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Forced-vibration testing of a reinforced-concrete building using the NEES@UCLA field testing site

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ABSTRACT

The development of the *nees*@UCLA Equipment Site is approaching completion, and will provide a valuable shared-use resource for field testing and monitoring of structural and geotechnical performance. The *nees*@UCLA equipment portfolio includes shakers for exciting structural systems, numerous sensors for monitoring accelerations and deformations within the excited structure (e.g., accelerometers and strain gauges), and real-time data acquisition and dissemination capabilities. The full *nees*@UCLA will soon be assembled and used to perform forced vibration testing of a four-story office building, termed the Four Seasons project. The Four Seasons project provides a valuable opportunity to collect a detailed dataset that will provide insight into the dynamic response of a real building and its components using the *nees*@UCLA equipment. This paper provides an overview of the nees@UCLA mobile field laboratory and the details of the Four Seasons experiment.

Keywords: NEES, forced-vibration testing, field testing

INTRODUCTION

The U.S. National Science Foundation is developing the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) Program with the goal of transforming the nation's ability to carry out earthquake engineering research. In particular, NEES seeks to shift the emphasis from current reliance on physical testing to integrated experimentation, computation, theory, databases and model-based simulation. To support this goal, 15 different advanced testing facilities, termed Equipment Sites, are being developed that will be geographically distributed across the United States. The Equipment Sites will consist of (a) structural laboratories, (b) shaking tables, (c) geotechnical centrifuges, (d) mobile and permanent field testing facilities and (e) a tsunami wave basin.

One such Equipment Site with a focus on field testing and monitoring of structural performance is being developed at the University of California, Los Angeles (*nees*@UCLA). The nees@UCLA equipment portfolio includes shakers for exciting structural systems, numerous sensors for monitoring accelerations and deformations within the excited structure (e.g., accelerometers and strain gauges), and real-time data acquisition and dissemination capabilities.

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The development of the *nees*@UCLA mobile field laboratory is nearly complete, and will be fully assembled and utilized to perform forced vibration testing of a four-story office building, termed the Four Seasons Project. The principal research objective of the Four Seasons project is to collect a detailed dataset that will provide insight into the dynamic response of a real building and its components using the *nees*@UCLA equipment. The archived data could form the basis of detailed analytical studies for many years. In the sections that follow, we provide an overview of the *nees*@UCLA equipment and testing capabilities, and describe the planned testing and analyses for the Four Seasons Building Project.

NEES@UCLA PROJECT OVERVIEW

The nees@UCLA equipment site provides state-of-the-art equipment for forced vibration testing and seismic monitoring of full-scale structural and geotechnical systems. This equipment is useful for identifying system properties through system identification analyses of recorded data, studying the nonlinear responses of systems with limited mass, and evaluating the interactions of various system components for realistic sets of boundary conditions.
The major equipment components of the site are illustrated in Figure 1 and include the following:

A. **Eccentric mass shakers** that can apply harmonic excitation across a wide frequency range in one or two horizontal directions. These shakers can induce weak to strong forced vibration of structures. For small structures, excitation into the nonlinear range is possible when the shakers are operated near their maximum force capacity. The shakers can be operated in a wired or wireless mode.
B. **Linear inertial shaker** that can apply broadband excitation at low force levels. This shaker can be programmed to approximately reproduce the seismic structural response that would have occurred for any specified base-level acceleration time history (assuming the properties of the structure are known). The shaker can be controlled in a wired or wireless mode.
C. **Above-ground sensors** that can be installed at the ground surface or on building, bridge, or geo-structures to record acceleration or deformation responses. Accelerations are recorded with uni-directional or triaxial accelerometers. Deformations (i.e., relative displacements between two points) are recorded with LVDTs or using fiber-optic sensors.
D. **Retrievable subsurface accelerometers** (RSAs) that can be deployed below-ground to record ground vibrations in three directions. The sensors and their housing are specially designed to be retrievable upon the completion of testing.
E. **Wireless field data acquisition system** that efficiently transmits data in wireless mode from the tested structure to the high performance mobile network (see following item).
F. **High performance mobile network** that (a) receives and locally stores data at a mobile command center deployed near the test site; (b) transmits selected data in near real time via satellite to the UCLA global backbone; and (c) broadcasts data via the NEESpop server into the NEESgrid for teleobservation of experiments.

We anticipate several general categories of application for the *nees*@UCLA equipment site. The data retrieved from these applications will have the potential to significant impact our ability to effectively model complex geotechnical/structural systems and to manage and interpret data collected from dense field sensor networks, which will ultimately lead to improved seismic design procedures and significant reductions in the public's seismic hazard exposure. Example application areas are described briefly in the following paragraphs:

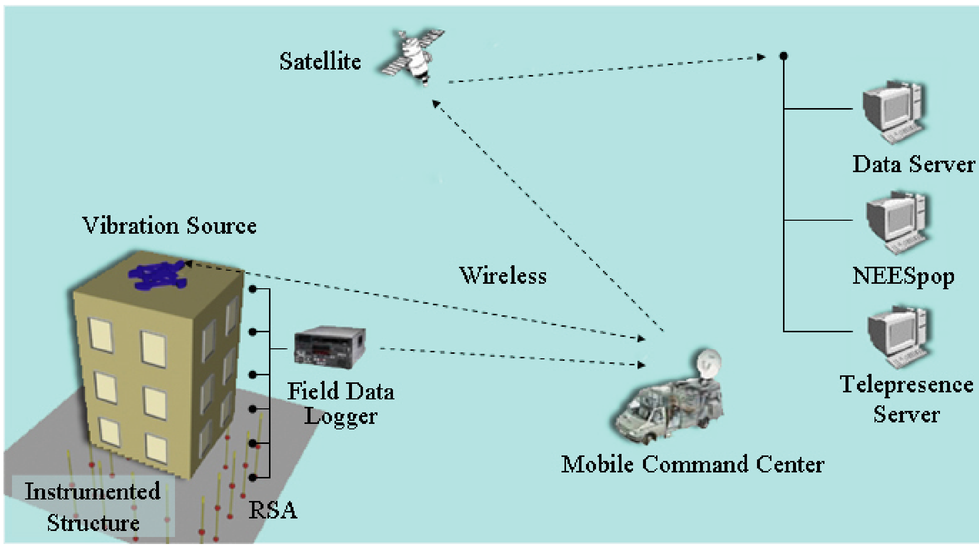

Fig. 1. Schematic illustration of deployed equipment from the *nees*@UCLA Site

Building or bridge structural response/performance studies. The equipment can be used to identify the modal responses of buildings (i.e., vibration periods, damping ratios, mode shapes), to evaluate the performance of non-structural elements within tested structures (i.e., HVAC, partition walls, equipment, etc.), and to evaluate the detailed response of structural components (e.g., beam-column connections, column-slab connections, etc.). Experiments can be performed at low levels of excitation from ambient vibration, micro-tremors, or over a range of excitation levels using the various shaker systems. For structures of small to modest size, the eccentric mass shakers can be utilized to excite structures into the nonlinear range. An important aspect of field testing is the ability to capture structural response and interactions without the shortcomings of scale and boundary conditions that commonly exist for laboratory testing. A unique feature of experiments performed using the *nees*@UCLA equipment relative to previous field testing programs is the potential for installation of dense instrumentation arrays that will provide more detailed insights into structural and non-structural response and performance characteristics. Potential applications might include forced-vibration studies of existing structures slated for demolition, full-to-moderate scale structures or sub-systems constructed specifically for testing, or use of the sensors and data acquisition system within structures during earthquake aftershocks.

Seismic health monitoring and sensor networks. A long-term vision for equipment use involves development of robust sensor networks for real-time seismic structural health monitoring by collaborating with other disciplines (e.g., computer science). Important issues to be addressed include: development of robust MEMS sensors, application of network time protocols in field sensor deployments, efficient transmission of data (e.g., multi-hopping or beam-forming), effective use of in-network processing, and development of efficient techniques for data management and interpretation.

Soil-foundation-structure interaction (SFSI) studies. The equipment can be used to apply forces and moments to foundation components, the response of which can be measured with acceleration and/or displacement sensors to evaluate SFSI effects. Load application to foundations is a natural consequence of vibration testing of buildings and bridges, so SFSI studies could be a component of any such experiment. Moreover, shakers can be directly installed on model foundations or simple structures mounted on model foundations to generate cyclic responses. Instrumentation would typically include an accelerometer array to record foundation motions and ground surface and below ground motions (using the RSAs). Specific research objectives of such work could include the evaluation of frequency-dependent stiffness and damping terms for foundation systems, as well as foundation-soil-foundation interaction effects.

Response/performance studies for geo-structures or soil deposits. As with building or bridge structures, geo-structures such as dams, embankments, and retaining wall systems can be tested though forced vibration or seismic monitoring. Such studies would typically be performed to evaluate seismic response characteristics (i.e., vibration periods, damping ratios, topographic amplification effects). Excitation at amplitudes that could induce soil shear failure is expected to not generally be possible. RSAs would enable measurements of internal response and deformations of geo-structures. Seismic monitoring of soil deposits is also possible with the RSAs. Monitoring of soil deposits might be of interest following a major earthquake, as data recorded from aftershocks could provide insight into wave propagation characteristics and soil pore water pressure generation.

FOUR SEASONS BUILDING EXPERIMENT BASED DEPLOYMENT

Project description

The Four Seasons building, shown in Figure 2, is a four-story reinforced concrete office building located in Sherman Oaks, California. This building was constructed in 1977 and the structural system includes a perimeter moment frame with an interior post-tensioned slab-column "gravity" system with drop panels, which represents a fairly common structural system used on the west coast of the US. The Four Seasons building was significantly damaged in the 1994 Northridge Earthquake, and post-earthquake studies of the building provide somewhat conflicting reasons for the observed damage. The building has since been yellow-tagged and is scheduled for demolition in approximately one year. Access to the building site has been granted by the building owner, and a series of forced vibration tests on the Four Seasons building have been planned.

The principal research objective of this project is to collect a detailed dataset that will be used to improve on our understanding of the dynamic response of real buildings using the *nees*@UCLA equipment. The data archived through the proposed research could form the basis of detailed analytical studies for many years. Both earthquake-type and harmonic force histories will be applied to the building and the building responses to these force histories will be recorded with a dense instrumentation array. The sensors used will monitor structural and non-structural responses (*e.g.*, partitions, suspended ceilings, sprinkler system components), as well as foundation and soil responses through the use of accelerometers, displacement transducers, and concrete strain gauges. Approximately 60 channels of Episensor accelerometers, 40 channels of LVDTs and 96 channels of strain gauges will be deployed during the forced vibration tests.

Fig. 2. Picture of the Four Seasons office building

Following the forced vibration testing of the Four Season building, two different time domain system identification techniques, the ARX (auto-regressive model with exogenous input) approach and N4SID (Numerical Algorithm for Subspace State Space System Identification), will be employed to identify the structural modal properties such as frequencies, damping ratios, mode shapes and the physical parameters of the building using the data generated throughout the testing.

The ARX approach is well known in electrical and system engineering field. In the case that the loading history of the shaker applied to a building is recorded, an ARX model can be used to construct the input-output relationship in the discrete-time domain. The coefficients of the ARX model are evaluated based on the least-square approximation. Once the coefficients of the ARX are determined, the transfer function of the system is completely known, which can be used to identify the modal properties of the building.

The N4SID is viewed as an alternative to the polynomial model but with a more complex numerical analysis. It can be applied when the excitation to a structure is measured or not measured. The key element of N4SID is the projection of the row space of the future outputs into the row space of the past outputs. It identifies the state space model of a structure based on the measurements and by using robust numerical techniques such as QR-factorization, singular value decomposition (SVD) and least squares. Once the mathematical description of the structure (the state space model) is found, it is straightforward to determine the modal parameters.

After using the ARX approach and N4SID to determine the state space model of the Four Season building, the second-order model of the building can be constructed based on the algorithm to determine some transformation matrices, which are used to transform the first-order state space equations to physical meaningful coordinates. Then, the physical parameters including the mass, stiffness and damping matrices of the building can be identified, which are useful for structural health monitoring and damage detection.

Aside from the potential societal benefits from improved understanding of dynamic structural response, the Four Seasons testing provides an opportunity to assemble and demonstrate the full *nees*@UCLA mobile field laboratory integrated with NEESgrid. The NEES System Integration team has been engaged in this effort, termed Experiment-Based Deployment and is described in detail in Whang et al., (2004).

CONCLUSIONS

The development of the NSF-funded *nees*@UCLA Equipment Site is approaching completion, and will provide a valuable shared-use resource for field testing and monitoring of structural and geotechnical performance. The *nees*@UCLA equipment portfolio includes shakers for exciting structural systems, numerous sensors for monitoring accelerations and deformations within the excited structure (e.g., accelerometers and strain gauges), and real-time data acquisition and dissemination capabilities. The full *nees*@UCLA will soon be assembled and used to perform forced vibration testing of a four-story office building, termed the Four Seasons project. The Four Seasons project provides a valuable opportunity to collect a detailed dataset that will provide insight into the dynamic response of a real building and its components using the *nees*@UCLA equipment.

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