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Soil-Foundation-Structure Interaction (Shallow Foundations)

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Background

This research focuses on strip footing foundations supporting shear wall type building structures. Understanding the nonlinear behavior of shallow building foundations under large amplitude loading is an important aspect of performance-based design. The 1997 Federal Emergency Management Agency NEHRP Guidelines for the seismic retrofit of buildings (NEHRP 1997a, 1997b) and the associated Applied Technology Council document (ATC 40) (ATC 1996) discuss alternative design issues associated with the response of shear walls when subjected to lateral

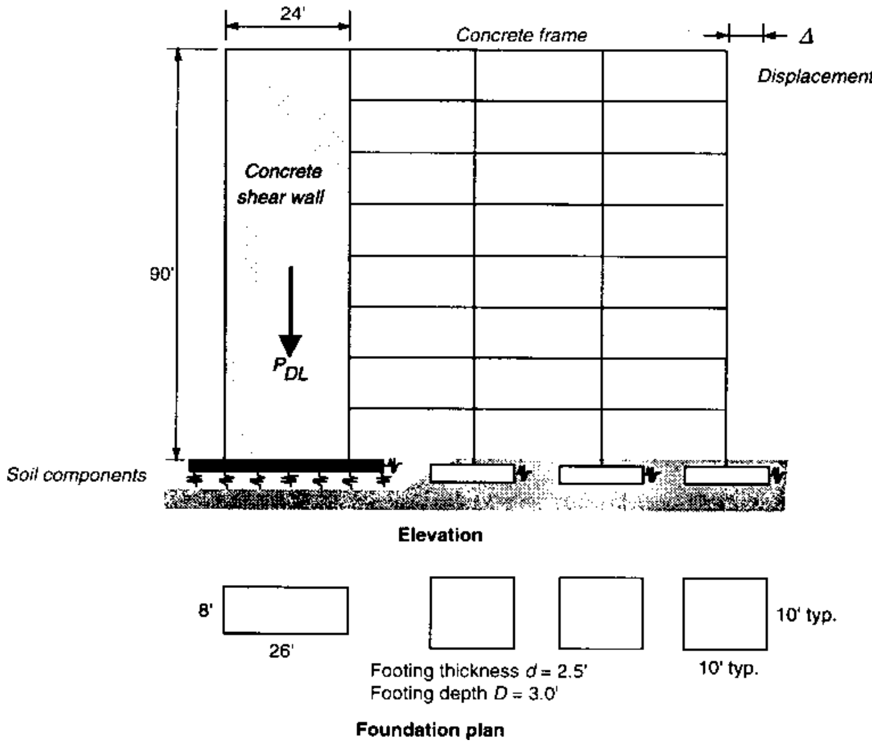

Fig. 1: *Shear wall and frame example (after NEHRP, 1997)*

earthquake induced rocking. Geotechnical components of the foundation are known to have a significant effect on the building response to seismic shaking. ATC-40 presents and explains techniques for performance-based design where the structural component behavior is represented by a nonlinear load-deformation relation (Comartin, et al. 2000). The nonlinearity of the soil and the interaction between the soil and foundation is shown to cause the building's stiffness and period to change to varying degrees. On the one hand, the nonlinearity of the soil may act as an energy dissipation mechanism, potentially reducing demands exerted on the structural components of the building. This associated nonlinearity, however, may result in permanent deformations (rotation or settlement) that cause damage to the building. The goal of this research is to further the understanding of soil-foundation-structure interaction with regards to seismic response.

Collaborative Research

The research includes physical model testing and numerical modeling using OpenSEES, and considerations of foundation design issues for performance-based earthquake engineering. Non-liquefiable site conditions are emphasized at this stage; liquefiable sites will be investigated in subsequent years.

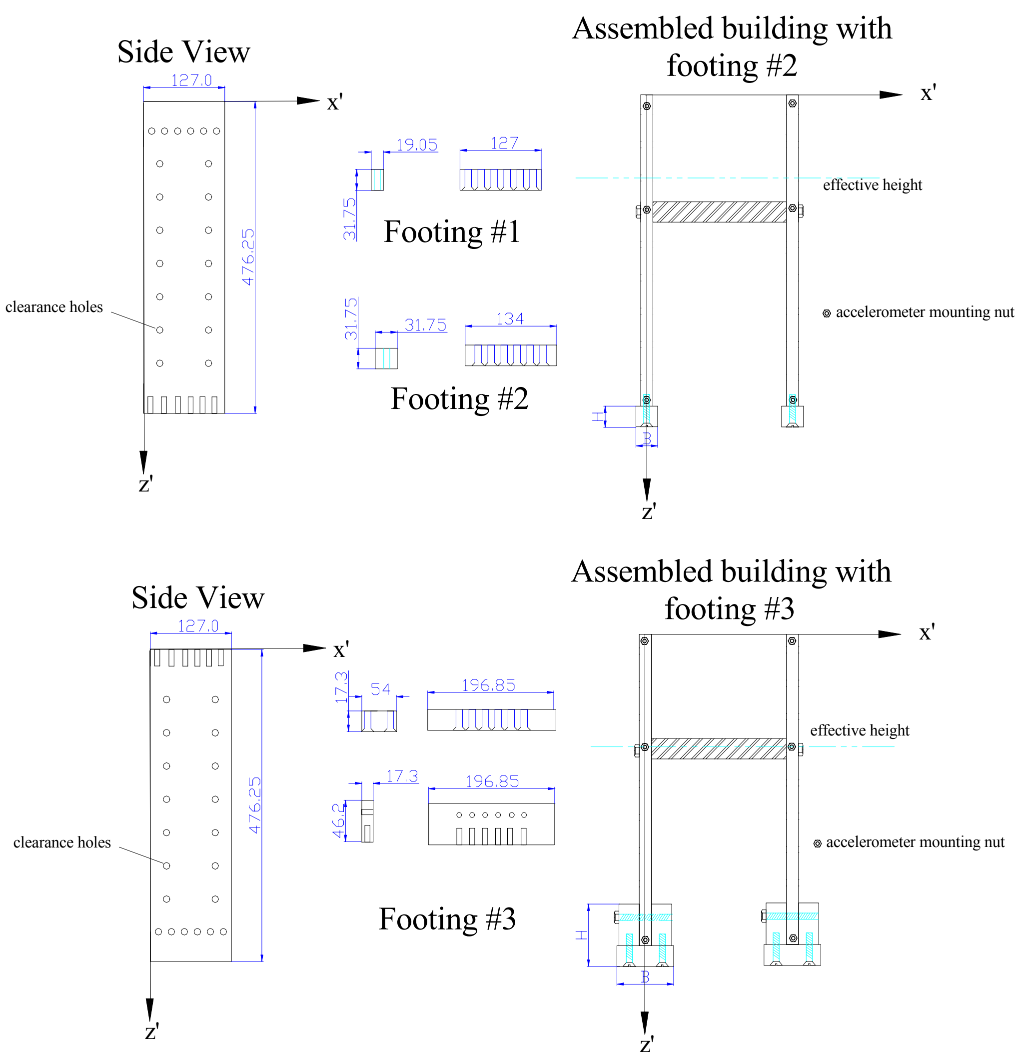

Fig. 2: Model building structure for KRR test series. All units are in millimeters (model scale).

The portion of the work performed at UCD by Kutter emphasizes model testing of shallow foundations. Centrifuge model tests are being used to explore the effects of foundation mass,

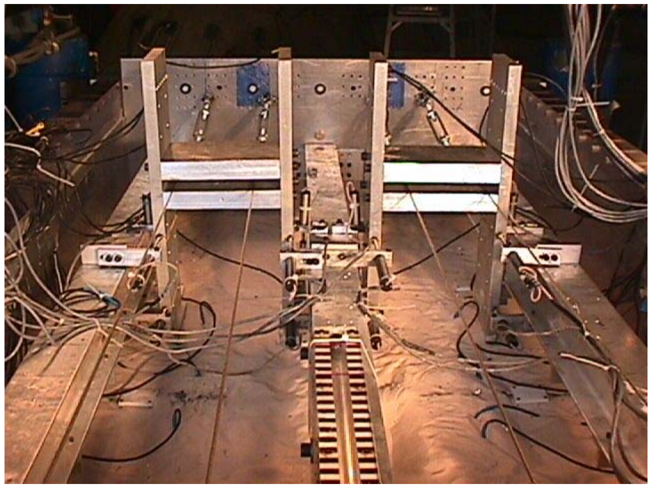

Fig. 3: Photograph of fully assembled building structures in place.

foundation size, foundation shape, foundation embedment depth, and soil density on load-deformation behavior. The data obtained from these tests are properly checked, documented and archived on the web so that Martin (USC) and Hutchinson (UCI) can easily access the data. UCD will also implement and test a single element foundation-soil interface constitutive model that couples the effects of moment-rotation-load-displacement behavior. This analytical work will complement the nonlinear subgrade reaction analysis planned by Hutchinson and Martin.

Work performed at UCI (Tara Hutchinson, PI) will focus on developing numerical tools for modeling this rocking behavior and predicting associated foundation and building settlements, and validating these models against available experimental data. Numerical studies at UCI will be based on a nonlinear Winkler-type framework for modeling the soil response (i.e., using nonlinear springs and dashpots, with gapping elements). Experimental data provided from centrifuge tests conducted at UCD, as well as other available data, will be used for validation of the analytical approach. Initial validation of the numerical models will lead to further parametric studies, which consider the combined dissipation of energy through nonlinearity in structural elements (e.g. in shear walls, at beam-column joints) and nonlinearity of foundation elements (through yielding of the soil). Parametric studies will consider moment resisting frame (MRF) structures as well as coupled structural systems (MRF's and shear walls combined).

The work conducted at USC entails the oversight and integration of work performed at UCD and UCI. This includes sequencing and prioritizing model tests and analysis directions and implementing analysis and experimental data into the framework of a performance-based engineering design approach. The work performed by USC will also include interfacing with practicing engineers in the US and Europe involved in implementation of nonlinear SSI into seismic design guidelines or codes. USC coordinates the research progress meetings, which will include Mark Moore of Rutherford and Chekene as an external adviser. In addition, input and expertise on foundation design issues will be provided for the Van Nuys building test bed including potential retrofit solutions using shear walls and shallow foundations

Centrifuge Model Tests

To-date, three series of centrifuge tests have been conducted at UC Davis (Rosebrook and Kutter, 2001 a, b, c) and Rosebrook (2001). Fig. 2 shows a sketch of the model building geometry, and Fig. 3 shows two models set up on the sand foundation in the centrifuge model container. The mass and center of gravity of the model buildings was designed to produce ratios of moment, shear, and axial loads typical of a full-scale building. The test program includes dynamic tests and slow cyclic tests.

An important aspect of these studies is to understand the moment-rotation characteristics of these shallow foundation systems. For the slow cyclic tests, a moment was applied to the foundation by a horizontal actuator that pushed and pulled on the building at the "effective height". For the dynamic tests, loads were supplied by shaking the base of the model container on the large centrifuge. The dynamic moment at the base of the footing was calculated using the following equation:

$$M = I\,\alpha + m\,a\,h_{cg} \qquad \text{Eq. 1}$$

Where I is the mass moment of inertia of the superstructure, α is the angular acceleration of the superstructure, m is the mass of the superstructure, a and h_{cg} are the acceleration and height of the center of gravity of the superstructure. Angular acceleration was determined by taking the difference in accelerations at different elevations of the buildings and dividing by their spacing.

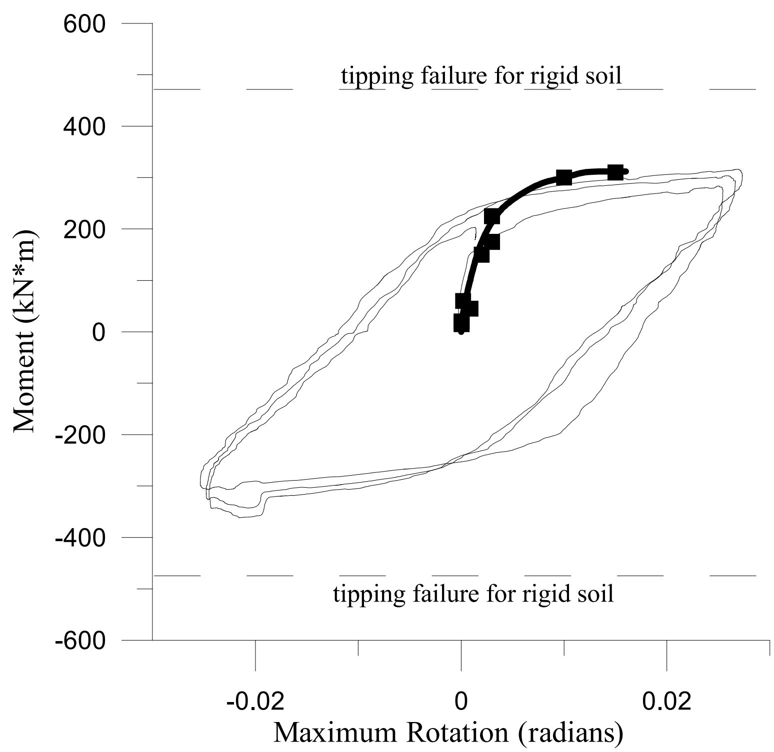

Fig. 4: Comparison of KRR02 dynamic data trend line with KRR02 slow-cyclic test KRR02_S21. Dynamic trend line and corresponding data points shown in heavy black line.

This is the first time that an experimental program has produced direct comparisons between slow cyclic moment rotation and dynamic moment-rotation relationships; one set of results for the case of footings on sand is compared in Figure 4. The dynamic trend line in Figure 4 is obtained from many different shaking events. Each data point represents the peak moment and peak rotation from one dynamic time history. The continuous hysteresis loops are the cyclic moment-rotation curves measured in three slow cycles. The rigid soil tipping moment shown in Figure 4 is calculated by $M=Q^*(L/2)$, where Q is the weight of the superstructure and L is the length of the footing.

One may have expected that dynamic shaking might cause densification and stiffening of the soil resulting in greater moment resistance during shaking tests. On the other hand, dynamic shaking could be expected to be more severe because dynamic shear stresses from the soil mass are superimposed on the shear stresses from the superstructure. The data in Fig. 4 are representative of our other results; the backbone curve for the dynamic tests is very similar in shape and capacity to the slow cyclic moment-rotation relationship for the range in parameters tested to date.

The data from the centrifuge model tests is providing valuable information for verification of the SFSI analyses to be conducted by the collaborators at USC, Irvine and Davis.

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