Dynamic Behavior of Simple Soil-Structure Systems

Department of Civil and Environmental Engineering
University of California at Davis

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****** INSTRUCTOR'S GUIDE ******

Dynamic Behavior of Simple Soil-Structure Systems

A PROJECT DEVELOPED FOR THE
UNIVERSITY CONSORTIUM ON INSTRUCTIONAL SHAKE TABLES

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Objective: This experiment illustrates the influence local geology and soil conditions can have on the intensity of earthquake induced ground shaking and structural vibration. A simple soil model will be constructed and connected in series with a 1-D structure model. Both the soil-structure system and the structure alone are subjected to identical base excitations via a bench-scale shaking table. The experiment serves as an introduction to the modeling of soil-structure systems and demonstrates some potential effects of site period on structural response.

1. Introduction

This laboratory is intended primarily for undergraduate students studying earthquake loads on structures. The soil column model, coupled with the 1-D structure, also serves as a teaching tool for K-12 students since, at least in a general sense, there is a distinct modeling of the two main components: the soil and the structure.

The 1-D structure model is either: 1) rigidly connected to the shake table platform; or 2) rigidly connected on top of the soil system, which is rigidly connected to the shake table. Each component, by itself, can be modeled as a linear single degree of freedom (SDOF) oscillator. The composite two degree of freedom system can be analyzed using the techniques covered in introductory courses in structural dynamics. Although simple, and in many ways a rough approximation, the experiment provides an awareness that structural response is affected by soil mass beneath the structure and, in particular, the natural period of the site.

This instructors' manual supplements the student manual and serves three main purposes. It provides: 1) guidance in the construction of the soil column model; 2) sample results; and 3) responses to questions at the end of the student manual.

2. Construction of the Soil Column Model

The soil column model consists of a foam matting core surrounded by a framing system, which is constructed from semi-rigid plates that are connected via hinges. The framing system serves to confine the foam matting, so that it deforms uniformly in pure shear, while providing no lateral resistance by itself. The plates are made of 3/8″ Plexiglas, but other materials could be used, too, if they are sufficiently stiff. 1/4″ Plexiglas, which is commonly available in hardware stores, was not rigid enough for the foam type and dimensions considered here.

Foam matting comes in a variety of types and often is available in a number of different thicknesses (e.g. 3″, 4″, 5″). The soil column model should be tuned to provide a natural period that is close to that of the 1-D structure model. Foam thickness is one free variable that can be adjusted to achieve that goal. Keep in mind, however, that if the foam is too thin, it may move out-of-plane during loading. Furthermore, thicker foam requires larger mass when tuning the soil model period to that of the 1-D structure. Sufficiently large mass is necessary to keep the influence of the 1-D structure on the soil model small. Here, mass was adjusted by attaching metal plates to the underside of the top Plexiglas plate (i.e. the plates are inserted between the plexiglas and the foam).

The foam should be sized slightly larger than the frame opening, such that a small amount of prestressing is produced when it is inserted into the frame. The prestressing will provide bearing stresses against the frame and therefore prevent slippage along the interfaces. Without such frictional resistance, slippage will occur and the foam element will not deform uniformly in pure shear. A network of orthogonal grids lines can be drawn on one side of the foam (see cover photo of test setup); the deformation pattern under lateral loading gives an indication of whether the foam is deforming uniformly in shear. Slippage between the foam and the plates can be further reduced by attaching coarse sandpaper to the inside faces of the Plexiglas frame.

High quality hinges should be used to reduce slack and the amount of friction during hinging action. Improper alignment of the hinges can also be a large source of resistance to frame movement. The goal is to provide a frame system that consumes a minimal amount of energy during hinging actions.

3. Sample Results and Calculations

Example results are given here for the tests described in section 4 of the student manual.

3.1 Natural Frequencies of the Structure and Soil Model

Both the 1-D structure and the soil column models are subjected to sinusoidal excitation with gradually increasing frequency (sections 4.3.1 and 4.4.1, respectively, in the Student Manual). The natural frequencies of both the 1-D structure and soil models are the values corresponding to the peaks in the frequency domain plots. The period of the structural model is approximately 0.25 sec (fig. 1), while the period for the soil model used in this experiment is approximately 0.2 sec (fig. 2). The natural frequency of the soil column model is not sharply defined, compared to that of the 1-D structure model. Attaching additional mass to the soil column model would bring the two periods closer together.

3.2 Damping Ratios of the Structure and Soil Model

Figure 3 shows the plots of acceleration versus time for free vibration testing of the structure and the soil column models. The damping ratio of each model is determined by the logarithmic decrement method, which makes use of peak values

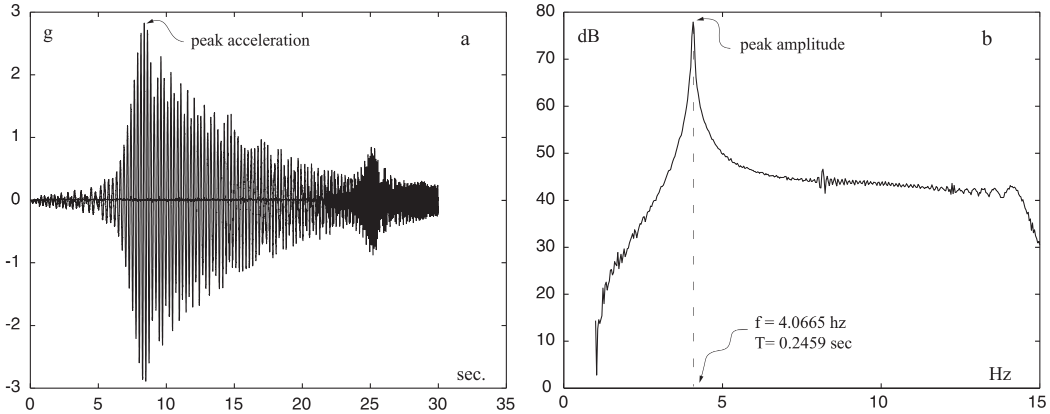

Fig. 1 a) Response of the 1-D structure model to the sweep function and b) corresponding transfer function plot

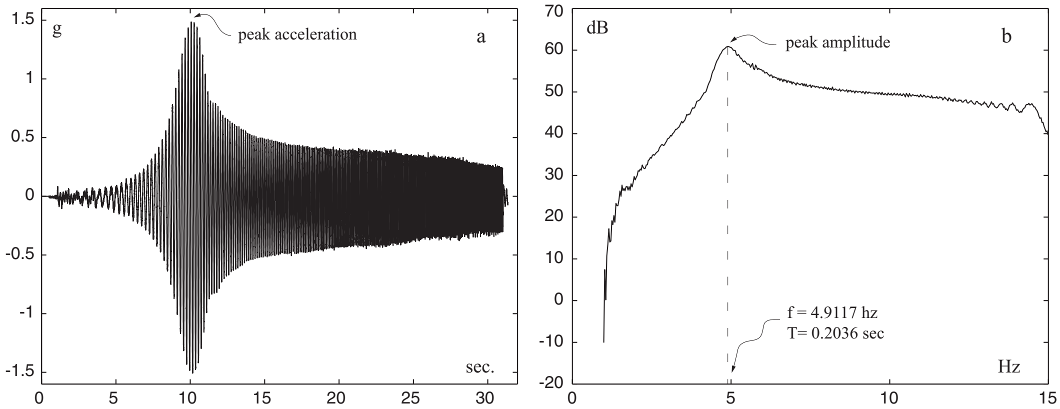

Fig. 2 a) Response of the soil column model to the sweep function and b) corresponding transfer function plot

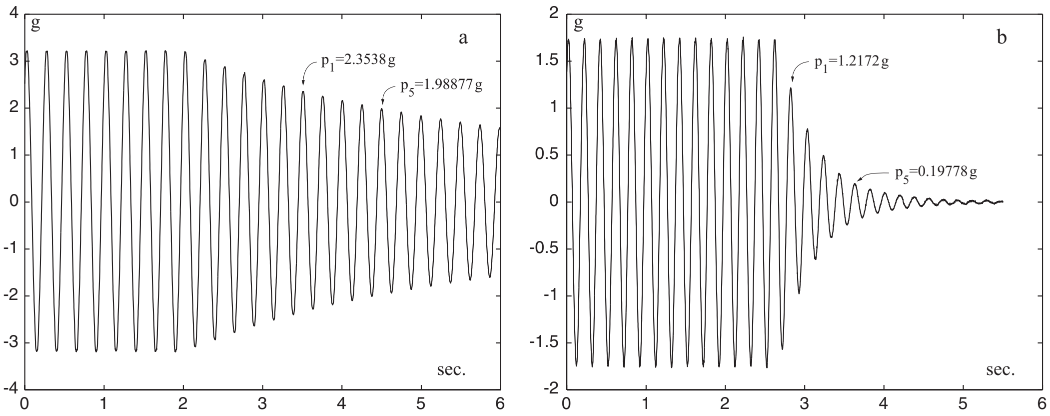

Fig. 3 Free vibration test of: a) 1-D structure and b) soil column model

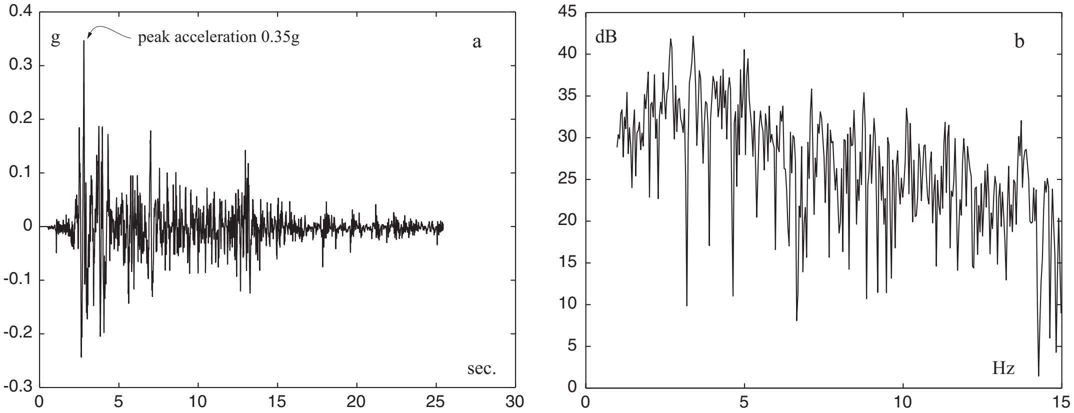

Fig. 4 a) El Centro input ground motion and b) corresponding Fourier amplitude spectra

on the acceleration (or displacement) curves. Using eq. 7 from the student manual:

$$\xi = \frac{1}{(5-1)2\pi}\ln\frac{p_1}{p_5} = \frac{1}{8\pi}\ln\frac{2.354}{1.989} = 0.00671 \qquad \text{structural model} \qquad (1)$$

$$\xi = \frac{1}{8\pi}\ln\frac{1.217}{0.1978} = 0.0723 \qquad \text{soil column model} \qquad (2)$$

3.3 El Centro Input Motion – Free-field Motion

The soil column model is excited at its base according to one component of the 1940 El Centro earthquake motion. The effect of the soil model can be seen when comparing the acceleration data (at the table platform and ground surface level) in the frequency domain. Figure 4 shows the table input accelerations in the time and frequency domains. Figure 5 shows the recorded acceleration at the ground surface in the time and frequency domains. Amplification of the peak values occurs for the frequency close to 5.0 Hz, as expected from the transfer function of Fig. 2.

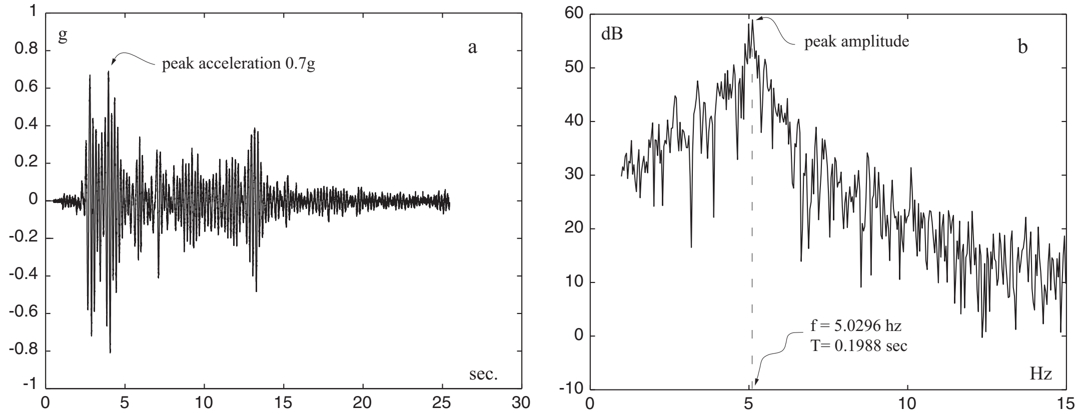

Fig. 5 a) Acceleration recorded at the top of the soil model for the El Centro input ground motion and b) corresponding Fourier amplitude spectra

3.4 Comparison of Results

The peak *absolute* acceleration recorded at the top of the 1-D structural model is $1.52g$ for configuration A and approximately $1.8g$ for configuration B (i.e., when the 1-D structure is attached to the soil column model), as shown in Fig. 6. Figure 7 shows the peak *relative* acceleration recorded at the top of the structure model is $1.52g$ for configuration A and approximately $1.95g$ for configuration B.

4. Responses to Questions

This section provides partial responses to the questions in section 6 of the Student Manual.

a. For the earthquake motion considered here, the relative peak acceleration of the 1-D structure with respect to its base (for the resonance condition with the soil model) is only slightly greater than the peak acceleration of the structure alone. Introducing the soil model provides the potential for amplification due to resonant behavior, but it also introduces relatively high damping between the table platform and the base of the 1-D structure. Influence of this damping is clearly discernible in acceleration histories shown in Figs. 6 and 7. The degree of amplification would be different for other input motions, so these results are not necessarily representative of general behavior.

   The 1940 El Centro record was used as a representative earthquake ground motion. For this exercise, it may be more appropriate to use a record representative of motion at bedrock, since configuration A could model the structure attached to bedrock. Alternatively, the soil column model could be viewed as just an additional soil layer within a soil system.

b. Because of the relatively large k^* of the soil model, a large m^* is needed to achieve resonance with the 1-D structure. The mass of the 1-D structure is small relative to m^*, so that the presence of the structure has only a secondary

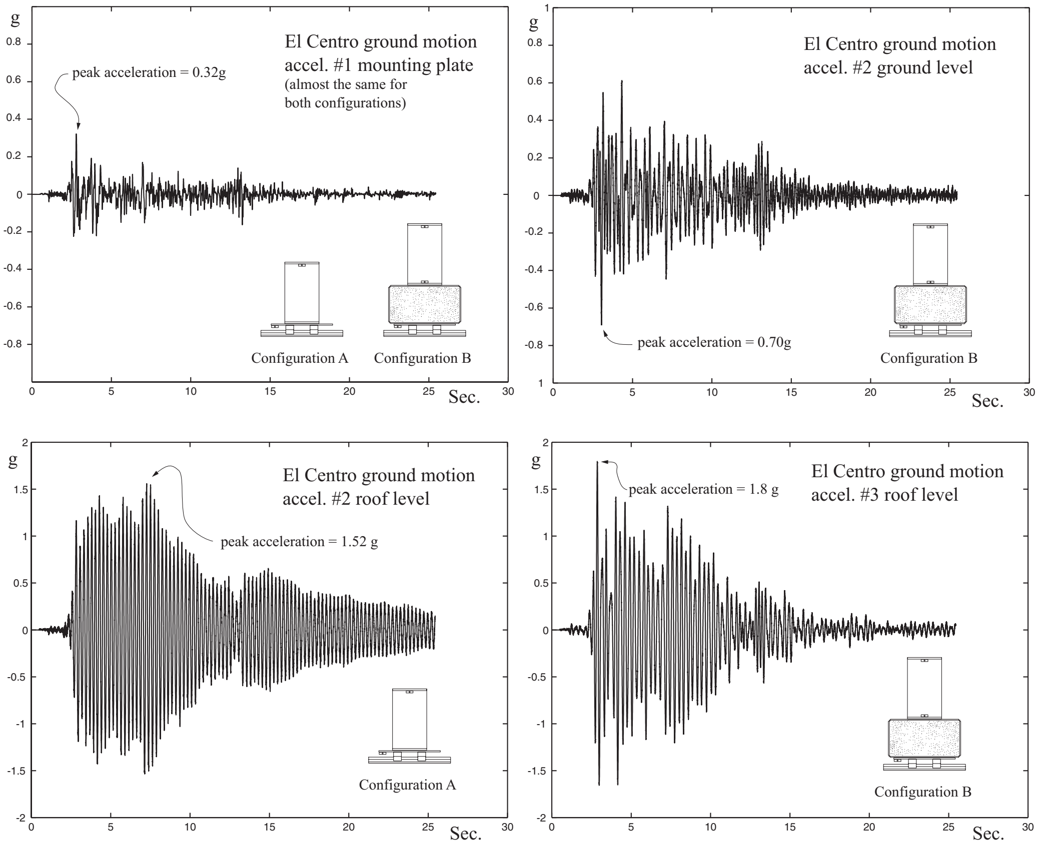

Fig. 6 Absolute acceleration data for configurations A and B

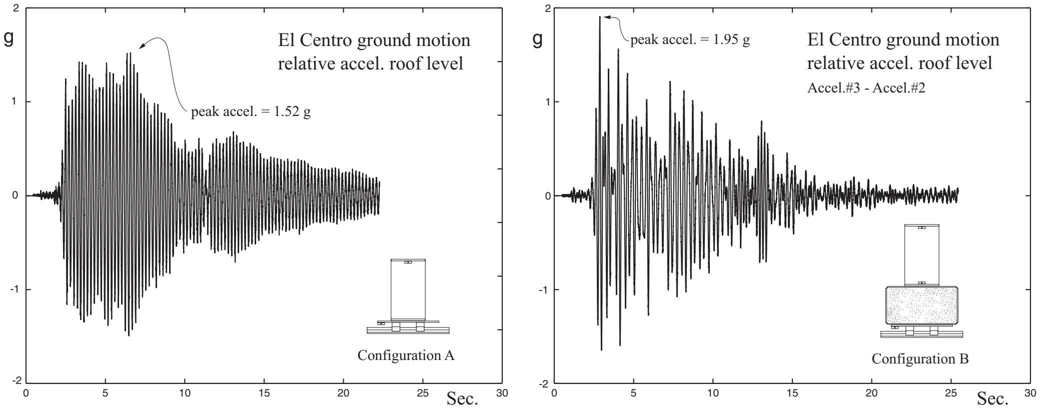

Fig. 7 Relative acceleration at the top of the 1-D structural model for configurations A and B

(but not negligible!) effect on the vibration of the soil model. There is always some sort of interaction, but the degree of interaction depends on the scale and properties of the two components (soil mass and structure) relative to each other. The case where the structure does not significantly influence the overall movement of the soil mass might be more common.

c. For this exercise, the students need to determine the generalized stiffness k^* of the soil model, from which the shear modulus of the foam can be easily calculated. In anticipation of coupling with the 1-D structure, we choose the lateral displacement of the top of the soil column as the generalized coordinate describing the motion of all elements of the soil column model.

   If the frame action is ideal (in the sense that it only confines the soil mass to deform in uniform shear and does not provide lateral resistance), then

$$k^* = \frac{GA}{h} \tag{3}$$

   where G is the shear modulus of the foam matting; A is the horizontal cross-section area of the foam matting; and h is the soil column height. Due to the differences in materials and boundary conditions, this exercise only loosely relates to actual soil systems, as discussed in exercise `e`. Nonetheless, the treatment of the soil model as a generalized SDOF system introduces useful concepts and procedures, which complement the simple shear building approximation that can be used for the 1-D structure model.

d. This exercise is similar to the previous one in that, according to eq. 3, doubling h reduces k^* to half its previous value. Along with a proportional increase in m^*, eq. 8 in the Student Manual indicates the natural frequency becomes half that measured in section 4.4.1. The period is therefore twice as long.

e. The soil column model used in the laboratory demonstration differs from actual soil systems in a number of ways.

   - The soil and foam material properties are very different. This laboratory is restricted to small deformations where the material response is essentially linear. Even so, the damping properties of soil and the foam matting are likely to be quite different.
   - Soil is massive, while the foam material is not. The framing system adds significant mass and, moreover, additional mass (in the form of steel plates) had to be added to tune the natural period to that of the structure model. The soil column model is abstract in that the resisting element (i.e., the foam matting) is not providing much of the necessary mass.
   - The framing system constrains the foam matting to deform uniformly in shear. This simplification facilitates the lab setup and the SDOF modeling of the problem. Actual soil systems exhibit more general deformation patterns.

Several factors present during dynamic excitation are not present in the soil-structure model, including

- the soil and structure generally interact in a local manner that cannot be represented by the simple 2 DOF system. A number of phenomena, such as local deformation of soil, gap opening and closing, structure rocking, etc., can occur along the interface between the two major components, soil and structure.
- actual soil and structures exhibit significant nonlinear behavior during moderate to strong shaking and there are associated changes in damping, as well. The soil-structure model considered here cannot account for such behavior.