PROJECT DESCRIPTION

1. PROJECT TEAM

The table below summarizes the members of the project team. The time column is the annualized full-time-equivalent in percent over the 4-year schedule of the project; NC in this column indicates No Charge participation in the project. Year-by-year person-months of effort are detailed on our Budget forms.

Table 1: Summary of Project Team

Name, Title, Affiliation	Expertise	Project Role(s)	Time
Jonathan Bray, Prof., U. of California, Berkeley (UCB)	Geotechnical earthquake engineering; soil-foundation-structure interaction; liquefaction; performance-based engrg	PI; lead role in coordinating project; lead geotechnical engineer; lead on performing 3 centrifuge model tests; lead on ground motions, soil model, and seismic site response analyses	11%
Gregg Fiegel, Chair of the Dept. of CEE and Prof., Cal Poly San Luis Obispo (CP)	Geotechnical earthquake engineering; centrifuge modeling; undergraduate education	Faculty Associate; assist in centrifuge modeling and involving undergraduate researcher in testing; education and outreach.	2%
Tara Hutchinson, Assoc. Prof, U. of California, San Diego (UCSD)	Structural engineering; soil-foundation-structure- interaction numerical analyses and centrifuge testing.	Co-PI, lead role in performing fully nonlinear soil-foundation-structural-interaction dynamic analysis; responsible for constructing nonlinear structural models	9%
Bruce Kutter, Director of the Geotechnical Centrifuge Facility and Prof., U. of California, Davis (UCD)	Geotechnical earthquake engineering; centrifuge modeling	Co-PI, lead advisor on all matters related to centrifuge testing; lead on performing 3 centrifuge model tests	7%
Robert Reitherman, Executive Director, CUREE	Outreach and education experience; project management.	Co-PI, Manages CUREE's education, outreach, and policy/implementation role.	6%
Andrew Whittaker, Prof., U. at Buffalo-SUNY (UB)	Structural engineering; performance-based design.	Co-PI; lead structural engineer; prototype building development; SFSI analysis; development of PBD tools and code guidelines	8%
Professional Practice Committee	Practitioner experience; involvement in current implementation projects.	Advise on the research plan, guide implementation of research results.	NC

2. EXPERIMENTAL FACILITIES

The 9-m radius centrifuge at the University of California, Davis, which can carry a 4,500 kg payload at up to accelerations of 75 g, will be used for the proposed research. The 1.7-m long by 0.7-m wide by 0.7-m deep flexible shear beam container with the uniaxial (horizontal) shaking mode earthquake simulator will be employed. Typical instrumentation already available and paid for under the NEES O&M funding of the UC Davis geotechnical centrifuge will be used, including pore-pressure transducers, accelerometers, and LVDTs. The distributed high-speed wireless data acquisition system and an array of high-speed video cameras available at UC Davis will be used to record data during the test, which will be available as streaming data during the experiment and archived later as part of the NEES data repository.

Ground conditions within the centrifuge container will represent foundation conditions commonly encountered in downtown Los Angeles (i.e., medium dense and dense unsaturated sand and in two cases a nonliquefiable clayey fill atop liquefiable loose sand which is in turn underlain by nonliquefiable dense sand). The properties of the model Nevada sand, a well-characterized clean fine sand, will be varied to evaluate the effects of soil density. In the last two experiments, it will be saturated in a loose and then medium dense state so that it liquefies during strong shaking, so that the buildings must respond to a highly nonlinear soil response. The cone penetrometer and an array of accelerometers will be used to characterize the strength and stiffness of the soil.

Due to its relatively large size, the Davis centrifuge can accommodate several small-scale model buildings during each experiment. In the first experiment, 3 plane strain nonlinear structural models will be separated so each model responds independently in a 2-D manner. In the second experiment, 3 rectangular nonlinear structural models will be placed so that each model responds independently and is free to move bi-laterally. In the remaining experiments, a grid of 3 x 2 nonlinear structural models (i.e., 6 buildings) will be placed adjacent to each other to replicate the arrangement found in a typical city block in Los Angeles (and in other urban settings). These structural models will be sophisticated in terms of centrifuge modeling wherein the building models are typically rigid or linear elastic one degree-of-freedom structures. Some buildings will have basements, some will not. All but one building will have a mat foundation, and one will have individual spread footings. They will vary from 2 to 6 stories in height.

A total of 6 centrifuge tests will be conducted over a 4-year project period. One test will be conducted in the second half of year 1 after completing the initial analyses of the proposed model; two tests will be completed in the second and third years; and one test will be completed in the last year of the project. This level of activity has been found by Professor Bruce Kutter (PI of the UC Davis NEES Geotechnical Centrifuge Facility) as being reasonable based on previous experiences with similar projects. Each test will require approximately 3 weeks of set up, 5 days on the arm (with 1 day of actual spinning time), and 1 week of model examination and take-down at the UC Davis site. With the amount of data produced through each experiment, 4 months of data interpretation and experiment back-analysis will be required, which will be conducted off the NEES equipment site at UCB, UCSD, and UB. Data will be archived in the NEES database after each test and then made available through an interactive web site for research collaboration and educational use.

Table 2 below provides the solicitation-specified information on NEES Equipment Site (ES) usage. The University of California at Davis (UCD) NEES ES will be used for the physical-simulation component of the research project. The shaded cells in the table indicate specific ES equipment usage in quarters. The numbers indicate the number of months of expected use of each piece of equipment over the shaded duration. The final schedule of work will be established with the NEES Consortium following contract award and discussions with other NEES users of the UCD ES.

Table 2. University of California at Davis Equipment Site Usage[1]

Equipment	**NEES Equipment?**	**Year 1**				**Year 2**				**Year 3**				**Year 4**			
Centrifuge	Yes			2		2		2		2		2		2			
FSB container	Yes			6		5		5		5		5		5			
Four high speed video cameras	Yes			1		1		1		1		1		1			
Approx 120 wired sensors	Yes			4		4		4		4		4		4			
Wireless DAQ – and 50 sensors	Yes			4		4		4		4		4		4			

1. Numbers in shaded cells represent the number of weeks of projected use over the shaded duration in quarters.

3. FUNCTIONAL BUDGET

Table 3 lists the project budget in functional terms using the breakdown identified in the NEESR solicitation. An approximate annual breakdown of expenditures is presented, noting that most of the tasks are tightly integrated and interdependent, making it difficult to assign exact dollars. Further details on the project budget are presented on the NSF Form 1030s in the Budget section.

Table 3. Functional Budget

Activity	**Cumulative subtotal**	**Cum. %**	**Year 1**	**Year 2**	**Year 3**	**Year 4**
Research activities budget						
Experimental activities	$880,000	55%	$225,000	$225,000	$225,000	$205,000
Specimen removal/disposal	$0	0%	$0	$0	$0	$0
Non-experimental activities	$410,000	25%	$112,000	$112,000	$94,000	$92,000
Education/outreach/implementation	$160,000	10%	$27,000	$25,000	$43,000	$65,000
Data archiving and sharing	$40,000	3%	$6,000	$13,000	$13,000	$8,000
Management	$110,000	7%	$30,000	$25,000	$25,000	$30,000
Total	$1,600,000	100%	$400,000	$400,000	$400,000	$400,000

4. SUMMARY OF PROPOSAL PREPARATION DISCUSSIONS WITH UCD NEES SITE

The extensive knowledge of the capabilities of the UCD ES is an essential element of this proposal, because the proposed project is innovative and technically challenging. Co-PI Kutter, who is also the PI of the UCD ES, understands the capabilities of the UCD centrifuge better than anyone. He and Hutchinson have already employed this centrifuge to perform experiments to investigate aspects of soil-foundation-structure-interaction. Bray and Hutchinson have discussed scope, cost, etc. with the UCD NEES ES PI, which is Kutter. The cost basis for the soil material and other supplies required for the experiments at the ES used the pre-existing contacts of the ES with local suppliers. The proposed work will be conducted at the NEES Equipment Site (ES) at the University of California at Davis (UCD). PI Bray and Co-PIs Kutter and Hutchinson have extensive knowledge of the UCD ES, and it was not necessary to engage NEES staff in further discussions regarding the use and capabilities of the ES.

5. OVERARCHING VISION AND THE "GAP" THAT THE PROPOSED PROJECT FILLS

Buildings do not typically exist in isolation. In our major cities, they are constructed adjacent to each other, and there are important physical interactions that the profession is missing by ignoring this fact. For performance-based earthquake engineering to advance, the profession needs to address this issue. Our vision of performance-based design of individual buildings within clusters of buildings forming dense urban environments can only be realized by fully integrating engineering seismology, geotechnical engineering, and structural engineering tools for numerical and physical simulation and loss computations. The cartoon of Fig. 1 illustrates the integration of scientific and engineering knowledge and analytical tools that is required if we are to assess reliably the potential aggregate loss within a city from the point of earthquake rupture, the modification of motions entering the base of a building, and through the response (damage) of individual building components and its entire system.

Fundamental scientific advances have been made in the past 5 years in the prediction of strong ground motion by researchers affiliated with the Southern California Earthquake Center (SCEC) and much knowledge related to the prediction of structural response through the point of incipient collapse and the response of nonstructural components and contents has been acquired through research efforts at the NSF-funded Earthquake Engineering Research Centers. However, substantial gaps remain in our knowledge of the interaction of soils, foundations, and superstructures under earthquake shaking of intensities ranging from minor to severe. Unless these gaps are filled in a rigorous and substantial manner, we as a profession will be unable to realize the benefits offered by performance-based earthquake engineering.

We plan to start to fill these gaps in the realization of performance-based earthquake engineering by capturing the soil-foundation-structure-interaction response of buildings within the overall concept of "*earthquake rupture-to-urban resiliency*" by developing basic science, knowledge, and enabling technologies in the interacting disciplines of geotechnical and structural earthquake engineering. Section 8.3 (*Research Outcomes*) provides a detailed list of our research products. Importantly, we recognize that our major cities are composed of clusters of closely spaced buildings rather than isolated buildings, that the seismic- and wind-induced response of one building will influence the performance (response) of adjacent buildings, and that interaction between buildings at the foundation level must be addressed if realistic estimates of performance and loss are to be made.

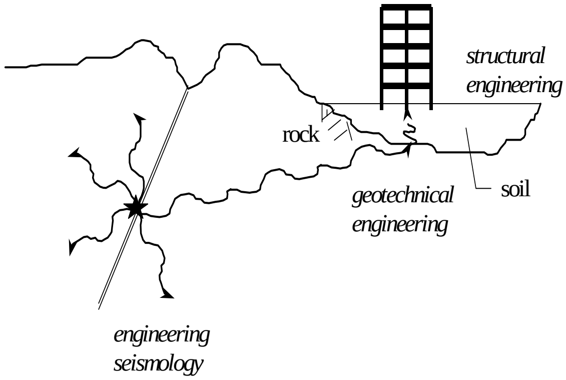

Fig 1. Interdisciplinary earth-science and earthquake engineering research (after Moehle)

The proposed project supports the long-term vision of our profession to provide realistic assessments of the resiliency of a major U.S. city that faces a seismic threat in that robust methods for capturing the soil-foundation-structure-interaction (SFSI) of a city block of buildings, including all critical elements of nonlinearity, are developed. There will be much more required in the areas of advancing ground motion prediction methodologies to better understanding societal response to major catastrophes, but we view the proposed project as a necessary step forward in one of the most pressing areas of performance-based earthquake engineering. The recent ATC-73 (ATC 2007) document that identified research priorities for NEES specifically cites building systems tests as a key research priority for calibrating engineering tools. The studying and development of models to capture SFSI are also identified as high priority research needs in ATC-73.

6. LITERATURE REVIEW

The PIs performed a detailed literature review. The literature review, coupled with technical discussions with colleagues working in the field of SFSI, some funded by NSF, enabled the PIs to identify clear gaps in our knowledge and to develop an innovative program of work that builds on past studies, leverages on-going NEES research, and avoids duplication of past or current work by others. The following subsections summarize the literature review completed for the development of this proposal.

Earthquake Ground Motions: For many major cities in the Nation (e.g., Los Angeles, Salt Lake City, San Francisco, and Seattle), the seismic hazard is dominated by nearby faults that are capable of generating intense forward-directivity (FD) motions from large magnitude earthquakes. Although in recent years the special characteristics of near-fault FD motions has attracted much attention (e.g., Somerville et al. 1997; Alavi and Krawinkler 2000; Mavroeidis and Papageorgiou 2003; Bray and Rodriguez-Marek 2004, Huang et al. 2008), their combined effects on soils, foundations, and structures are not well understood and are studied far less than those SFSI effects of "ordinary" ground motions, which were not recorded in the near-fault region.

Analytical studies of the nonlinear response of multi-story structures with fixed bases indicate that the seismic performance of these systems depends greatly on the peak ground velocity (PGV), period of the velocity pulse (T_v), and number of significant pulses (e.g., Hall et al. 1995; Krawinkler and Alavi 1998; Sasani and Bertero 2000; Mylonakis and Reinhorn 2001; and Zhang and Iwan 2002). Few studies, however, have examined the response of a structures founded on soil to FD motions while considering important nonlinear SFSI effects. Moreover, we know of no studies of the seismic performance of clusters of adjacent structures, some with basements, to near-fault FD ground motions. A sufficient number of near-fault FD motions have been recorded (i.e., > 60) so that it is now possible to use this empirical set of FD motions in experiments and simulations and capture many aspects of the special characteristics of near-fault motions. However, for a more robust examination of near-fault effects, the numerical simulations will also take advantage of the hundreds of FD motions generated as part of the Pacific Earthquake Engineering Research (PEER) Center Next Generation Attenuation (NGA) relationship study, which has just recently been completed (e.g., Campbell and Bozorgnia 2007), as well as the extensive "database" of numerical simulations of both near-fault and "ordinary" ground motions developed by the Southern California Earthquake Center (SCEC) through its "TeraShake" simulations of several earthquake scenarios that could impact the LA Basin (Jordan 2005).

Seismic site response studies that consider the nonlinear response of soil profiles to bi-directional shaking from near-fault FD motions (e.g., Rodriguez-Marek and Bray 2006) indicate that the important FD ground motion parameters of PGV and T_v depend significantly on local site conditions. The PGV is amplified at stiff soil sites that can sustain the high earthquake-induced shear stresses produced by intense FD motions and attenuated at soft soil sites, where soil failure occurs. Soil failure may attenuate the intensity of the transient values of PGV and PGA, but it leads to permanent displacements that may adversely affect structural performance. Deep soil profiles tend to increase the T_v of a FD motions, which in turn also affects structural performance. It is clear that additional work is warranted to investigate the effects of intense, pulse-like FD motions on the nonlinear response of soil, foundations, and structures.

Soil-Foundation-Structure Interaction (SFSI): The interaction between soil, foundation, and structure during seismic shaking was for many years neglected by the profession during routine design. However, SFSI simulation procedures have garnered much attention in the past seven years (e.g., Stewart et al. 1999; Pecker and Pender 2000; Martin and Lam 2000; Pitilakis et al. 2004). As a result of these and other studies, analytical procedures for addressing SFSI effects for buildings with at-grade foundations are presented in FEMA guidelines for new (e.g., FEMA 2004) and existing (FEMA 2000) construction. Kinematic and inertial interactions have been addressed, with approximate methods suitable for nonlinear static analysis in FEMA 440 (FEMA 2005). These procedures were based in part on important analytical studies in the 1970s (e.g., Bielak 1975; Chopra and Gutierrez 1974; Jennings and Bielak 1973; Liu and Fagel 1971; Roesset et al. 1973; Veletsos and Meek 1974; Veletsos and Nair 1975; Veletsos 1977), which were supported by empirical evidence in an average sense (Stewart et al., 1999). However, the variability (dispersion) was shown to be too large for the procedures to be useful in performance-based earthquake engineering. Further, studies such as those by Harden et al. (2006) indicate that the nonlinearity introduced by uplifting of and yielding below shallow foundations can increase displacements resulting in overstress to some structural components. Using various code-based procedures to investigate the effects of foundation uplift, this study found that current codes of practice can be highly unconservative. Moreover, the effects of building embedment and building-to-building interaction are not considered with existing procedures. Nor have these analytical procedures been validated by earthquake-simulator testing of moderate-to-large-scale soil-structure systems. The proposed research project will provide the data to validate or refine these analytical procedures. Importantly, low- to medium-rise buildings of conventional (non-nuclear) construction are typically supported on shallow foundations of a depth of about a meter or atop single or multi-level reinforced concrete basements. These foundations and/or basements modify the free-field earthquake motions through SFSI (see FEMA 440). The engineering profession's understanding of SFSI for low- and medium-rise buildings is limited, which is problematic, because more than 95% of the engineering buildings are either low- or medium-rise.

Since the early 60s (Housner 1963), engineers have realized that rocking of stiff (or low-rise) structures on shallow foundations can effectively dissipate earthquake-induced energy but that overloading the soil can produce foundation deformations that can damage foundations and superstructures. Over the years there have been a number of Winkler-based approaches adapted in an effort to harness these benefits (e.g., Bartlett 1976; Weissing 1979; Chopra and Yim 1985; Nakaki and Hart 1987; Allotey and Naggar 2003, 2007), and as a result modern building codes and guidelines suggest a Winkler spring approach to analyze shallow foundation response under earthquake shaking. It is recognized however that, while useful insights into SFSI result from such an approach, the numerical models are not comprehensive, because the soil is represented as discrete independent springs, and this simplified approach requires a number of significant assumptions.

Recently, experimental data supporting evaluation of modeling approaches has been generated both in the centrifuge and at 1-g. At the UC Davis centrifuge, for example, Rosebrook and Kutter (2001) and Gajan et al. (2003) completed an extensive series of tests evaluating the cyclic and dynamic response of isolated (building) shear walls on strip footings. In the past two years, this work has been extended to bridge structures (Ulgado et al. 2007) Soil-foundation response data from these centrifuge experiments was then used by Harden et al. (2005) to evaluate and refine the effectiveness of available spring-based methods to predict the observed responses. The building-footing centrifuge test data was also used by Gajan and Kutter (2007) to develop a macro-element modeling tool for locally capturing soil-foundation response. Similarly, at the 1-g scale, prior experimental studies have typically involved small-scale tests of isolated columns on spread footings or individual shear walls on strip footings (e.g., Taylor et al. 1981; Faccoili et al. 2001). To the authors' knowledge, only one series of experiments of an entire building-foundation system has been conducted to date (Chang et al. 2007). These tests, however, modeled only a 2D portion of a building, and did not systematically investigate issues such as footing embedment, footing size, etc. A comprehensive experimental study that employs large-scale earthquake-simulator tests of a complete structural system founded on soil, with and without significant embedment, has not been conducted.

We recognize that research work is under way on a variety of topics related to SFSI for buildings and bridges; some of the work is funded by NSF and some is being undertaken by faculty involved in this project (i.e., Bray, Kutter, and Hutchinson). This other work involves the use of the UB-NEES laminar box, the shakers at UCLA-NEES, the centrifuge at UCD-NEES, and the shakers at UTA-NEES. We discussed the scope of these projects with either the PIs (where possible) or the Equipment Sites conducting the work and concluded that we are not duplicating on-going research activities with our proposed work that is described below.

The centrifuge models of buildings with basements will also allow us to measure the seismic earth pressures on basement walls. Recently, several investigators have noted that the use of a modified Mononobe-Okabe, Wood (1973), or Steedman and Zheng (1991) method, for example, is overly conservative in estimating the dynamic earth pressures that actually develop on embedded walls (e.g., Al Atik and Sitar 2007). There is still much controversy in this area, however, for example, the recommendations of Ostadan (2004) differ greatly from those of Al Atik and Sitar (2007), and so additional work is warranted to measure seismic earth pressures on basement walls.

Performance-Based Earthquake Engineering: A key goal of the PEER Center (www.peer.berkeley.edu) was to develop the framework for performance-based earthquake engineering (PBEE). The framework was developed in the late 1990s (Moehle 2003), and many archival journal papers have been published on its mathematical underpinnings and aspects of its implementation in design practice, including work on structural components and framing systems, collapse, nonstructural components and contents, fragility curves and damage states, and computation of direct economic loss (repair costs), business interruption (downtime) and casualties. The ATC-58 project on Performance-Based Seismic Design (www.atcouncil.org, Whittaker et al. 2007) is developing the tools and additional knowledge required to implement PBEE in design practice for common structural framing systems and typical occupancies. The loss computation tools, which are now well advanced, rely on representations of earthquake shaking and structural analysis to compute demands on structural components, nonstructural components and building contents. Demands on such components and contents are then transformed into damage states and common repair measures (or collapse probabilities), which are then aggregated over the building to compute losses (casualties). Detailed information is provided in the 35% draft of the *Guidelines for Performance Based Seismic Design of Buildings* (ATC 2007), which can be found at the above website. Two types of analysis are presented in the draft *Guideline*, simplified linear and nonlinear response-history, but procedures have not been developed to address SFSI with either analysis method. The lack of such procedures is a substantial impediment to the successful implementation of performance-based design. Further, the lack of knowledge on the effects of adjacent buildings (as a function of geometry, embedment and dynamic properties) on earthquake shaking inputs represents another key impediment to performance-based design, because the input ignores the presence of adjacent buildings.

7. RESEARCH GOALS AND NEED FOR PROPOSED CENTRIFUGE EXPERIMENTS

Soil-foundation-structure-interaction (a high priority NEES research topic, e.g. NRC 2004; ATC 2007) is a central theme of this research project. The primary goals of the proposed research are five-fold:

1. Investigate the interacting relationships of nonlinear soil response, nonlinear foundation response, and nonlinear structural response in a group of adjacent structures that represent buildings in a dense urban environment. Describe the relative importance of the ground motion characteristics, soil conditions, foundation type, and structural response characteristics in this SFSI problem of multiple buildings shaking at the same time.
2. Develop a "catalog" of well-documented model "case histories" of building performance within a dense urban environment at sites undergoing moderate and severe ground shaking with and without ground failure, so that researchers can use these "case histories" to advance our understanding of these phenomena and our ability to analyze them. These illustrative model "case histories" can also be used by engineers, emergency managers, and university/K-12 instructors to show how buildings within a model city block would likely perform during an earthquake. Instead of looking at static pictures of the damaged buildings after an event, video clips augmented with animated measured response data will become available.
3. Translate the challenge of solving this realistic problem to undergraduates (and others) via a "shaking of a city block" EERI Annual Shaking Table Competition by having CUREE work with EERI to have students characterize the influence of adjacent structures on building response. In addition, undergraduates will be brought in directly to work on the centrifuge test through our association with Cal Poly at SLO and NEES REU scholars. Work at Cal Poly will focus on involving minority and women students.
4. Perform "Class A" predictions of each building's performance for each of the ground condition, and then after testing, thoroughly back-analyze the generated small-scale model "case histories" to evaluate the importance of soil-foundation-structure-interaction in response of buildings to ground shaking. The NEESR fully nonlinear analysis computational software OpenSees will be employed. This program has relatively sophisticated material elements available to represent the soil, foundation, and structure in an integrated manner.
5. Develop guidance, based on the findings from studies of 1 and 4 above, for the design professional community on: a) the impact of SFSI on building response and loss computations, b) including SFSI in the analysis of buildings using the simplified linear and nonlinear response-history procedures presented in the ATC-58 Guidelines, and c) the need to consider adjacent buildings for performance-based assessment and/or design of individual buildings and the likely impact of ignoring such buildings.

Recent earthquake events that have occurred near major cities have in some cases caused extensively damaged buildings and in most cases isolated damage to a few buildings in a few localized areas of the city. A critical examination of actual field case histories, although a noble goal, is typically not possible due to the significant uncertainties involved in their back-analyses. Key sources of uncertainty are the characteristics of the ground motions, lack of detailed documentation of ground response and its resulting impact on foundation and structural performance, and the inherent variability of the quality of construction, foundation conditions, and the post-earthquake reports. Thus, the well-documented field case histories that are required to calibrate our numerical simulations and to advance our understanding of the complex phenomenon of SFSI effects for a group of adjacent buildings in a dense urban environment simply do not exist. Hence, the advancement of performance-based engineering for realistic conditions that one might encounter in a major U.S. city is hindered significantly. A comprehensive program of relatively large-scale centrifuge testing, where the input motion, surface motion, ground conditions, ground response, and structural response can be carefully tracked and documented, followed by advanced back-analyses of these model tests, are warranted to enhance the profession's understanding of SFSI of buildings in a dense urban environment.

8. RESEARCH PROGRAM JUSTIFICATION, PLAN, AND EXPECTED OUTCOMES

8.1 Research Program Justification

A fully integrated understanding of fault rupture, wave propagation, geotechnical site response, soil-foundation-structure interaction, structural and nonstructural component response, loss estimations, and urban response, from *end-to-end*, which we coin as *earthquake rupture-to-urban resiliency*, is needed to advance substantially the practice of performance-based earthquake engineering.

Current numerical simulation procedures for estimating the effects of ground shaking on buildings use simplified ground motion parameters (e.g., peak ground acceleration, response-spectrum acceleration) for response, damage and loss calculations. Such parameters are substantial simplifications of the earthquake-shaking environment and are unproven indicators of damage and economic loss. The standard numerical procedures used by engineers at this time, which generally utilize simple nonlinear *fixed-base* building models, have not been validated and produce approximate results at best because of simplifications of the earthquake input, no consideration of soil-foundation-structure interaction (SFSI), and inadequate constitutive models of structural components and systems. These widely-used design procedures consistently overestimate the damage potential of ground motions on most engineered buildings in our Nation. Conservative estimates of demand translate directly into unnecessary costs for seismic protection and inaccurate estimates of potential loss (direct economic, downtime and casualties) in future earthquake shaking.

Importantly, the approximate procedures for SFSI analysis of a building that are included in seismic codes and guidelines (e.g., the 2003 *NEHRP Recommended Provisions*) do not address the influence of adjacent buildings and foundations (extended SFSI) on seismic demands. In major urban areas such as Los Angeles (see Fig. 2), San Francisco and Seattle, buildings are clustered together and the foundations in aggregate will substantially modify the free-field motions that are characterized by probabilistic seismic hazard assessment. The effects of clusters of buildings on free-field seismic demands are largely unknown, but will be quantified by the proposed studies and transformed into guidance for code-based design and performance assessment. Such an approach is entirely consistent with analysis and design of tall buildings for wind loadings, where the complex interactions of air flow around adjacent buildings are routinely characterized by wind climate studies and wind tunnel testing (Fig. 3) that considers the building as both a stand-alone structure and a part of the urban landscape.

Fig. 2. A typical city block in downtown Los Angeles

The interdisciplinary project team developed a multi-task research implementation plan using the three-plane chart of Fig. 4 to define the program and its products. In this chart, tasks and products are presented on three planes, which are defined here as Systems Integration and Public Policy; Enabling Technologies; and Fundamental Science and Technologies. The three-plane strategic plan is a useful construct for both ensuring balance among the coordinated research projects and systems studies, and for exchanging data and information. Work in the upper planes defines information needs in the lower planes, which will be organized through regular communications between the investigators using the NSF-funded NEESit infrastructure. <u>Systems Integration and Public Policy</u>: This plane presents the primary long-term objectives of the research program, specifically the development and promulgation of knowledge and tools to characterize SFSI for individual buildings and clusters of buildings; improvements to performance-based assessment and design, revisions to codes and guidelines; policy guidance to regulators and building officials on the importance of SFSI calculations involving considerations of adjacent buildings (similar to that provided for wind-engineering considerations); and education and training of students and design professionals. <u>Enabling Technologies</u>: The system-level studies of the upper plane require the development of enabling technologies that are presented in the middle plane of the figure, which include prototype buildings; validated simplified models for consideration of SFSI, validated SFSI codes, loss computation tools (provided by the ATC-58 project); and numerical platforms for fully coupled geo- and structural engineering response calculations for individual buildings and clusters of buildings. Each of these enabling technologies is to be fully tested using the appropriate prototype buildings. <u>Fundamental Science and Technologies</u>: The enabling technologies of the middle plane of the chart are built upon the fundamental scientific studies shown in the lower plane. Fundamental science and technologies needed include: definition of the earthquake hazard, soil and site characterization and response, soil-foundation-structure interaction, and individual building characterization and response.

Fig. 3. Wind tunnel testing in an urban setting

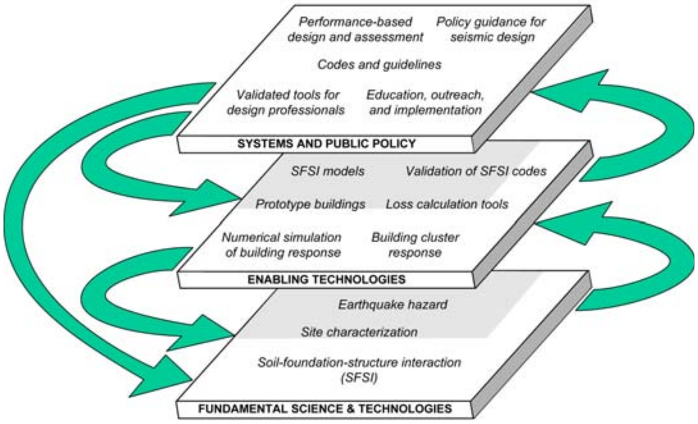

Fig. 4. Research strategic plan

The research project will be organized, managed and executed using the NSF Engineering Research Center model. The proposed research program is tightly integrated with our plan for education, diversity, outreach and implementation. Our project has three high-priority user groups who will benefit from the education, outreach, and implementation activities: 1) undergraduate and graduate underrepresented students; 2) undergraduate students at teaching universities; and 3) practicing engineers, who are the key group that can implement the results of this research project. The project also targets the broad-spectrum audience (including K-12 and general public) with two accessible general avenues to our content: a video magazine and a professional-quality website. Details on our plan for education and outreach are presented in Section 9.

8.2 Research Plan

8.2.1 Introduction

It is impractical within one NEESR-SG project to address all aspects of the broader vision of *earthquake rupture-to-urban resiliency*. As discussed previously, there are many aspects that need to be addressed before the vision can be realized. However, it is useful to keep the broader vision in mind as we attack one of the most critical aspects of the *earthquake rupture-to-urban resiliency* vision, because it reminds us that the inputs to the specific problem addressed in this proposal are realizable from the engineering seismology and earth sciences professional communities and that the outputs of the proposed study advance the eventual end-product of improving urban resiliency. In the proposed project we focus on the very important problems of seismic site effects to near-fault motions, soil-foundation-structure-interaction, nonlinear structural response, and the resulting seismic performance of a cluster of buildings in a dense urban environment.

The geo-structural engineering focus of the project is the *soil-foundation-structure system*. We plan to focus on the geo-structure interface because the effect of soil-foundation-structure interaction on low- and medium-rise buildings is poorly understood. Much improved understanding of this topic is needed to facilitate to support on-going developments in performance-based seismic design. We will not focus on buildings and their components per se, because such studies are already being supported by other NSF-funded research. Specifically, we seek to first understand and second simulate numerically and experimentally the effects of foundations and basements (embedment) on the seismic demands of buildings and clusters of buildings. The NEES centrifuge at UC Davis will be used to develop an inventory of test data that will enable the research team to characterize the effects of SFSI on single buildings and clusters of buildings of varying heights, embedment mass, and dynamic properties. Scale models of prototype buildings will be constructed for installation in one of the flexible shear beam containers on the UC Davis centrifuge as illustrated in Fig. 5. Use of the UC Davis centrifuge, with its relatively large payload capacity will permit the experimental evaluation of multiple soil-foundation-structure systems at the largest scale feasible.

We considered augmenting the work described in Section 8.2.2 with companion field testing but such work would involve a significant increase in scope and budget. We will instead develop payload projects in future years, involving other investigators, for companion testing using other NEES equipment. Instrumentation of the model will include monitoring of accelerations and pore pressures in the soil; accelerations, forces, displacements and strain distributions within the buildings; as well as using high speed video cameras and still imagery of the overall region and local areas. Over 200 sensors will be needed for the densest urban configurations.

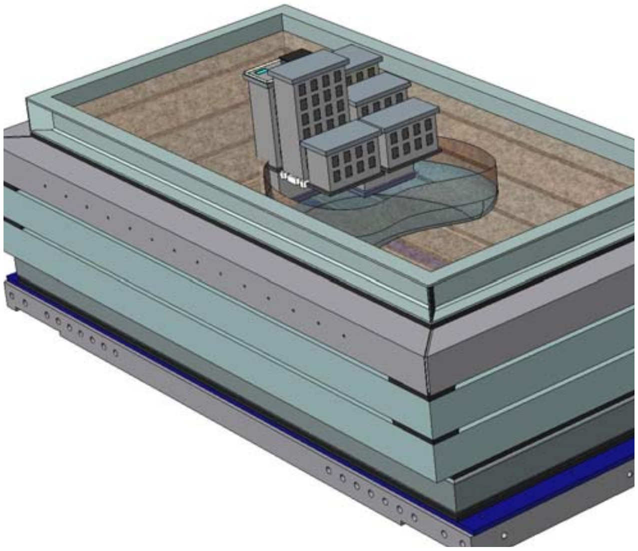

Fig. 5 Schematic of NEES test fixture

Low- and medium-rise buildings were chosen for our study because they represent most of the building inventory in the United States, and they could be scaled in size for installation in the centrifuge. The Los Angeles basin was selected to best leverage past earth-science research at the Southern California Earthquake Center (SCEC), and because losses from a future large-magnitude earthquake in the downtown Los Angeles region will likely exceed those of the 1994 Northridge earthquake by a factor of 5 (Reitherman 1998). Although our study will focus on the effects of near-fault forward-directivity motions, because their high intensity typically govern the seismic performance assessment of structures within cities such as Los Angeles, Salt Lake City, San Francisco, and Seattle, we will also apply a suite of empirical intermediate distance “ordinary” ground motions to achieve a sound general assessment. Selected motions will be scaled appropriately and used as input motion for the centrifuge model tests and numerical simulations.

As a key component of this project, we will undertake sample loss computations, which are the final product of performance-based assessment. Such computations of repair cost, downtime, and casualties will provide valuable guidance to the profession on the importance of SFSI and the need to address the proximity of adjacent structures in the characterization of the seismic input(s). A commercial-office occupancy will be assumed and the normative quantities of nonstructural components and contents already developed in the ATC-58 project will adopted. The ATC-58 loss computation tools will be used for these loss computations.

The primary contribution of the proposed research project, however, is the centrifuge testing. The centrifuge testing will enable development of a robust dataset that will be substantially expanded using validated numerical tools to analyze clusters of buildings being shaken by different types of ground motions. Such a dataset is required if the profession is to realize the goals stated in ATC-73.

8.2.2 Research description by task

The research plan was developed and defined by the project team members using the vision and outcomes of Section 8, the gaps identified in part by the literature survey of Section 6, and the research goals of Section 7 and the strategic plan of Figure 4. A flowchart was prepared to refine the research plan and to show the interdependent tasks. Education and Outreach is central to the research effort. Six key research tasks were identified, and each task is described below; some emphasis is placed on tasks partially completed to enable the preparation of this proposal. Each task is not weighted equally and the bulk of the NEES funds will be spent on experimentation (Tasks 1, 2 and 4). Management and administration are addressed in sections 12 and 13 and are not considered part of the research plan for this presentation. The Practice Committee, which is described in Section 12.2, will be engaged in all aspects of the research plan. The initials of the lead persons for each task are shown in parentheses following the task number. Coordination with NEESinc and NSF is considered an overarching task and that work is not discussed below. Table 4 in Section 12.1 provides a summary schedule by task and quarter.

Task 1: Develop program for centrifuge testing (JDB, TH, BK, and ASW)

Centrifuge testing of model buildings and building clusters is the backbone of the proposed study. This task will generate the “database” of nonlinear SFSI responses of a cluster of model structures within well-defined conditions. The project team has already devoted a considerable amount of time to develop the proposed program of centrifuge experiments. During this task, the detailed centrifuge testing plans for each of the proposed six centrifuge experiments will be prepared and submitted to the UCD NEES equipment site manager, Dr. Dan Wilson. As the following two tasks are completed, the testing plans will be refined and finalized.

The soil within the centrifuge container will represent typical site conditions in downtown Los Angeles. In the first three experiments, dry Nevada sand will be placed in a dense state. In the fourth experiment, dry Nevada sand will be placed in a loose state. In the final two experiments, liquefiable loose sand will be included in the soil profile to explore the effects of a highly nonlinear soil response. For all tests, the cone penetrometer and an array of accelerometers will be used to characterize the strength and stiffness of the soil.

The Davis centrifuge can accommodate several model low to medium rise buildings during each experiment. In the first experiment, 3 plane strain nonlinear structural models will be separated so each model responds independently in a 2-D manner. In the second experiment, 3 rectangular nonlinear structural models will be placed so that each model responds independently and is free to move bi-laterally. In the remaining experiments, a grid of 3 x 2 nonlinear structural models (i.e., 6 buildings) will be placed adjacent to each other to replicate the arrangement found in a small city block in a dense urban setting such as Los Angeles. The development of realistic nonlinear structural models is a key aspect of the project, and their development is discussed further under Task 2. Some buildings will have basements, some will not. All but one building will have a mat foundation, and one may have individual spread footings. They will vary from 2 to 6 stories in height. All will exhibit fully nonlinear responses.

The centrifuge will be shaken by a suite of strong ground motions developed for this project. As mentioned previously, although the focus will be on utilizing near-fault forward-directivity ground motions, the results of the SCEC "TeraShake" simulations as well as simulations produced through the PEER NGA project will be used, which include both near-fault and "ordinary" ground motions. They will be scaled to the *conditional mean spectrum considering* ε (CMS-ε) for structures of low to intermediate periods at several hazard levels. This method of ground motion scaling was proposed by Baker and Cornell (2006) for developing a more realistic target acceleration response spectrum that accounts for the magnitude (M), distance (R) and variability (ε, i.e., the number of logarithmic standard deviations of the ground motion intensity estimate) values likely to cause a given target ground motion intensity at a given site. The first four experiments employ dry sand so the centrifuge container can be shaken by multiple events while in flight. Previous experiments (e.g., Nova-Roessig and Sitar 2004) suggest we will be able to apply a dozen different acceleration histories for each experiment involving dry sand. The experiments involving liquefiable soils will only be able to be shaken by two or three significant ground motions.

This comprehensive database of experimental results, where the input motion, surface motion, ground conditions, ground response, and structural response can be carefully tracked and documented, is required to support the advancement of the analytical procedures required to complete performance-based earthquake engineering analysis in a dense urban environment.

Task 2: Development of prototype and model structures and construction of models (TH, ASW, and BK)

The centrifuge is an ideal environment for the proposed study, allowing us to capture prototype soil stresses and therefore realistically assess SFSI. The UC Davis centrifuge allows us to apply up to 75g centrifugal acceleration to model soil-structure systems, resulting in a model structure 1/75th of the prototype size. For these studies, we plan to use a model scale of N = 50, to maintain reasonable sizing of the structural components within the building models. Some model buildings will be simple idealized mass-column style, while others will include more detail, such as basic framing and/or wall elements. All building structures will be designed and constructed to be consistent with modern design practice to the degree possible and incorporating inelastic behavior, as would be expected in practice. It is envisioned that modeling of the inelastic structural components can be realized using reduced sectional properties. We have successfully undertaken this in the past at the centrifuge scale for modeling reinforced concrete beam-column joints (Chang et al. 2007). The components of the structures will be constructed of metal, however, some can be designed to model reinforced concrete behavior in a lumped sense. Model building structures will be designed and constructed at UCSD and shipped to both UCD and UB for testing. Small scale 1-g push tests will be conducted on the models to evaluate their elastic behavior and calibrate predictive models. The selection of building geometries, periods, design details and expected ductility, will be undertaken by first surveying the existing building stock in the LA region. Once a suite of candidate prototypical buildings is developed, we will consult our Practice Committee to finalize the building definitions.

Task 3: Soil-foundation-structure numerical simulations (TH and ASW)

Two phases of numerical simulations of the soil-foundation-building structures will be undertaken, namely in the pre- and post-test phases of the project. Pre-test numerical models of the complete geotechnical and structural systems, including the embedded foundations, will be developed in the OpenSees environment. These simulations will be used to aid in the final design of the instrumentation, selection of input motions for the physical tests, and provide preliminary results on the effects of embedment on seismic demands of typical structural systems. The multi-yield-surface plasticity soil model implemented in OpenSees (Elgamal et al. 2002; Yang et al. 2003) will be used to model the soil media. This model has been shown to reasonably capture the nonlinear, hysteretic response of sandy and clayey soils well. Moreover, it has proven to be reliable in capturing the seismic response of soil at the element level, in comparison with cyclic simple shear tests results, and for soil deposits, in comparison with recorded motions at soil sites. Structural components will be modeled using nonlinear fiber elements available in OpenSees, with nonlinear material models available for concrete and steel. Preliminary analysis results will be published on the CUREE website.

Task 4: Experimentation using the centrifuge (JB and BK)

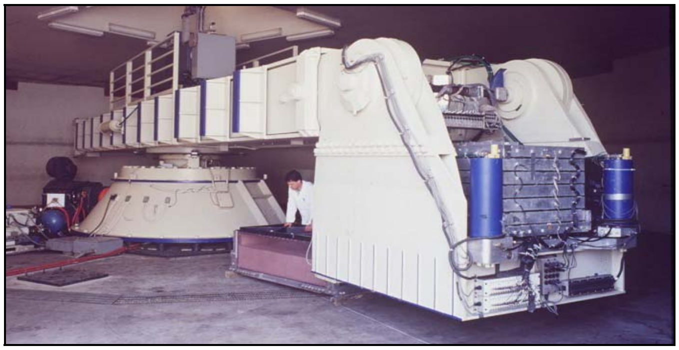

Fig. 6 UCD centrifuge

Task 4 is the central activity in this NEES project. Figure 6 is a photograph of the UCD centrifuge that will be used for the physical simulations.

For experiments with dry sand, the soil container (see Fig. 5) will be instrumented with about a dozen accelerometers to enable characterization of the ground motion distribution. For the experiments involving liquefaction, 20 to 30 accelerometers and pore pressure transducers will be required to define the pore pressures and accelerations in the soil deposits. Each model building will also be instrumented with several accelerometers (about 12 accelerometers on average in each of six structures) so that the base shear and moment at the base of the structure can be deduced and loads on any nonlinear elements in the buildings can be quantified. Strain gauges and miniature load cells may also be built into the structures to enable determination of forces and deformations in nonlinear structural elements. The large number of interacting structures along with the soil will thus require a total of about 100 accelerometers. This is possible if we use 30 wired sensors and 70 accelerometers in the WIDAQ (wireless data acquisition system) at nees@ucdavis. With load cells, strain gauge bridges, pore pressure transducers, and displacement transducers, a total of about 200 sensors will be required per experiment. In addition we will record each shaking event with four high speed (200 frames per second) video cameras and several conventional video cameras.

While the staffing will vary for each experiment, three or four students will participate in each experiment. One Ph.D. student (from either Berkeley or Davis) will be designated as the lead Ph.D. student researcher, and another will be the primary helper, working together full time for about six weeks, placing soil, installing sensors and recording sensor locations, installing structures, calibrating sensors, creating the sensor channel lists, and they will also be responsible for creation of the data archive. At least one other student (from Buffalo, San Diego, or Cal Poly) will be present during the two most intense weeks of testing for each experiment. The third student would be charged with setting up and running one of the instrumentation subsystems (e.g., wireless data acquisition or high speed cameras) to ensure they are fully engaged in the test details. The primary role of the 3rd student will be to either analyze results or run numerical simulations between shaking events and in real-time reduce data, so the PIs and students can visualize the response of the structures. If a fourth student is available, either on-site, or through remote participation, she/he could be uploading and organizing photographs, data sets, and sensor data in the NEEScentral archive as they are generated. If this is done, data viewing tools available in NEESforge, such as N3DV, may be used to enable rapid visualization of the experimental data.

Each model container will be subject to a series of ground motions. The following sequence is typical of most centrifuge tests on the NEES facility at Davis. The first event will be a small step wave, which will be just large enough to confirm that all the critical sensors are functioning. Then, one or two small shaking events, representative of events with 50% chance of occurring in 50 years, will be imposed on the model. These events should not produce significant nonlinearity or soil densification. This will be followed by a series of intermediate shaking events that will cause nonlinearity, but not failure (representative of a event with 10% chance of occurring in 50 years), Finally, at least one larger shaking event will be applied (2% in 50 year event). The centrifuge will then be stopped for inspection of the structures. Numerical analyses will be conducted, and preliminary comparisons between experiment and analysis will be obtained. Based on these comparisons, the PIs and researchers will discuss the next course of action. One option will be to end the experiment and carefully inspect the specimen as it is disassembled. If the damage is not too severe, and we decide that we might gain insight by additional shaking events (perhaps with structures altered by, for example, adding mass) the team may decide to spin the centrifuge back up to speed and impose more shaking events.

All test data will be curated and archived in accordance with the NEES-wide standards per Section 10 below.

Task 5: Validation of numerical tools and post-test simulations (TH and ASW)

The NEES laboratory experiments of Task 4 will provide the means to test and validate analytical and numerical approaches to modeling SFSI across a wide range of ground shaking environments. First, numerical tools for predicting the linear and nonlinear response of combined geo-structural systems, such as those available in OpenSees (and perhaps LS-DYNA), will be validated using the dataset of Task 4. This will include updating the models developed in the design phase of Task 3. Second, existing code-based SFSI analytical approaches for at-grade and embedded foundations for new (FEMA 2004) and existing (ASCE 2006) buildings will be evaluated. Third, the effect of deep basements on seismic input to, and structural response of, low- and medium-rise buildings will be characterized using the test data of Task 4 and extended to tall and ultra-tall buildings by numerical simulations. Finally, the influence of the geometry and foundation-type of adjacent buildings on the response and performance of the prototype buildings will be quantified.

Task 6: Development of code guidelines and tools for PBEE and policy guidance (ASW, JB and TH)

The test data of Task 4 and the post-test simulations of Task 5 will drive the development of multiple research products that will influence design practice and public policy in the United States, including:

- Rational and robust design-oriented SFSI rules and commentary for possible inclusion in building codes (e.g., ICC 2006), standards (e.g., ASCE 2005) and performance-assessment and loss guidelines (e.g., ATC 2007);
- Guidance on the bias in response and loss associated with ignoring SFSI for generic structural types, heights and basements/foundations, across a range of earthquake shaking intensity;
- Validated SFSI analysis tools for use by design professionals; and
- Guidance to the regulators of building construction on the need to address the presence of adjacent buildings for seismic design and performance assessment.

We will validate (or develop) both simplified and detailed numerical SFSI models and tools for use in both traditional design practice and performance-based earthquake engineering, which will enable the engineer/analyst to:

- modify free-field earthquake shaking to account for the presence of foundations and basements/embedment; and
- modify free-field earthquake shaking to account for the presence and response of adjacent buildings of varying geometries.

These tools, numerical models and knowledge will be incorporated into the next edition of the ATC-58 *Guideline for the Seismic Performance Assessment of Buildings* and made available to the design professional community through the project website. Draft provisions and commentary for code- and standards-writing committees will be developed in conjunction with key committee members. Technical briefs have proven to be an efficient mechanism to transfer the results of research into design practice. We will prepare a 20-page maximum length brief that will convey the key discoveries and new tools developed in the research project. The technical brief will be made available through the project website and transmitted to FEMA and NIST for review and possible publication under the NEHRP banner.

Wind engineering of a new medium- and high-rise building in a dense urban region often requires wind tunnel testing as illustrated in Figure 3 to estimate localized wind pressures and global loadings for design and to judge the impact of the proposed building on adjacent structures and wind profiles at ground level to characterize pedestrian discomfort. Companion knowledge for earthquake engineering does not exist. We will develop a body of knowledge to fill this void and enable building officials and regulators to judge whether adjacent structures must be considered in the design and construction of new buildings in dense urban settings.

8.3 Research Outcomes

The key outcomes and products of this research project will be:

- Archived data set, available to the community for verification of other methods of accounting for interaction of closely spaced structures.
- Demonstration of a new paradigm for conducting earthquake engineering research through the careful integration of geotechnical engineering, structural engineering, and loss estimation.
- Tools and numerical models for the robust simulation of the seismic response and loss of single buildings and clusters of buildings.
- Code-oriented guidance for inclusion of soil-foundation-structure interaction in building design.
- Procedures for the inclusion of soil-foundation-structure interaction effects in performance-based design, suitable for immediate inclusion in the ATC-58 Guidelines.
- Public policy guidance to building officials and regulators.
- A technical brief on project outcomes suitable for use by geotechnical and structural engineering design professionals.
- Ph.D., M.S. and undergraduate students with experience in interdisciplinary geotechnical and structural engineering research, collaboration, and research project management experience.
- Development of fundamental science and knowledge, including soil-foundation-structure interaction for buildings and clusters of buildings
- Development of enabling technologies, including
  - analytical approaches for soil-foundation-structure-interaction (SFSI) analysis
  - numerical models for soil-foundation-structure systems
  - guidance on the effects of interacting foundations on seismic inputs to individual buildings
  - guidance on seismic earth pressures for use in design
  - rules for the assessment of SFSI suitable for including in seismic building codes and guidelines for seismic performance assessment.

9. BROADER IMPACTS

To meet general educational and workforce development goals of NSF as well as its specific diversity objectives, and to be consistent with objectives of the NEES EOT strategic plan, we have identified three high-priority user groups who will benefit from its education, outreach and implementation activities: (1) Undergraduate and Graduate Underrepresented students; (2) Undergraduate students at a predominantly teaching university (Cal Poly SLO); and (3) Practicing Engineers, the key group who can implement the results of this research. Plans have already been made to involve undergraduate and graduate students from under-represented groups and undergraduate students from a teaching university in the research endeavor. Web-provided information will be via several avenues. A project-wide website for public access will be established by CUREE, in a way that has proven successful in CUREE's current Education & Outreach role in the NEESR Grand Challenge project on nonstructural systems headed by the University of Nevada at Reno. The UC Davis Equipment Site website will feature detailed experimental information. We will work closely with the NEESInc EOT staff to integrate our education, outreach and implementation activities with on-going NEESInc activities.

Undergraduate Students and Underrepresented Students: The project team will include faculty and students from California Polytechnic University (Cal Poly), San Luis Obispo (SLO), a predominately undergraduate teaching university. Professor Gregg Fiegel, the Chair of the Department of Civil and Environmental Engineering, is the lead investigator at Cal Poly SLO. Undergraduate students at Cal Poly will participate in the research project by contributing to the experimental studies at the UCD Equipment Site in Years 1, 2, 3, and 4 and the simulations of building response in Year 4. Funds have been allocated in this project for stipends and to support travel to and living expenses in Davis for the Cal Poly undergraduate students and Professor Fiegel. Fiegel has extensive experience working with undergraduate students on sponsored research projects. The civil engineering program currently serves approximately 800 undergraduate students. The percentages of women and Hispanics in the Cal Poly program are relatively high. There is a unique opportunity to provide research experiences for students from traditionally underrepresented groups. Fiegel will work with the faculty advisors for the Multicultural Engineering Program (MEP), the Society of Hispanic Professional Engineers (SHPE), and the Society of Women Engineers (SWE) to promote the undergraduate research opportunities and to recruit students.

To increase student interest in engineering-related careers, and to fulfill NSF’s diversity criteria, we will engage the Alliance for Graduate Education and the Professoriate (AGEP) and Louis Stokes Alliance for Minority Participation (LSAMP) through the UC Berkeley. Letters of support from the UC Berkeley AGEP and LSAMP coordinators are appended to this proposal. Diverse participation of graduate research assistants for this project will be ensured through collaborations with AGEP. Minority undergraduate students in Science, Technology, Engineering and Mathematics (STEM) fields will be recruited through the LSAMP program at the University and affiliated institutions, including predominantly undergraduate institutions, to participate in the experimental facets of the research program in Years 2 and 3, and to contribute to the numerical simulation of building response in Year 4. Co-PI Hutchinson will actively engage with the LSAMP students, presenting research work in earthquake engineering to motivate the students to pursue graduate studies in STEM and helping the students prepare for and enroll in graduate school. PI Bray and Co-PI Reitherman will coordinate and integrate the research work and contributions of the undergraduate students over the course of the 4-year project. We plan to document the process and products of this component of the research project and submit the document in report format to the Foundation.

We will also engage the popular annual EERI shaking table competition that was originally developed through NSF funding through PEER to make undergraduate students (and the professional engineers who watch the competition) aware of SFSI effects and the important aspects of evaluating the seismic response of adjacent buildings. We propose to work with the student leadership council one year to have the undergraduates construct two adjacent mid-rise buildings that are founded on a compliant base that represents soil beneath the building foundations. It is important for the students to recognize the buildings to not respond in isolation and that their structures are founded on soil. The PI Bray is the Vice-President of EERI and Co-PI Whittaker also serves on the EERI Board of Directors and so we are confident that we can successfully engage EERI to model this scenario in the third year of the proposed study.

Implementation via Practicing Engineering Community: Practicing geotechnical and structural engineers are key end users of our research. Co-PI Andrew Whittaker is the Structural Performance Products Team Leader of the FEMA-funded ATC-58 project, Performance-Based Seismic Design. Funding from that separate project allows him the time to extract from our NSF-funded effort relevant research findings that fit the framework of those in-progress guidelines: substantially leveraging the NSF resources and ensuring that relevant data and numerical tools are made available to design professionals immediately. The practical benefits of more precise SFSI analysis methods extend to both new and existing buildings. For the new design, variables such as the mass of building, its periods of vibration, whether it has a basement or how many basement levels, and other variables can be related to structural response and its impact on cost and performance via the ATC-58 framework. For the existing building, the primary structural variables are somewhat inflexible (e.g., mass and presence or absence of basement) but the ability to obtain more accurate (and, it is expected, generally lesser) calculated levels of building response will make seismic rehabilitation a more attractive implementation option. Implementation will also be realized through the *NEHRP Recommended Provisions* and ASCE Standard 7: Co-PI Whittaker is a member of each of the committees developing these documents. CUREE and the Applied Technology Council (ATC) have formed the NEHRP Consultants Joint Venture and are under contract to the National Institute of Standards and Technology (NIST) for a variety of Task Orders over the next five years. One current Task Order is the production of Technical Briefs for practicing engineers, translating research findings into design guidelines. We will acquaint NIST with the results from our NEESR project and suggest how a Technical Brief on our topic could be included in the NIST program.

Video/Web Outreach: Video clips will be developed by CUREE, modeled after its successful series of videos produced for the CUREE-Caltech Woodframe Project, to enhance the project's outreach. Short, web-accessed video files are valuable for several purposes. Brief Question and Answer clips with the PI and other project personnel can explain in simple language an overall point, then allowing the web user to access more detailed information on the project. Having the students who will be involved in the research shown on the web explaining what they are doing and learning will be a way to engage their peers—the next generation of earthquake engineers—in pursuing this field in greater depth. Videos of experiments can be edited to concisely show key features, forming in effect a video index and quick overview preparing the user to access more detailed information that exists in the form of PDFs of papers, experimental data, simulations, and other more in-depth content. As an example, a Davis professor will be filmed in front of the centrifuge, producing a video clip keyed to more in-depth information on the webpage to that centrifuge's and other centrifuges' characteristics. Either an engineer or instructor, or student at approximately the upper middle school/high school range and above will find these video introductions an accessible way to delve deeper into the subject on the project website.

As an *In-reach* activity, we will seek to integrate NSF-funded work on SFSI by calling a meeting of all SFSI-related researchers funded by NSF at the NEES Annual Meetings. The purpose of the annual gathering would be to share data, findings and numerical tools, thereby avoiding duplication of research effort and maximizing the benefit of the NSF funding.

10. DATA ARCHIVING AND SHARING

All data derived from the experimental and numerical portions of this study will be submitted electronically to the NEES-curated central data repository. The experimental data will include recorded data from the experiments, instrument calibrations, images, video, metadata, documentation describing the experimental setup and testing protocol, and testing logs and notes in electronic format. The experimental data will be archived using NEEScentral data archiving tools, similar to the data archived in the publically accessible NEEScentral project titled "SFSI (UC Davis)", which may be accessed at https://central.nees.org/index.php?action=ListPubProjects. Data resulting from the numerical studies will also be archived using the OpenSees data model for simulation (Fenves and McKenna 2004). The experimental data and the numerical studies will be uploaded to the NEES data repository within 6 months of completion of the respective tasks. The data will be made available to the public after an additional 6-month period according to the NEES guidelines (NEESinc 2004). Kutter will work closely with the UCD-NEES System Administrator to ensure the most current NEES data and metadata guidelines have been implemented and to store the test data in the UCD repository during curation. Table S3-1 in the Supplemental Documents presents the status of NEES experimental data collected by the PIs.

11. PAYLOAD OPPORTUNITIES

In the year following the project award, we plan to write a payload proposal to NSF and encourage others to do likewise. The annual discussions of SFSI researchers at the NEES Annual Meeting (see the *In-reach* activity of Section 9) should help identify payload opportunities for the laminar box at the Buffalo ES, for the RPI and UCD centrifuges, and the UCLA and UTA shakers.

12. PROJECT IMPLEMENTATION PLAN

12.1 Project Schedule

Table 4 presents a summary schedule for the 6 tasks identified in Section 8.

Table 4. Summary schedule of work by task and quarter (T# refers to the test that is the focus)

Task No.	Task Description	Year 1				Year 2				Year 3				Year 4			
1	Develop testing program	■															
2	Develop/construct models	■	■	■													
3	Pre-test SFSI simulations		T1		T2		T3		T4		T5		T6				
4	Experimental studies			T1		T2		T3		T4		T5		T6			
5	Analytical/numerical simulations					T1		T2		T3		T4		T5		T6	
6	Guidelines and PBD tools									■	■	■	■	■	■	■	■

12.2 Project management plan and organization chart

PI Bray and Robert Reitherman, CUREE Executive Director, will share the project management responsibilities. The CUREE staff members available to work on this project are the same professionals who have been credited by many with doing an excellent job on the NEES Consortium development project. CUREE has developed a national and international reputation for effective project management of large, multi-university, multi-disciplinary projects. Under the direction of the Bray and Reitherman, the CUREE staff will 1) assure appropriate internal and NSF financial and budgetary needs are met; 2) subcontracts are executed smoothly and quickly with project member institutions; 3) support the needs of the project team (e.g., travel reimbursements, editorial assistance in report preparation) so as to allow the team members to concentrate on research; and 4) enforce project-wide criteria, including deadlines and budgets. The proposed organization chart for the project is shown in Figure 7.

Co-PIs Kutter and Hutchinson have already employed the Davis centrifuge to perform experiments to investigate aspects of soil-foundation-structure-interaction. Although the proposed experiments are novel, they fully understand what is required to perform these experiments. Additionally, Bray is just completing a series of centrifuge tests that examined the response of isolated buildings on liquefied ground. Whittaker's knowledge of research and practice-related issues regarding nonlinear structural response and performance will be used to ensure that the structural models used in the centrifuge realistically capture critical aspects of performance-based earthquake engineering.

We will form a Practice Committee to critique our research plan, annually review our work and progress versus the proposed schedule of work, review the key findings of the research project, and aid in the implementation of the research results in professional practice through training, guidelines development and code writing. The PIs have extensive contacts in engineering practice, and the Practice Committee will include leaders in the field of performance-based seismic design, an expert on soil-foundation-structure interaction, and an expert in the field of seismic hazard assessment.

We will measure our progress on an annual basis in a number of ways, including, asking the Practice Committee to provide a brief report on our progress and product, the PI and co-PIs undertaking an annual self assessment of progress with respect to the project schedule, documenting the involvement of undergraduate students in our research project, and listing project-related papers in archival journals and conference proceedings. Such results and those developed using other assessment tools will be documented and submitted to NSF.

12.3 Plan for use of NEES cyberinfrastructure resources

We plan to use the NEES IT tools for conferencing and data sharing, which will facilitate collaboration between the project participants in Berkeley, Buffalo, Davis, San Diego, and San Luis Obispo. The PI and co-PIs will place great emphasis on these critical interactions, which will accelerate advances in both geotechnical and structural engineering. NEES cyberinfrastructure will also be used to coordinate the intra-engineering numerical- and physical-simulation studies and report writing by all project participants. The project team will be able to communicate through a private channel before and during testing. Live public telepresence capabilities will allow the general public to participate in the experiments. Further, we will make extensive use of the NEES simulation tools such as OpenSees and the NEES central data repository as discussed in earlier sections of this proposal.

12.4 Project website

A project website will be maintained at CUREE, which will include details of the experimental program, testing schedules, links to real-time and archived video of hybrid simulations and education components. The website was described in more detail in Section 9, Education and Outreach Activities.

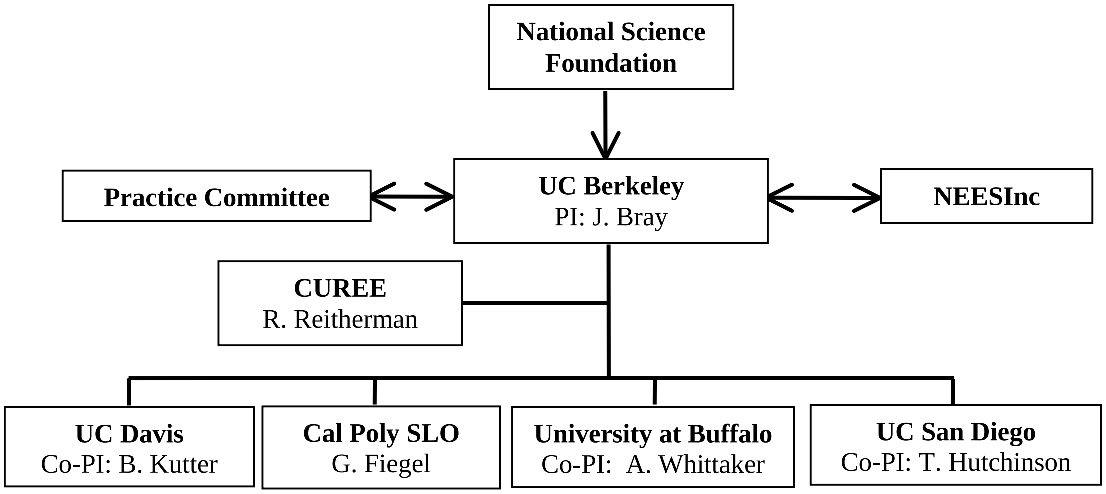

Figure 7. Project management plan

13. RISK MANAGEMENT

The Risk Management Plan for this project is presented in Supplementary Documents.