

# FIELD TESTING CAPABILITIES OF THE NEES@UCLA EQUIPMENT SITE FOR SOIL-STRUCTURE INTERACTION APPLICATIONS

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## ABSTRACT

The *nees@UCLA* field testing site has developed equipment for field testing and monitoring of structural and geotechnical performance. The equipment includes shakers for exciting structural and/or foundation systems, numerous sensors for monitoring accelerations and deformations within the excited structure (e.g., accelerometers, displacement transducers, strain gauges), and real time data acquisition and dissemination capabilities. One of the important applications of this equipment will be testing of soil-foundation-structure systems. Such testing could, for example, be used to evaluate the stiffness and damping associated with foundation-soil interaction. Existing test data for such phenomena is shown to be limited, hence there is a major need for this type of research. The results would enable the verification and calibration of computational and design models used in practice.

## INTRODUCTION

The U.S. National Science Foundation funded 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 geographically distributed, advanced testing facilities, termed Equipment Sites, have been developed. 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 has been developed at the University of California, Los Angeles (*nees@UCLA*). 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. The equipment portfolio includes shakers for exciting structural systems, numerous sensors for monitoring accelerations and deformations within the excited structure (e.g., accelerometers, linear variable displacement

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transducers and strain gauges), and real-time data acquisition and dissemination capabilities.

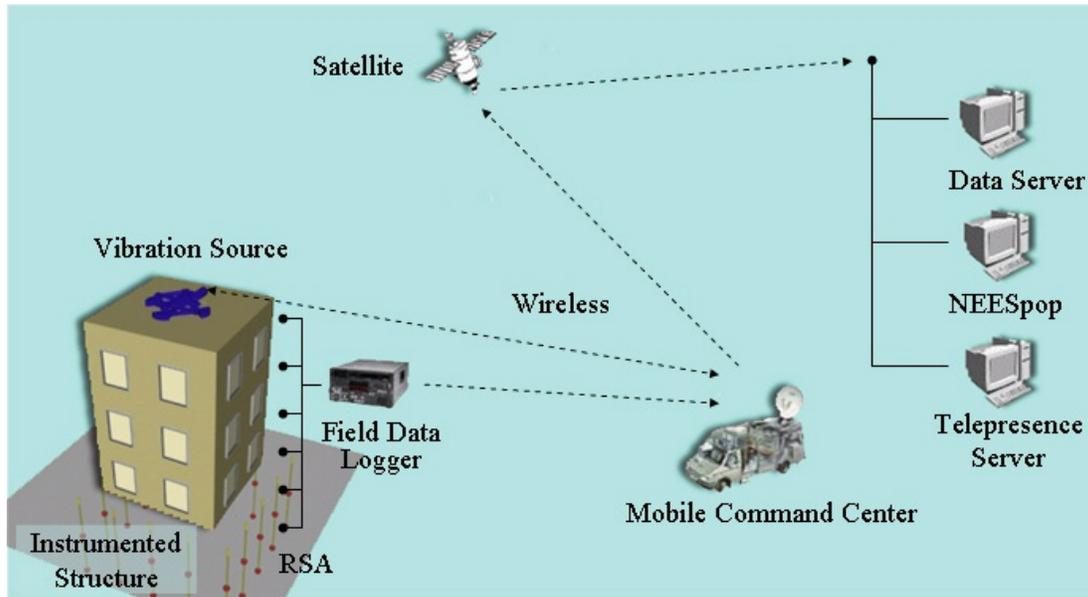
The major equipment components of the site are illustrated in Figure 1 and include the following:

- A. **Eccentric mass shakers** that can apply harmonic excitation across a wide frequency range with forces up to 200 kips. These shakers can induce weak to strong forced vibration of structures. When larger shaker forces are used, it may be possible to excite structures or structural components into the nonlinear range. 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).
- C. **Above-ground sensors** that can be installed at the ground surface or on buildings, bridges, 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.
- 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). Each of the field data loggers contain embedded GPS time synchronization capabilities to ensure data compatibility across different data acquisition nodes.
- 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.

As shown in Fig. 1, a typical application of the equipment would have shakers installed on or within a structure, a dense array of sensors throughout the structure and RSAs deployed below the ground surface. Data from the building sensors and RSAs are transmitted wirelessly via field data loggers to the mobile command center where all data are locally stored. Selected data channels and video streams could be transmitted via satellite to the UCLA global backbone for subsequent dissemination via NEESpop for teleobservation of the experiment.

One point that should be emphasized is that the *nees@UCLA* equipment can be utilized with several types of vibration sources. Obviously, the eccentric mass shakers

and linear inertial shaker are two such types, but the equipment is also ideally suited for seismic monitoring of structural or geo-systems (i.e., aftershock or microtremor sources).



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

## EQUIPMENT SPECIFICATIONS

This section summarizes the specifications of the equipment available at *nees@UCLA*. Further details can be found at the website <http://www.nees.ucla.edu>.

### Eccentric Mass Shakers

- Manufacturer: ANCO Engineers
- MK14A
  - Quantity = 1
  - Omni-directional (single rotating mass)
  - Frequency range: 0-4.2Hz
  - Maximum vector force = 88.9 kN
- MK15
  - Quantity = 2
  - Uni-directional (counter rotating mass)
  - Frequency range: 0-25Hz
  - Maximum vector force = 444.8 kN each
  - Maximum vector force frequency range = 2.7 to 25 Hz
  - Maximum synchronized vector force = 889.6 kN

### Linear Inertial Shaker

- Manufacturer: ANCO (shaker) and dSPACE (controller)
- 66.7 kN actuator
- 340.7 lpm servovalve
- 113.6 lpm HPS
- Four 37.9-liter accumulators
- Digital control
- Maximum displacement = +/-38.1 cm
- Maximum velocity = 198.2 cm/sec
- Maximum force = 66.7 kN

### Above-Ground Sensors

- Accelerometers
  - Manufacturer: Kinematics
  - Quantity: 55 uniaxial, 15 triaxial
  - Frequency range= 0-200 Hz
  - Maximum acceleration: +/-2g
- Displacement Sensors
  - Manufacturer: Transtek
  - Type: DCDT
  - Quantity = 45
  - Range = +/- 25 and +/-50 mm

### Retrievable Subsurface Accelerometers

- Sensor type: capacitive MEMS accelerometer
- Sensor Manufacturer: Silicon Designs
- Frequency Range = 0-200 Hz
- Maximum Acceleration = +/-2g
- Packaging: retrievable package designed for placement with Hogentogler CPT truck

### Wireless Field Data Acquisition System

- Wireless Data Loggers
  - Manufacturer: Kinematics
  - Model: Q330
  - Quantity = 20
  - Channels per unit = 6
  - Resolution = 24-bit
  - GPS time synchronization: < 1 ms accuracy
  - 802.11a/b WiFi
  - TCP/IP protocol
  - Real-time data streaming
- Data Management Software
  - Manufacturer: Kinematics
  - Model: Antelope

- Wired Data Acquisition System
  - Manufacturer: National Instruments
  - Model: rack-mounted PXI-SCXI chassis with GPS receiver/counter-timer board
  - Channels = 96
  - Modular signal conditioning
  - GPS time synchronization: < 1 ms accuracy

#### High Performance Mobile Network

- Mobile command center truck
- Satellite uplink system
  - 1.8m diameter dish on top of truck
  - Data rate = 1.54 Mbits/sec (T1)
- Networking Hardware
  - WiFi concentrators and hub
  - Field LAN

### **SOIL-STRUCTURE INTERACTION RESEARCH OPPORTUNITIES**

We anticipate several general categories of application for the *nees@UCLA* equipment site, including (1) building or bridge structural response/performance studies; (2) seismic health monitoring and sensor network studies; (3) response/performance studies for geo-structures and soil deposits; and (4) soil-structure interaction (SSI) studies. The remainder of this paper briefly describes opportunities for SSI research with the *nees@UCLA* equipment portfolio.

#### Some Previous SSI Experimental Studies

A frequent goal of soil-structure interaction testing is the evaluation of effective stiffness and damping associated with foundation-soil interaction, which is often quantified by so-called foundation impedance functions. Table 1 presents a summary of forced vibration tests that have been performed in the field with the objective of identifying foundation impedance functions. It should be noted that laboratory-scale studies of SSI for shallow foundations have also been performed (e.g., Gajan et al., 2004). Such tests can also provide valuable insight, but the limited scale and laboratory boundary conditions of the models may preclude the tests from properly capturing important SSI phenomena such as radiation damping.

Testing by Lin and Jennings (1984) was performed on a small model structure and provided spring and dashpot coefficients near the fundamental-mode system frequency. The results were used to evaluate the effect of foundation embedment on the impedance functions. Comparisons to impedance function models for unembedded foundations were favorable, but a bias was noted for embedded foundations.

**Table 1. Summary of representative forced vibration tests  
used to infer impedance functions**

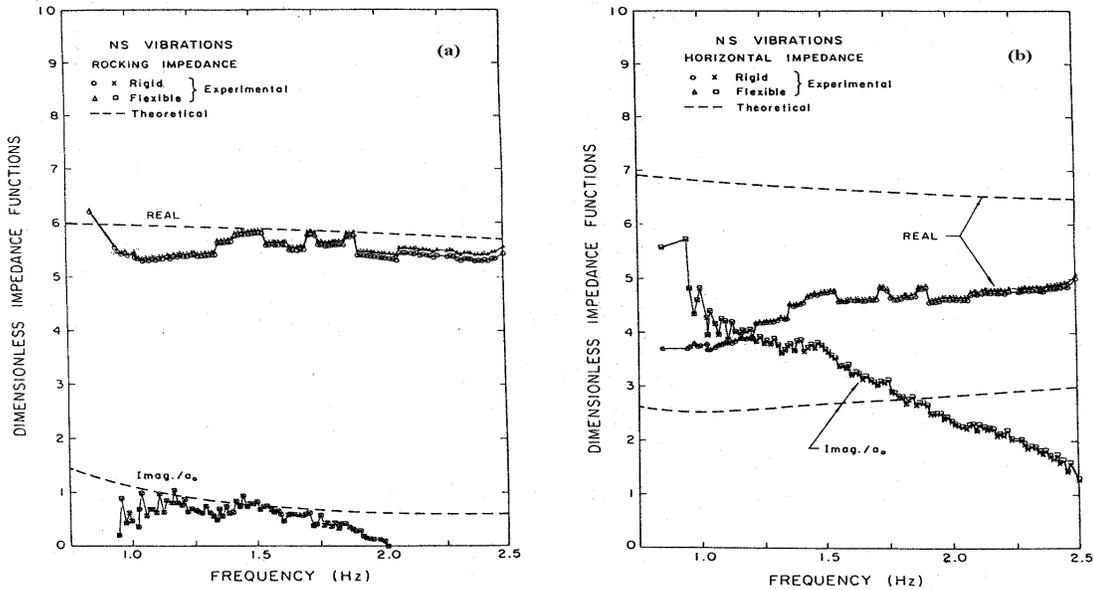
Foundation Dimensions	Embed. (m)	$f_1$ (Hz) <sup>1</sup>	$V_s$ (m/s)	Excitation		Results			
				Source	Freq (Hz)	$f / \tilde{f}$	Impedance obtained	Freq range (Hz)	Reference
3m×3m	0-1.5	17.5	305	Vibrator on ground	7-70	1.3 (e=1.5); 1.5 (e = 0)	$k_u, c_u, k_\theta, c_\theta$	modal freq. only	Lin and Jennings, 1984
25m×25m	4-5.5	NS: 2.16; EW: 1.26	300	Vibrator on roof	NS: 0.8-2.5; EW: 0.8-1.75	NS:1.06; EW:1.1	$k_u, c_u, k_\theta, c_\theta$	NS:0.8-2.5; EW:0.8-1.75	Luco et al., 1988; Wong et al., 1988
1.3m×1.3m; 1.2m×1.1m	0	n/a	120; 75	Vibrator on fndn.	10-60	n/a	$k_u, c_u, k_\theta, c_\theta$	0-60	Crouse et al., 1990
d=10.8m	5.2	9.37	300	Vibrator on roof/fndn	2-20	2	$k_u, c_u, k_\theta, c_\theta, k_{u\theta}, c_{u\theta}, k_v, c_v$	5-14	DeBarros and Luco, 1995

<sup>1</sup> Fundamental mode, fixed-base frequency

Testing by Luco et al. (1988) was performed on a full-scale structure (i.e., the 9-story Millikan Library on the Caltech campus). The results were used to evaluate whether simple impedance function models could reproduce the observed foundation impedance functions. Example results are shown in Figure 2 for normalized translation and rocking impedance functions. The “rigid” and “flexible” experimental results in the figure relate to how base rotation was evaluated from the foundation sensors (rigid refers to rotation taken as average foundation rotation, flexible refers to rotation at the base of the shear walls). Normalized results are plotted in Figure 2 against the predictions of the Apsel and Luco (1987) theoretical impedance function model. There are no significant differences between the results for the “flexible” and “rigid” foundation assumptions. The results for rocking (left frame) compare favorably to the predictions from theory, while the results for translation (right frame) do not.

Testing by Crouse et al. (1990) was performed on foundation pads for typical accelerograph installations. Tested foundations were ~ 1.2m square concrete pads with and without corner piers. Adjustments to the site shear wave velocity were needed to match the observed impedance functions.

Testing by deBarros and Luco (1995) was performed on the one-quarter scale reinforced concrete Hualien, Taiwan containment model. The model structure is of a similar design to the well-known Lotung, Taiwan containment model, but is sited on foundation soils with considerably larger shear stiffness than those at Lotung ( $V_s \approx 300$  m/s at Hualien vs.  $\approx 100$ -150 m/s at Lotung). As with the Millikan library, results compared to theory more favorably for rocking than for horizontal translations. Data interpretation was complicated by differences in the results for perpendicular horizontal directions, which was attributed to laterally heterogeneous soil properties.



**Fig. 2. Comparison of theoretical and experimental estimates of impedance functions for Millikan library building, NS direction (after Wong et al., 1988)**

Attempts to evaluate impedance from seismic data have been made by Moslem and Trifunac (1986) and Kim (2001). The results for rocking stiffness were meaningful only near the first-mode frequency. The identification exercises were not particularly successful for translational stiffness nor for damping in either translation or rocking due to noise effects and potential synchronization problems in the data acquisition systems (i.e., small time lags can produce significant errors in measured damping). An interesting finding from the Moslem and Trifunac (1986) work was that the rocking stiffness during earthquake shaking was reduced from that during forced vibration testing, which was attributed to soil nonlinearity.

### Opportunities for Future Foundation Testing

Several pertinent observations can be made from the testing/analysis in the literature. First, investigators often found that linking the site shear wave velocity profile to the velocity that provides the best match to the field data to be non-trivial. This highlights both the difficulty of fitting simplified theoretical models to field measurements and the subsequent need for an inventory of test data to guide parameter selection. Second, the results from the Millikan library highlight the importance of soil nonlinearity on foundation-soil stiffness. Unfortunately, these test data were not sufficient to define the soil strain field beneath the foundation, which is needed to enable rational predictions of nonlinear soil properties within this domain. Third, the available data generally does not address, or provides very limited coverage, of a number of significant issues including: (1) localized foundation settlement induced by cyclic loading, which has been widely observed following earthquakes (e.g., see Bray and Stewart, 2000); and (2) foundation-soil damping associated with soil hysteresis or radiation effects.

## SUMMARY

The NSF-funded *nees@UCLA* Equipment Site 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* site is now “on line” for shared-use as of October 1, 2004. The site provides equipment that is ideally suited to soil-structure interaction testing and research.

The *nees@UCLA* equipment is suited for meeting the SSI research needs described above. Whether employed on existing structures or specially constructed model structures in the field, the equipment can be used to:

1. Dynamically excite the structure with eccentric mass shakers or the linear inertial shaker, thus creating base shear forces and moments that would lead to relative foundation/free-field displacements and rocking;
2. Record foundation and ground vibrations with accelerometers, displacement transducers, and/or strain gauges, that quantify foundation vibrations and potential foundation deformations.
3. Record subsurface accelerations with RSAs, thus enabling recordings of the wave field emanating from the foundation and the inference of subsurface shear strains.
4. Transmit the data wireless to the mobile command center, where it can be locally stored and viewed, and also sent via satellite to the UCLA global backbone for dissemination over the internet.

Accordingly, foundation vibration testing is expected to be a major application of the *nees@UCLA* equipment site.

## ACKNOWLEDGEMENTS

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