approach for instructional activities is therefore to engage students with what they know and give them opportunities to refine their understanding with multiple learning experiences [10].

NEES EPICS Low Shake Table

Small-scale shaking tables are often used to teach 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 [1]. Typical small-scale instructional shaking tables apply a unidirectional dynamic load on a structure to simulate earthquake ground motions that vary in frequency and amplitude. A variety of instructional shaking tables have been developed, ranging from expensive computer controlled systems that have highly repeatable events (Figure 1a) but are expensive and not portable, to low cost manually operated tables for basic demonstrations of concepts (Figure 1b).

NEES is developing a servo-controlled, portable, and low cost but very accurate shake table to fulfill the needs for their community education and outreach programs through their EPICS: Engineering Projects In Community Service project (Figure 1c). EPICS is a unique program from Purdue University where teams of undergraduates design, build, and deploy real systems to solve engineering-based problems for local community service and education organizations. The EPICS table supports three types of input motions: harmonic motion with variable frequency and amplitude, an option to make your own earthquake input, and replication of existing earthquake records. The project described in this paper is making use of the EPICS low cost shake table for broad dissemination of engineering curricula into the K-12 community.



(a) (b) (c)

Figure 1: (a) Quansar table [6], (b) Hand operated table [7], and (c) NEES EPICS table

NEES Shake Table Working Group

Recently, the NEES Education, Outreach and Training (EOT) Committee initiated an effort to develop, harden and broadly disseminate earthquake engineering curriculum primarily targeting high school students with the overarching objective of exposing and ultimately recruiting students into the engineering field. To do so, they established a shaking table working group (NEESstwg) of interested EOT representatives from the NEES community to inventory existing curriculum across the country, select a handful of exercises and projects, make them production quality with adequate student and teacher documentation, and broadly disseminate the curriculum to K-12.

The vast curriculum available in the earthquake engineering community has been inventoried and evaluated based on a rigorous rubric. The NEESstwg reviewed curriculum that fell into three categories (one hour K-12 outreach, one day K-12 outreach, and 3-4 week project based learning activities). In coordination with high school teachers as part of Project Lead the Way (PLTW, described further below), the NEESstwg evaluated the inventory and select several activities/projects to implement, which are aligned with the existing PLTW curriculum.

Inventory of Curriculum

A review of available earthquake engineering curriculum was conducted to assess whether the activities identified are sufficiently developed with enough documentation and learning outcomes to be easily scalable. Two undergraduate students at UC San Diego perused activities found on a variety of educational websites such as NEESAcademy, the United States Geological Survey, the Incorporated Research Institute for Seismology (IRIS), teachengineering.org, as well as curriculum provided by the members of the NEESstwg (such as materials from the California State Summer School for Mathematics and Science (COSMOS) earthquake engineering cluster). The lessons and activities were inventoried using a prescribed rubric that assessed the following:

- Curriculum Title
- Category (identifying code such as shake table "ST" or liquefaction "LQ")
- Sub-Category (term describing primary subject of activity such as "Base Isolation")
- Source
- Author(s)
- Activity Objective
- Targeted Age Level
- Documentation (whether it exists and the quality of the documentation resources)
- Assessment (whether it exists and the quality of the assessment tools)
- Target Type of Activity (1-2 Hour Outreach, 1 Day Outreach, or 3-4 week curriculum)
- Cost

The inventory was reviewed by the NEESstwg to provide overall ratings for each activity or module to identify the top activities to vet with high school teachers.

Implementation

Project Lead The Way (PLTW) is a non profit organization that is a leading provider of rigorous and innovative Science, Technology, Engineering, and Mathematics (STEM) education curricular programs used in elementary, middle, and high schools across the U.S. (http://www.pltw.org/). They develop hands-on, project-based engineering courses for high schools and middle schools. Their engineering courses have been integrated in more than 4,700 schools across the country. In addition, PLTW trains more than 3,000 teachers each year to instruct its engaging, rigorous STEM education curriculum.

To ensure the curriculum developed in this project is aligned with state standards and appropriate for high school implementation, the NEESstwg is collaborating with the local PLTW organization through San Diego State University (http://www.pltwcalifornia.org). Four high schools in San Diego that teach PLTW courses (Principles of Engineering (POE) and Civil Engineering and Architecture (CEA)) have been identified to pilot the engineering activities and assessment tools in their classrooms. The three schools target a variety of socio-economic backgrounds (Scripps Ranch, Construction Tech, Mira Mesa and Morse High Schools). Ultimately, the schools will be given an EPICS shake table for use in their classrooms. These California teachers have expressed interest in bringing seismic concepts into their engineering courses, which are currently focused on loads more representative in other parts of the country.

The author has met with the teachers over the course of the year to better understand the existing engineering curriculum and identify areas where new seismic curriculum could be included. The teachers in the Principles Of Engineering (POE) course indicated that the area requiring improvement was the capstone project. A graduate student at UC San Diego has worked closely with one of the teachers to develop a seismic design capstone project that includes lecture material and a culminating balsa wood design-build project. This has recently been implemented in the classroom and was well received. In the Civil Engineering and Architecture (CEA) course, several areas to infuse seismic concepts through lectures, demonstrations, and projects were identified. These are described further below. The author and students will support the teachers as they integrate these activities into their high school classrooms during spring 2014. The required documentation as prescribed by PLTW will then be developed for the chosen curriculum. Results from formative and summative assessments (whether objectives met, whether curriculum is self explanatory, the effectiveness of the lessons in generating interest in STEM careers) during these pilot implementations will be used to improve the curriculum, documentation, and implementation details.

The project will culminate with a teacher development workshop to train high school teachers on how to implement the modules in their own courses. This will be tied closely with teacher training conducted by PLTW. The training workshops provide yet another opportunity to do formative and summative assessments of the material and documentation before placing the modules in the NEESAcademy, and will serve as a pathway for integration into national PLTW curriculum for broader adoption.

Representative Curriculum

The educational resources being developed across the NEES network [1] and beyond provide an excellent framework for learning about physical science, engineering, mathematics, and technology (i.e., STEM education). 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 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.

The following section provides representative learning experiences developed and tested as part of outreach efforts within NEES community. Although these activities may not be the final projects and lessons integrated into the pilot study described above, they serve as examples of the types of activities being further developed and hardened.

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, Figure 2) 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 [1].

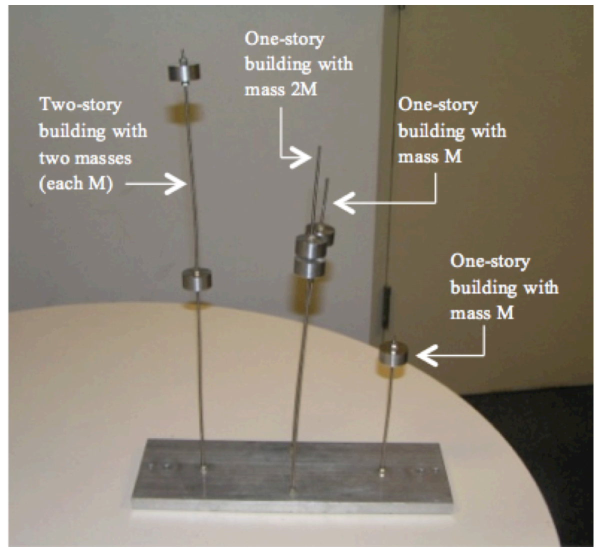


Figure 2: Masses on rods demonstration.

The model also allows users to change various parameters such as the length of rods which represents the height of a building, the number of masses representing the number of stories in the building, and size of masses representing the 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.

This activity is scalable for all age levels to demonstrate the concepts of vibration. Younger students learn about modeling structures, effects of mass and stiffness on frequency, sine waves, and resonance, while older students can use equations to calculate the natural frequencies of the structures and compare their predictions to the experimental results.

COSMOS High School Program

The California State Summer School for Mathematics and Science (COSMOS) 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 "When Disaster Strikes" cluster at 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. Three of the group projects using shaking tables are described below.

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 causing regular masonry structures to perform poorly during an earthquake. 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 program asks a team of three students to research and report on the structural aspects of unreinforced and reinforced masonry construction ([12] and [1]). 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 (Figure 3). Two different masonry structures are constructed using sugar cubes (simulating the masonry units) and cake frosting (simulating the mortar), one representing an as built unreinforced building, and one with retrofit strategies employed.


Figure 3: Retrofitted masonry structure.

Students must answer questions about *basic concepts* 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?


Figure 4: Timber design project.

Seismic Design of Timber Structures

Another COSMOS project involves the design, repair and/or retrofit of timber building structures and the evaluation of their seismic performance (Figure 4) [12]. Through this project students gain a better understanding of how timber structures perform in earthquakes and recognize the importance of diagonal bracing, shear walls, and strong connections between wood members. A preliminary structure is constructed without lateral bracing in the walls or floors, is tested on the shake table, and then either repaired or given a retrofitted design with bracing to improve its performance.

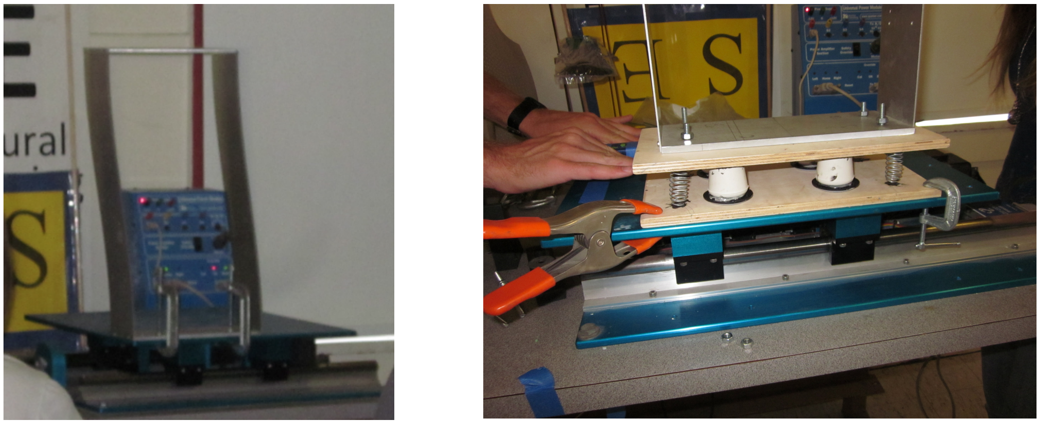
Students are asked to research *basic concepts* such as: 1) How are timber structures built? What types of wood are generally used? 2) What are the critical areas in timber structures during an earthquake? and 3) How have timber structures performed in past earthquakes? Students are also asked to research *structural design principles* such as: 1) How are vertical and lateral loads carried different through the members of a structure? 2) What is a structural diaphragm and how is it used? What are its potential weaknesses in an earthquake? and 3) How are lateral (shear) forces transferred to the ground in multi-story timber structures? Finally, *advanced seismic design techniques* are investigated such as: 1) What is a shear wall and what does it do? 2) What is a gusset plate and why would it be useful in timber structures that are subject to earthquakes? 3) What types of structural bracing are used in timber structures, and what are the advantages and disadvantages of each?

Base Isolation

Base isolation devices 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 resulting in structures with lower total acceleration. In the COSMOS program, one team conducts 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 the shaking table ([12] and [1]).

As with the other projects, 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. The team is then asked to design two different mechanisms to isolate their structure to avoid resonant vibrations near its natural frequency. After each modification to their base isolation system, students test the system on the shaking table to improve their designs. Figure 5a shows the fixed-based SDOF building being

tested on the shake table to determine its natural frequency, and Figure 5b shows the SDOF on a base isolation system during testing. Acceleration data are collected at the same amplitude and frequency so the team can tune their base isolation systems.



a) Fixed-base SDOF building b) Base isolated SDOF building

Figure 5: SDOF structures on the shaking table.

Future Work

The project described in this paper is an ongoing effort to take existing earthquake engineering curriculum and modify, enhance and harden it so that it can be broadly disseminated into K-12. The curriculum is being designed to use the low cost shaking table being developed by NEES for outreach and education activities. Existing curricula was inventoried and evaluated using a predefined rubric to assess the feasibility of incorporating the activities into high school classrooms. The activities are being fleshed out, tested on the NEES shake table, documented with teacher and student assessments, and will be piloted in spring 2014 in several high schools in San Diego as part of the Project Lead The Way (PLTW) organization. Ultimately, the activities will be vetted and selected in collaboration with the high school instructors to ensure that they compliment and can be easily integrated into their existing engineering curriculum. Following the pilot implementation, the activities will be refined and then incorporated into the summer PLTW training courses for broader dissemination.

This project has been a very rewarding experience because it has engaged the NEES community of researchers and educators who are passionate about teaching earthquake engineering concepts to K-12, undergraduates, graduates and the general public. The members of the NEESstwg are determined to develop tools and resources that can be easily adopted by others. The PLTW teachers are equally enthusiastic about integrating new curriculum into their courses that are more relevant to the issues faced in seismic regions such as California.

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Appendix

Appendices only should be used to provide information that would otherwise interrupt the principle focus of the paper or to provide supplemental information to be read by a small portion of the readership. If more than one appendix is necessary, they should be numbered. Appendices should precede the References section.

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