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EDUCATIONAL MODULES TO EXPLORE SOIL-STRUCTURE INTERACTION AND NONLINEAR BEHAVIOR OF COLUMNS

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ABSTRACT :

In most engineering curricula, students analyze idealized or simplified structures without the benefit of being able to compare their results to the behavior of real structures. Textbook examples often rely on simplified models of structures, with embedded assumptions that are not always obvious to the reader. Students rarely have the opportunity to examine these assumptions in detail to discover how the assumptions and simplifications are affecting their analyses. As part of a research project developed through the George E. Brown Network for Earthquake Engineering Simulation (NEES) the authors have developed two modules in which the behavior of concrete structures are analyzed and then compared with experimental data. The first module, designed for an advanced course in concrete design, explores the nonlinear behavior of individual reinforced concrete bridge columns. The second module, designed for a course in indeterminate structural analysis or nonlinear structural analysis, allows students to investigate the effect of soil modeling assumptions on the behavior of a bridge bent subjected to lateral loads. The modules incorporate data collected from several experiments on bridge bents and concrete columns, allowing students to compare analytical results such as strains, deflections and pushover curves with actual data. The modules are designed so that students may perform their analyses using different sets of assumptions, for example fixed base versus soil springs, and then evaluate the suitability of their assumptions. The modules are currently being tested at San José State University.

KEYWORDS: Education, NEES, concrete, nonlinear analysis, soil foundation structure interaction

1. INTRODUCTION

The George E. Brown Network for Earthquake Engineering Simulation (NEES) is an innovative research facility comprising 15 geographically distributed, shared-use equipment sites. The testing facilities at each equipment site are different so as to support various types of experimental work such as geotechnical centrifuge research; shake table tests; large-scale structural testing; tsunami wave basin experiments; and field site research. The goal of NEES is to advance earthquake engineering research and education through collaborative and integrated experimentation, theory, data archiving, and model-based simulation. NEES was several decades in planning, five years in development and construction, and began its operational phase in October 2004.

In 2003, National Science Foundation funded a “pre-NEES” research project to demonstrate the potential of the collaborative research model facilitated by the NEES networked laboratories and powerful information technology infrastructure. The project entitled *Collaborative Research: Demonstration of NEES for Studying Soil-Foundation-Structure Interaction* brought together 18 researchers from 10 universities and conducted tests at three NEES equipment sites and one additional university (Wood et al, 2004). In addition, the project team performed numerical simulations to design test specimens and evaluate the test results. While the primary goal of the project was to investigate some key aspects of soil-foundation-structure-interaction (SFSI) and refine SFSI computational models, secondary goals included testing the management and archiving of data, and piloting education and outreach activities. This paper summarizes two educational modules that were developed using test results from the project.

One objective of the educational modules is to involve students in engineering research (Anagnos and McMullin, 2004). The traditional model for undergraduate and graduate research is to work on a focused project under the mentorship of a faculty member or post-doctoral researcher. The research concept here is quite different. Instead of a one-on-one mentor-student research model, the goal is to create a research environment for the classroom. By taking advantage of the data archiving capabilities of NEES, students can review experiments, run simulations, analyze data, and participate in the research process under the direction of a faculty member who is not directly involved in the research project and who may be located at a site remote to the research university. Students can perform the research, individually or in groups, as an independent study or as an extension of concepts being taught in a course.

Another objective is to engage students in activities that lead to deeper understanding of theory and its limitations (Anagnos and McMullin, 2004). Often engineering courses, particularly in the area of analysis, present theory and require students to complete closed-form problems that embed a number of simplifying assumptions. The motivation for this is quite understandable; the problems are tractable, the theory is not obscured by deviations from expected behavior, and because problems have a single answer the students know when they get it "right." A disadvantage of this approach is that students don't necessarily understand that they are making simplifying assumptions, nor what the limitations of the theory are. By providing students with activities that complement the lecture and allow them to explore and discover underlying assumptions, and limitations, students gain a deeper understanding of engineering theories.

2. SOIL-FOUNDATION-STRUCTURE-INTERACTION PROJECT

Dissipation of energy by the yielding of soils and the foundations they support can influence the performance of a structural system. The degree and nature of these effects are not well defined by documented field evidence or by experimental testing. The interaction between vertical and horizontal foundation response is not understood well either. To account for this lack of understanding and to eliminate inelastic structural deformation in the foundation, designers often create very expensive designs for new construction or seismic retrofits for existing, deficient construction. Soil response is often idealized as being linear for soil-structure interaction problems, yet design-level loading will generally induce nonlinear soil response. The accurate evaluation of the seismic response of structures is limited by the ability to model the behavior and interactions among a structure, its foundation, and the supporting soil. Earthquake engineers use laboratory experiments to understand the performance of the key components of structural and foundation systems under controlled loading conditions. Experiments and the data collected therein are used to calibrate and validate computational models of component behavior. Although past research has produced significant knowledge about the behavior of *components*, the earthquake performance of *complete structural systems* is less well understood. The experimental, computational, and information technology resources provided by NEES have made it possible to test complete systems.

This project chose a continuous bridge on drilled shaft foundations as the prototype structure to study soil-foundation-structure-interaction (SFSI). This structure was selected because it represents a common construction type in regions of moderate and high seismicity. To account for the size and complexity of the prototype system, bridge performance was studied through a series of four, complementary experimental programs: centrifuge tests of individual bridge bents to evaluate the nonlinear response of the soil and foundation system; field tests of individual bents to evaluate the linear response of the soil, foundation, and structure in situ; shaking table tests of a two-span model to evaluate the nonlinear response of the structure subjected to bi-directional, incoherent support motion; and static tests of bents and individual columns to evaluate size effects and strength degradation in shear under cyclic loads. In addition, computational simulations were used to interpret the data from individual experiments, relate test specimen response to the performance of the prototype system, and understand the limitations of the boundary conditions of the experiments (Wood et al. 2004).

Two of the experimental programs were used as the starting points for the educational modules: static tests of columns and field tests of individual bents. These were chosen because they encompassed theory that is typically taught in senior level or first year masters level analysis and design courses: nonlinear behavior and indeterminate analysis. Specifically the modules focus on hinge formation in concrete columns and the modeling of the interface between the columns and the soil on a planar frame.

3. CONCRETE HINGE MODELING MODULE

The Concrete Hinge Modeling module was developed for a graduate level course in concrete design. Students explore two models to predict the formation of plastic hinges in concrete columns: FEMA-356 plastic beam model and a cross-section based fiber model. Predictions are compared to the results of a 1/2-scale model of the bent column that was tested at the Bowen Large-Scale Civil Engineering Laboratory of Purdue University. Figure 1 depicts the test specimen and test setup.

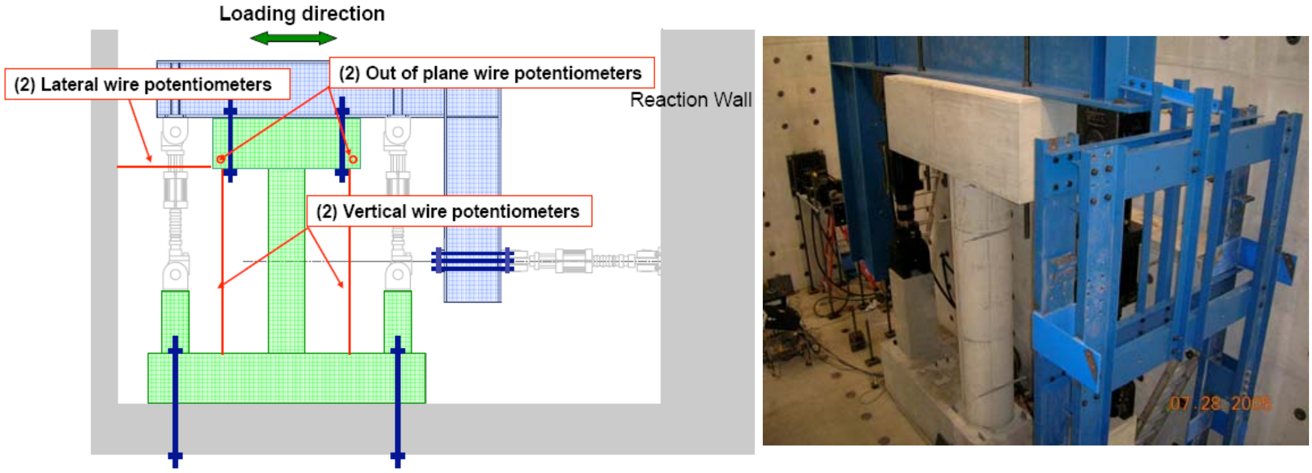


Figure 1 The 1/2 scale column is placed in testing apparatus with vertical and horizontal actuators to simulate seismic motion (credit: J. Ramirez)

Three 1/2-scale circular spiral reinforced concrete columns with varying shear span to depth ratios and spiral reinforcement ratios were tested. Columns were subjected to displacement reversals to evaluate strength degradation in flexure and shear under cyclic loads. Axial load was applied using two 220-kip capacity hydraulic actuators. The lateral load was applied using a 330-kip capacity hydraulic actuator attached to a strong wall and the loading frame attached to the top cap. The test setup simulated a column fixed against rotation at top and bottom, and fixed against displacement at the bottom. Lateral movement of the top of the columns produced a double curvature deflected shape and a plastic hinge at column top and bottom.

The module helps students work through the modeling process sequentially:

1. The first step is transferring the experimental test specimen to a simplified analytical model. Using the expectation that the double curvature will behave the same as two cantilevers connected at mid-height, students are asked to represent the entire column by a half-height cantilever. This allows students to use a statically determinant structure to relate horizontal shear to bending moment at the plastic hinge. During this modeling step, students derive the relationships that will allow them to convert the shear and deflection of the cantilever to the shear and deflection of a full-height column as well as a multi-column bent. Students discover that the horizontal deflection of the full-height column or multi-column bent is double the cantilever deflection while the column shear equals the cantilever shear and the multi-column bent shear is the cantilever shear times the number of columns.
2. Students then calculate the ACI bending strength of a circular concrete column. This bending strength is used as a normalizing value for results of the analytical models.
3. The first analytical model students develop uses the concepts of FEMA 356 (FEMA, 2000). This standard provides specific values for a multi-linear representation of the moment-rotation relationship for a concrete column. From the moment-rotation relationship, students develop the pushover curve for the

full-height column.

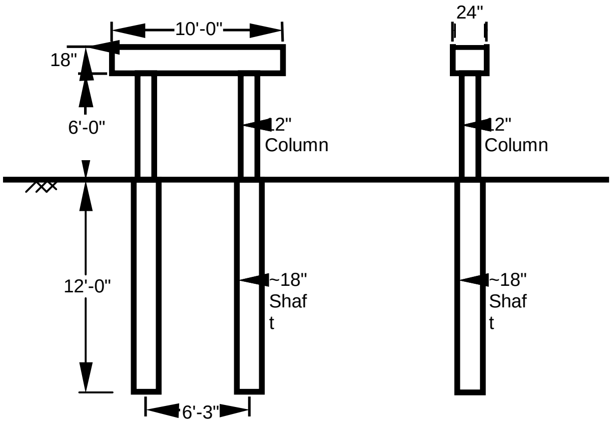
4. One of the primary inputs for a fiber model is the assumed relationship between axial stress and strain. For this project, students are provided the material relationships developed by Mander et al. (1988). The students are asked to plot the relationships for confined concrete in compression, unconfined concrete in compression, and reinforcing steel. Combined with the Akkari and Duan (2002) model for concrete in tension, the students have the necessary stress-strain relationships for modeling. To simplify the student work in the next step, the continuous functions of these relationships can be converted to multi-linear functions.
5. To develop a fiber model for the cantilever column, students require a structural model indicating the relationships between hinge length, hinge location, elastic behavior outside the hinge zone, and the relationships between axial strain, curvature and rotation. Students develop a spreadsheet, which has a row for each unique fiber in the model, to complete the model. The spreadsheet calculations determine the fiber force and displacement, and convert these values into equivalent curvatures and applied shears.
6. Iteratively, students can increase the rotation of the hinge while monitoring the behavior of each fiber to ensure structural equilibrium while the rotation slowly increases. At particular points of loading, the spreadsheet must be adjusted to adapt to changes in the material behavior, such as cracking of concrete, crushing of concrete, or yielding of steel reinforcement. In addition, at each event during the loading, students are asked to determine the horizontal shear and deflection of the column, thus developing a pushover curve incrementally.
7. Students interpret the output from the two analytical models by comparing pushover curves of the cantilever column structure. The models are compared for their ability to indicate various failure modes of concrete columns (concrete cracking, peak strength, etc.) and their engineering complexity.
8. Finally, students compare their analytical models with the results from the experimental testing and compile their work into a report.

Pedagogical features of the module include:

1. Teams of students work together, which reduces the amount of work while allowing students to learn from each other's understanding of the challenge. Teams of two to three students seem most effective.
2. Students are assigned pre-lecture assignments to prepare for the coming discussion. These pre-lecture assignments include online research, structured reading assignments, and/or summary reports. The pre-lecture assignments are tightly scripted so that students do not require inordinate amounts of time to complete the work, but are required to consider the concepts and arrive at class with a working understanding of the topic for the day.
3. The instructor performs a short pre-assessment of students' learning at the beginning of the lecture period to evaluate the students' preparation for the day. This pre-assessment is done in the first few minutes and allows the instructor to adjust the presentation for the audience's knowledge level.
4. The instructor presents a digital mini-lecture that describes the main topics of the day, presents critical terminology, and describes the primary concepts of the day's tasks.
5. Student teams then perform hands-on active learning by completing some portion of the assigned tasks in class. These may include manual sketching of structural models, development of the moment-rotation relationship defined by FEMA 356, initial development of spreadsheets for material or fiber models, or use of their spreadsheet to initiate the incremental analysis of the fiber model.
6. The instructor provides interactive feedback to student teams during the classroom period and office hours. By reviewing the current state of the team's work and the use of probing questioning, the instructor responds to the students' knowledge gaps by facilitating a discussion among the team members rather than instructing the team in which direction to proceed.
7. An emphasis is placed on evaluating student research skills in addition to their technical accuracy. Online research assignments include a short review of a student-selected NEES site and work is assessed on the team's ability to collect and report specific information about the site, rather than a detailed evaluation of the site. This allows students to gain a more global view of the NEES environment rather than focusing their attention on a single site. Additionally, students are able to explore sites that peak their interests.

4. SOIL FOUNDATION STRUCTURE INTERACTION MODULE

The soil-foundation-structure-interaction module was developed for a senior level or graduate level course in indeterminate structural analysis or computer methods in structural analysis. Students are asked to develop analytical models of two 1/4-scale bridge bents that were tested at University of Texas, Austin and compare computed pushover curves with pushover curves developed from experimental data. Elevations of Bent #1 are shown in Figure 2. Bent #2 has identical dimensions except that the columns are 3 ft. (0.914 m) tall.



(a) Transverse Elevation (b) Longitudinal Elevation

Figure 2 Elevations of Bent#1 tested at University of Texas, Austin (source: Lee, 2007).

The bents were subjected to both static and dynamic tests in the field. A modal hammer was used to excite the bents for the purpose of measuring free vibration response. Subsequently, the bents were shaken using T-Rex the tri-axial shaker at the University of Texas, Austin NEES equipment site and forced vibration response was measured. The bents were subjected to pseudo-static cyclic lateral loads using both T-Rex and Liquidator to pull on each bent (Figures 3 and 4). Lastly the bents were pulled laterally until they failed completely and collapsed. Various load and performance data were collected using load cells, string potentiometers, linear potentiometers, displacement transducers, strain gages, and accelerometers.

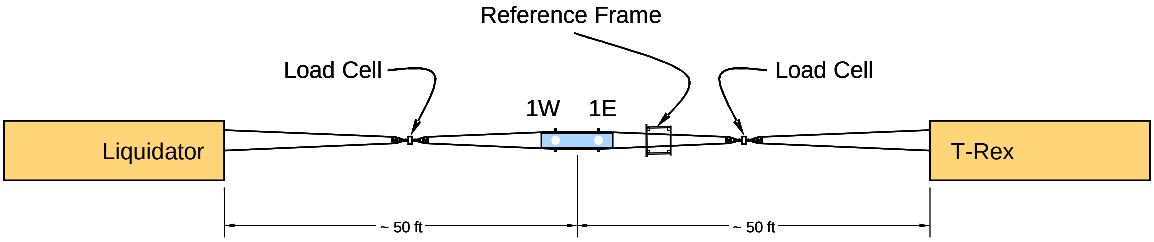


Figure 3 Plan view of two NEES shakers applying loads to scaled bridge bent (credit: S.L Wood).

Figure 4 T-Rex preparing to pull on Bent#1 (credit: S.L. Wood)

Three approaches were used to model the column-soil interface of the bridge bents as shown in Figure 5. These three sets of modeling assumptions were chosen for demonstration purposes, but a student has many choices to experiment with. The first model uses an infinitely rigid support at the base of the column. This fixed-base model in which no translational or rotational movements are allowed at the base of the columns is a common model in structural analysis courses. This reactions and moment diagrams of this simple model are readily calculated by hand making it a useful model for practicing both approximate methods and matrix methods. While the fixed-base model would be a reasonable representation of the behavior of the bent if it were anchored on solid rock, it does not account for the flexibility of other types of soil. The second model attempts to account for the stiffness of the pile but not the stiffness of the soil. In this very simplified model, the stiffness of a linear rotational spring at the base of the column is developed by treating the pile as a propped cantilever with the fixed end at depth and the propped end at the soil surface. The multiple spring model, the most realistic of the three, assumes that the soil is not rigid and that the interaction of the pile with the soil affects the soil stiffness. This nonlinear behavior is modeled with 11 nonlinear springs that also take into account the increased stiffness of the soil with depth. The nonlinear stiffnesses of the springs (Rao, 2005) were calculated from p-y curves determined from an LPILE analysis (Black, 2005)

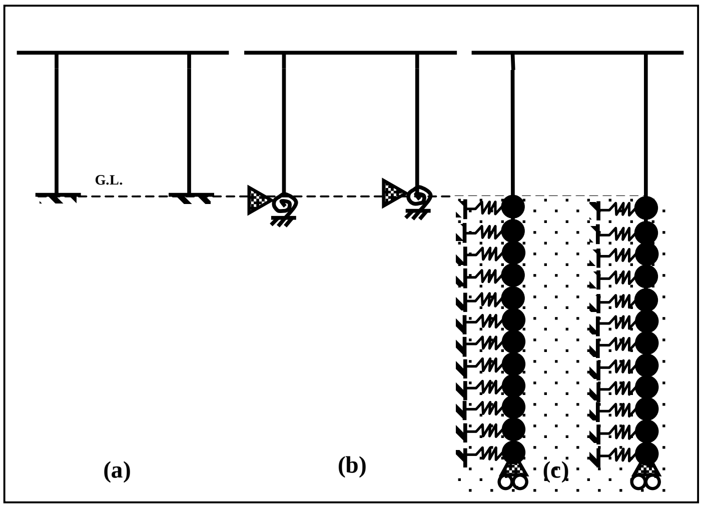


Figure 5 Three analytical models of bridge bent: (a) fixed base, (b) rotational spring, (c) multiple nonlinear springs (source: Lee, 2007)

The structural analysis software SAP2000 distributed by Computers & Structures, Inc. was used for modeling. SAP2000 was selected because the demonstration version can be downloaded from their web site and used for free by any student. The demonstration version is limited to 30 nodes which posed a number of modeling challenges. Centerline to centerline dimensions were used to represent structural members and “end offsets” were used to account for the depth of the beam at the beam-column joints. Placement of steel reinforcing and as-built dimensions were modeled as closely as possible. For example, though the piles we designed to be 12” (305 mm) in diameter, construction equipment restraints resulted in them being 18” (457 mm). This was included in the model. For the all three models, hinge formation was enabled at locations of maximum moment: a) at the top and bottom of the columns for the fixed base, b) at the top of the columns for the rotational spring, and c) at the top of the columns and at 3 ft (0.914 m) and 6 ft (1.83 m) below grade for the spring model.

By simply performing a linear analysis students can see the impact of their modeling choices on moment and shear diagrams. Figure 6 compares the moment diagrams of model (a) and (c). The student will see that the fixed based model produces a moment diagram with maxima at the top and base of the columns, resulting in hinging at these two locations. The multiple spring model produces maximum moments at the top of the columns and halfway down the pile.

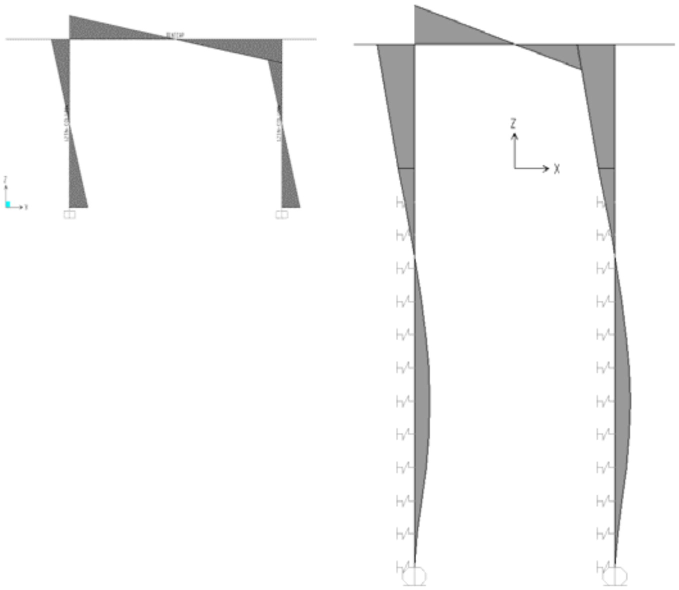


Figure 6 Comparison of moment diagrams from fixed-base and multiple spring models

Running a nonlinear analysis allows students to observe hinge formation using animation features of the SAP2000 software and to compare pushover curves from the three analyses with each other and with those developed from experimental data. Figure 7 compares the pushover curves for (a) Bent#1 and (b) Bent#2. Students observe, for example, that the fixed-base and multiple spring models overestimate the capacity of the experimental bent with hinges forming at much higher loads for Bent#1. The capacities for Bent#2 more closely match those of the experimental data. They also observe that the analytical models predict much stiffer behavior than the test specimen, with hinging and collapse occurring in most cases with less than an inch of frame displacement.

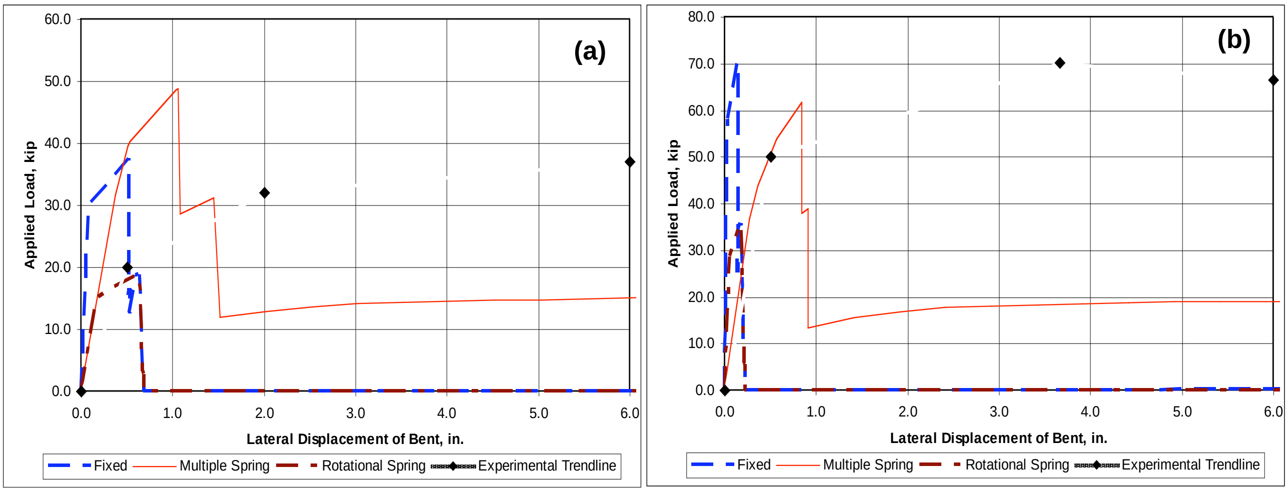


Figure 7 Comparison of pushover curves from the three models and from (a) Bent#1 experimental data and (b) Bent#2 experimental data.

At this point students become the researchers trying to interpret their models and the data, and proposing reasons why the models differ. Students have access to a written case study of the tests as well as photographs and videos. Students might focus on the cracks and gaps that formed around the tops of the piles during testing or on modeling features such as the behavior of the plastic hinges as defined by SAP2000. There is no right answer here; the point is for students to explore different ideas through varying the model parameters and boundary conditions. This type of inquiry allows them to discover on their own the impact of the modeling assumptions they are making.

5. NEXT STEPS

Dissemination to the educational community is one of the primary goals for the project. Dissemination of modules of learning can now be done digitally, allowing for better interaction between users and sharing of updated information. A proposed method of dissemination includes:

1. An online repository of instructor notes, student handouts and presentations for access by individual faculty. This includes a course timeline, educational objectives and expected outcomes. Sample questions and grading criteria from exams may also be provided.
2. An online discussion forum for sharing of experiences that educators have in using the modules. This discussion will allow for better understanding of the wide variety of student needs and the various methods instructors pursue for meeting those needs.
3. Professional development of instructors. The challenge of implementing new educational modules and/or pedagogical techniques is the significant time required for instructors to incorporate these ideas into their class schedule. Skills in facilitating active learning, probing questions, and inquiry-based learning are adjustments necessary to significantly enhance engineering education. Potential forums for professional development include the development and delivery of two-day instructional workshops appended to national conferences where large numbers of university faculty are likely to converge.

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