

# Advance Simulation Tools for Soil-Structure Interaction under Earthquake Loads

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## Abstract

Traditionally, in earthquake engineering, it has been common to assume that soil-structure interaction (SSI) is beneficial during an earthquake. Because of this it has become common practice to avoid the complication of accounting for SSI by simply ignoring its effects. This avoidance is thought to lead to improved safety margins while simplifying the analysis. New trends in earthquake engineering include analyzing the displacement that a structure undergoes during an earthquake, and considering the structural as well as nonstructural damage that this causes. Even though soil-structure interaction induces dampening, it can also cause increased displacement in the overall structure. Due to this possibly detrimental effect, it is necessary to take soil-structure interaction into consideration during analysis. The problem is that this interaction is a very complex phenomenon, dealing with nonlinear and frequency-dependent behavior. Although methods for analyzing SSI in a linear environment have been developed, a method that includes the nonlinear behavior of the soil and foundation is not available. The objective of this article is to develop advanced response analysis methods that can estimate the response of different structures subject to earthquake induced ground motion, and include linear as well as nonlinear behaviors.

**Keywords:** Earthquake, Building, ABAQUS, SSI, REU

## Introduction

Large structures such as buildings and bridges depend on their strong foundations to support their mass and their vertical load demands. Structures are more than what can be seen above the ground. Their foundations continue under the ground in different forms including shallow foundations, embankments and pile foundations. Pile foundations, the foundation type that this paper will be focusing on, are long underground columns used to support large vertical loads. When a structure is built on soft or unstable soil, the piles provide support by reaching down to more stable rock in the depths of the ground.

In Mid-America there has not always been a strong concern about the dangers of earthquakes. Most structures have been built simply to hold their own mass and predicted vertical loads. Consideration for environmental loads has

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typically been limited to the demands of wind, rain, and snow. Structures here have not necessarily been designed to withstand the lateral forces and displacements that can be caused by seismic ground motion. Although earthquakes in this area are infrequent, the damage they cause can be severe in some cases. Research in this area has revealed the hazard posed by the New Madrid seismic zone. This zone extends from the western edge of Memphis Tennessee to the southern tip of Illinois. It is here that one of the largest historical earthquakes in the continental United States took place, during the winter of 1811-1812. According to the U.S. Geological Survey, the hazard in this region is as high as some places in California, despite the present lower level of earthquake activity.

## Advanced Simulation Tools

The Mid-America Earthquake Center, based at the University of Illinois at Urbana Champaign, has three thrust areas in which all of the research articles are categorized. The three areas, Consequence Minimization, Hazard Definition, and Damage Synthesis, are guided by the principles of consequence based engineering developed in the Framework Development article. The relationship of these thrust areas is illustrated in Fig1. The DS-3 article, titled Advanced Simulation Tools, is one of the articles under the Damage Synthesis thrust area. The objective of the article is to develop and maintain advanced response analysis methods that can be used in estimating peak structural response quantities. The intention being that the responses can be utilized to accurately and efficiently define vulnerability functions.

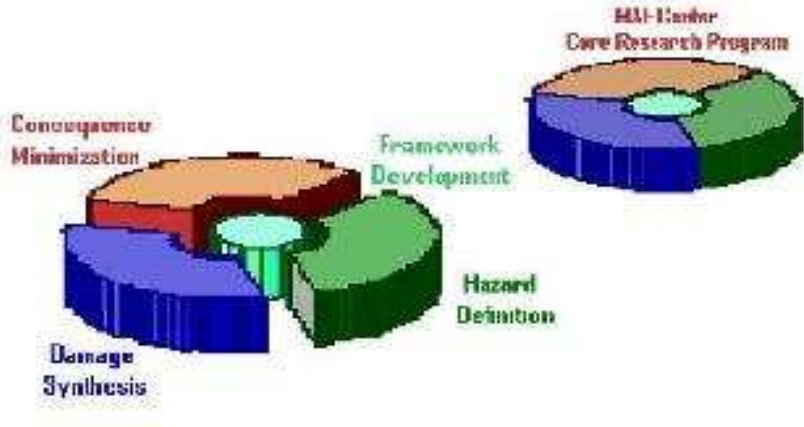


Figure .1. MAE Center Core Research Program

This paper reflects the REU (Research Experience for Undergraduates) work done during a ten week period from May to August, 2004. The work done during this period is a small specific portion of the entire DS-3 article, and will be the main focus of this paper. DS-3 is divided into three main sections, focusing on the articles more specific objectives. The first section of the article is referred to as Detailed Analysis Environment. The second section of the DS-3 article concentrates on Simplified Demand Estimation.

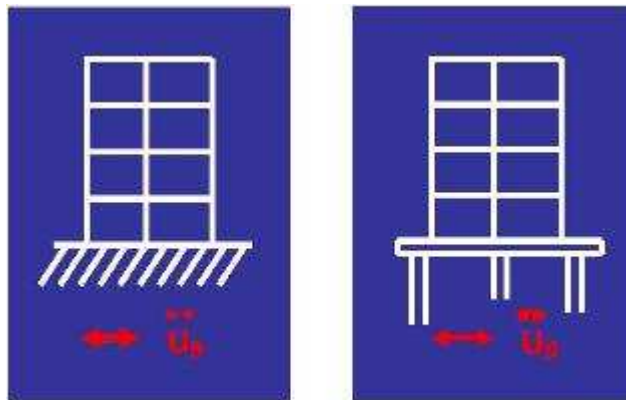
The third division, and focus of this paper, is the section that deals with Soil-Structure Interaction. This portion of the article focuses on assessing current analysis procedures as well as the development of simplified analysis procedures, accounting for the effects of SSI in different foundation types. It also investigates the effects of the interaction on the overall response of structures and implements them in the current analysis environment.

## Soil-Structure Interaction

There has been a significant amount of controversy over the perceived effects of soil-structure interaction on the overall performance of structures, especially on soft soils. Soil-structure interaction has been initially deemed beneficial during seismic motion, but trends in research are changing and this causes different notions of the phenomenon.

Conventionally, it has been common practice in Earthquake Engineering to study the force that ground motion imposes on a structure during an earthquake, when analyzing its seismic capacity. During this type of analysis soil-structure interaction consistently appears to be beneficial for seismic response. Large pile foundations, for example, dissipate energy into the soil. This phenomenon, known as dampening, reduces the force imposed on the structure above. Because of this, the complication of accounting for soil structure interaction is typically avoided, thus its effects ignored. This is done by inputting the ground motion of an earthquake directly at the base of the structure, instead of including its effects on the foundation first. The avoidance of SSI is thought to simply lead to improved safety margins while simplifying the analysis. This practice is even suggested in a number of seismic codes.

New research reveals flaws in this concept. More recent trends in Earthquake Engineering include analyzing the displacement that a structure undergoes during an earthquake, and considering the structural as well as nonstructural damage that this causes. Even though soil-structure interaction increases dampening, which is beneficial, it can also cause additional displacement to the overall structure. This demand in the structure can, in some cases, have detrimental effects. In tall, rigid structures on softer soil, the interaction can cause large increases in the natural period of the structure, leading to much larger relative displacements.



## Figure. 2. Soil-Structure Interaction

This is illustrated in Fig.2. The first image in Fig.2 shows ground motion being applied to the base of the above ground structure. The second image shows the pile foundation being taken into consideration during analysis.

## Objective

The problem arising is that soil structure interaction is traditionally seen as beneficial and ignored for simplification. SSI can in fact have dangerous effects during an earthquake depending on the type of soil and seismic input. Although this is not always the case, it is important to include SSI in analysis so that this potential problem can be foreseen. But soil-structure interaction is not something easily taken into consideration. Its nonlinear and frequency-dependent behavior is very complex, leading to the need for this article.

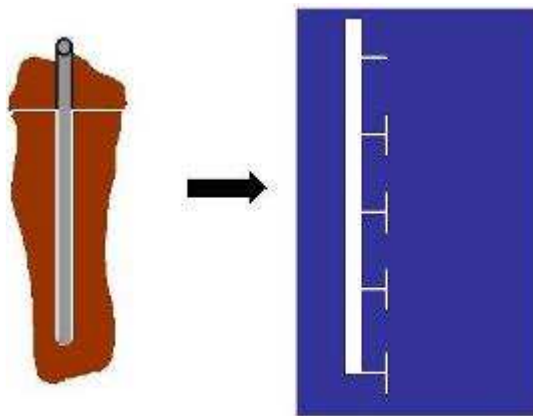
As stated above, the objective of the soil-structure interaction portion of the DS-3 article is to assess current analysis procedures for analyzing soil structure interaction as well as develop simplified procedures. It is important to provide a simple method for researchers to use so that they can accurately include the effects of soil structure interaction during analysis of a structure. Although some methods for analyzing the interaction in linear environments have been developed, there has been little development in the cases of nonlinearity in the soil and pile shaft. This behavior can produce very different results. This article focuses on creating a method that can be used in both linear and nonlinear conditions

## Modeling

Movement of soil can be studied through physical equipment such as laminar boxes, shake tables and centrifuges. The problem with these devices is that they can be very time and economically expensive to build and run. To avoid the financial expenses, as well as create a method that can be preformed in a timely fashion, this article uses finite element analysis software to model foundations and surrounding soil. ABAQUS is one program used in this article.

If the entire pile can be analyzed during ground motion using software, and the behavior at the head of the pile found, then the behavior of the entire pile can be represented on a shake table with springs and dashpots at the base of the structure. This collaboration between physical and virtual modeling provides a way to test a structure more accurately on a shake table. The foundation is represented without the entire foundation and surrounding soil needing to be built onto the table.[4]

The type of model that this paper focuses on is a single pile foundation. Pile groups and pile-soil-pile interaction are considered in this article, although not the focus of this paper. It is important that this effect is later inspected because the behavior of a pile group is much more complex than a single pile. For example, the stiffness of a pile group is not equal to the sum of the individual pile stiffness' because each pile has a lateral effect on each other.[5] In ABAQUS the pile shafts are modeled as well as subjected to finite element analysis. The piles, and the soil in which they are embedded, are modeled in ABAQUS using the Beam-on-Winkler foundation model. This modeling begins with the linear behavior of a single pile shaft embedded in soil. The object of the analysis is to receive a dynamic response from a system limited to a single degree of freedom.[7]



**Figure .3. Beam-on-Winkler-Foundation Model for Single Pile**

As shown in Fig.3, the Winkler foundation is a model that can be created in order to represent the stiffness and the dampening effects of the soil surrounding a pile shaft. The stiffness of the soil is represented with springs and the dampening effect of the soil is represented with dashpots. These are simple interactions existing in ABAQUS, which can be attached to each element of the pile, representing the soil that it is founded in. Different types of soil from hard clay to soft sand can be represented in this manner. The three dimensional beam is shown as a single line in the model, but all of its properties including cross section, density, and young's modulus are entered into ABAQUS and assigned to the pile. ABAQUS uses these properties during analysis. In this study, beam piles with consistent cross section were used. For specific dimensions and properties to create the pile models, Deepak Badoni's Paper titled Nonlinear Response of Pile Foundations Under Inertial and Seismic Loading was used as a reference[1]. The soil surrounding the pile was assumed to be of a homogeneous spectrum, therefore all the spring and dashpots held consistent values down the length of the beam. Layered soil can be modeled using this same method simply by adjusting these values at each element on the beam. The number of elements used to analyze the beam are subjective,

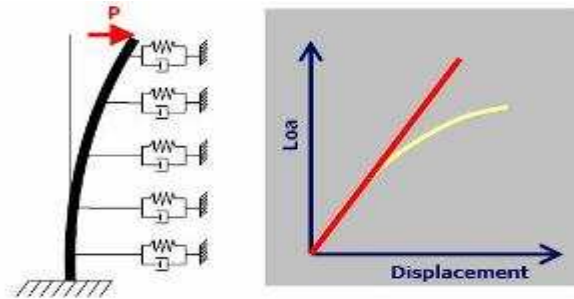
but the more the beam is divided the more accurate the results will be.[9]

## **Analysis**

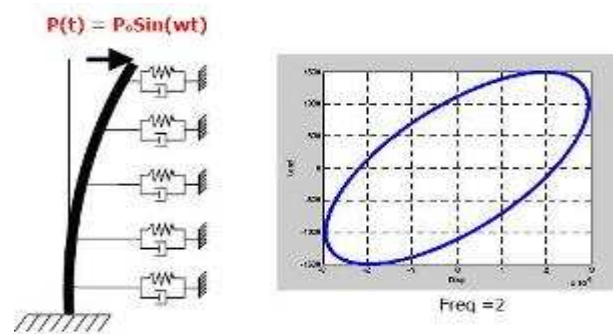
Once the models of pile beams were created in ABAQUS they were subjected to different tests. There are three different tests used in this study to analyze the models. The first test is a Static Pushover test. This test applies a static, lateral load to the head of the pile, and the displacement resulting can be measured. The second test, a steady-state dynamic analysis, is similar to the first, using a dynamic load instead of a static load at the head of the pile. The third type, referred to as Dynamic Time-History Analysis, applies a dynamic displacement to the foot of the pile to simulate vertically propagating S-waves. The resulting displacement at the head of the pile is recorded over time.

The analysis started with a single pile subjected to the static pushover test. Different loads were applied to the head of the pile modeled in ABAQUS. In this model it is not necessary to specify if the pile is an end-bearing pile or a floating pile because only the upper portion of the shaft experiences significant displacement. This part of the pile is referred to as the active length. The actual length of the pile has little effect on the results as long as the model is longer than the active length of the shaft. By adjusting the load applied to the head of the pile, graphs similar to the one shown in Fig.4 could be made for each individual pile modeled. The linear portion of the graph is representative of the results of this test. This test is only accurate for linear behavior of the beam and soil. The curve in this figure is a representation of how nonlinear results would differ from the results given in this analysis.

The second test used was the steady state dynamic analysis. Instead of using an instantaneous load P, this test applies a dynamic load consisting of a sine function to the head of the beam. With the output from ABAQUS, a Matlab program is written to plot the displacement versus load at the head of the pile at every .01 seconds. An example of the resulting scatter plot output from Matlab is shown in Fig.5. In these plots, the points form a shape in which the area enclosed represents the quantity of the energy dissipated into the soil due to dampening. The less dampening that takes place, the smaller or more slender the shape appears. Once again the length of the pile is insignificant to the results, as well as whether the pile is end-bearing or floating.[5]



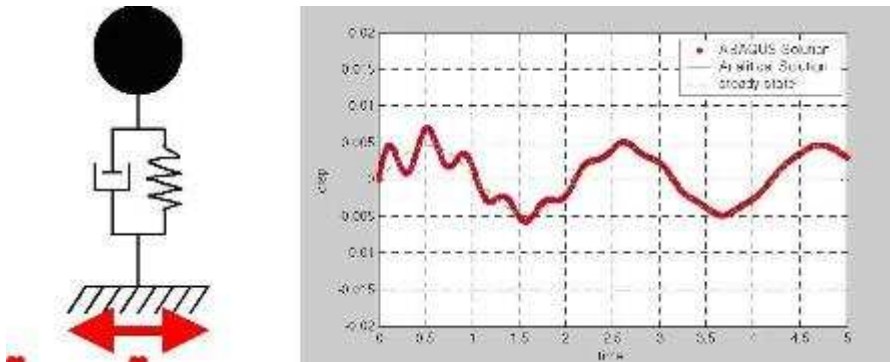
**Figure .4. Static Pushover Analysis**



**Figure .5. Steady-State Dynamic Analysis**

This third type of analysis, Dynamic Time-History Analysis, consisted of subjecting the piles to harmonic motion from below. This was done by moving the boundary condition at the base of the pile in a sine function motion, representing the type of motion induced by an earthquake. The area of interest is the relative displacement resulting at the head of the pile. This is the added displacement that the structure as a whole would be subject to. This analysis differs from the head loading tests because this motion will cause excitation over the entire length of the pile. For these cases the length of the pile must be specified because it does have an effect on the results of the analysis. These models were also assumed to be end bearing where the displacement at the base of the pile is equal to the

forced movement, without separation.



$$U_g(t) = U_0 \sin(\omega t) \quad (1)$$

**Figure .6. Time History Dynamic Analysis**

Because this test is slightly more involved than the earlier examples, it was first tested with a simpler model. Before running the analysis on a full length pile, it was run on the simple system shown in Fig.6. This model consists of a lumped mass, one spring and one dashpot. The input motion was added to the base of the system. The reason for using a simple model was because the analytical solution for the system could easily be solved. When the analytical solution is shown to be the same as the ABAQUS solution then the model is verified to be accurate. The analytical solution comes from the formula of dynamics shown as Eq.1. The input ground motion is expressed as Eq.2 below. Using the initial conditions, the analytical solution for this simple system was found. These mathematics was guided by Chopra's textbook, Dynamics of Structures[2].

$$M\ddot{U} + C\dot{U} + KU = -M\ddot{U}_g \quad (2)$$

$$\ddot{U}_g = \ddot{U}_0 \sin(\omega t) \quad (3)$$

Matlab was used to write a program that would plot this analytical solution along with the ABAQUS results. Fig.8 also shows an example of this graph. As the legend shows, the thick dots are the output given from the ABAQUS analysis. The solid line is the graph of the analytical solution, and the dashed line is the steady state analytical solution. The dashed line is plotted just to show that the solutions eventually calm to the steady state due to dampening. This graph shows that the analytical solution coincides with solution given from the simple ABAQUS model. Now that the ABAQUS procedure is verified, the analysis is done with the entire full size pile models.

## Conclusion

In this paper, This is where the REU (Research Experience for Undergraduates) portion of the article ended, but the DS-3 article as a whole has an important future that will continue on. Not only are these models of single pile foundations important, but models of pile groups will be analyzed as well, because the motion of one pile can actually have an effect on the piles adjacent to it. This is a phenomenon referred to as pile-soil-pile interaction. In addition, other types of foundations are being analyzed as well, including embankments, and shallow foundations. The analysis will also extend to include three dimensional finite element analyses, where more degrees of freedom can be explored.

One important output of this article is to the Mid-America Earthquake Center's DS-4 article, titled Vulnerability Functions. The methods developed in DS-3 will give the researchers working on DS-4 a resource for estimating demand on a structural system, including its foundation, during an earthquake. And from this they are able to derive vulnerability functions. These procedures can also assist the DS-5, Response Simulation across Regions with developing models of large populations of structure. The results of this article also reach across to the Consequence Minimization thrust area, where methods can be used in CM-4 with structural retrofit strategies.

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