A PARAMETRIC STUDY: EFFECT OF SOIL AND MATERIAL CHARACTERISTICS ON SEISMIC BEHAVIOR OF STRUCTURES

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ABSTRACT:

In this parametric study, effect of soil and material characteristics on seismic behavior of structures is investigated. The soil parameters such as shear strength, unit weight; geometrical parameters of the structure such as foundation depth and height of building; and material properties such as weight of concrete were selected as input parameters. A real accelerogram of 1989 El-Centro Earthquake recorded by the USGS in Imperial Valley is used for this study. It is contained in the standard Strong Motion CD-ROM (SMC) format, which can be recognized and interpreted by FEM software used. The soil-structure interaction model subjected to above-mentioned earthquake was analyzed for 729 cases. Effect of input parameters on relative displacements occurring in the structure was then investigated and the interaction between the input and output parameters is presented in graphical form. Findings showed that all input parameters have significant effects on relative displacements occurring in the structure.

KEYWORDS: Soil structure interaction, finite element method, relative displacement, seismic behavior.

1. INTRODUCTION

Most civil engineering structures are designed for earthquake effects assuming that the structure base is fixed to the ground (control point). The ground motion at the control point, termed as control motion, is typically calculated empirically based on variables such as the seismic hazard at the site, the design life of the structure, and local site conditions, but not accounting for the presence of the structure. For a structure founded on rock, the ground motion is almost the same throughout the supporting medium, and its presence does not affect the characteristics (frequency content, amplitude and duration). Since the rock does not deform due to the forces imposed by the foundation above, the fixed base assumption is reasonable. For soft soil sites, the presence of a relatively rigid foundation changes the ground motion in the vicinity of the structure, forces from the structure deform the soil, fixed base assumption is invalid and therefore, the responses of the soil and the structure are coupled. This coupled response is termed soil structure interaction (SSI) and its effects are described below.

SSI effects can be best explained by comparing the response of a structure founded on the rock to the response of the same structure on soft soil, subjected to the same control ground motion. Consider the soil-structure system shown in Figure 1 with point A as the control point. Both structures are identical and only vertically propagating SH waves are considered for simplicity. (Wolf, 1985) Assuming that the two structures are equidistant from the earthquake source, the incident seismic waves in the rock below the structures are assumed to be identical. For the structure on founded rock, the motion of the foundation is the same as control ground motion, and its response is determined by subjecting its base to the control motion. Although inertial forces developed in the structure due to this base excitation generate base shear and overturning moment at the foundation that are transferred to the rock, no additional displacements occur at the foundation because the rock is very stiff: the fixed base assumption.

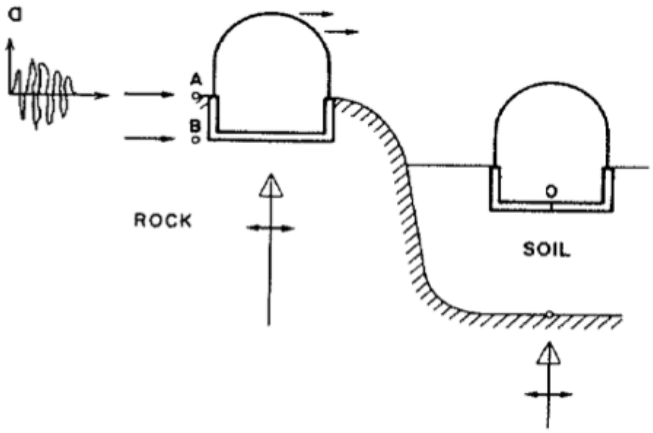

Figure 1. Seismic response of a structure founded on rock and soil (Wolf, 1985)

Seismic soil-structure interaction has been investigated since the 1950's. Early studies such as Merritt and Housner (1954) and Housner (1957) examined the effects of SSI, referred to as 'ground coupling' in Housner (1957), on conventional buildings using data recorded from instrumented sites. Numerous studies were later carried out to understand and quantify these effects due to their increasing importance, especially in the nuclear industry. (Kausel, 2010) Jennings and Bielak (1973) showed that the seismic response of a building-soil interaction system with n resonant frequencies can be found by the superposition of n+2 damped linear oscillators subjected to modified excitations, with the two additional oscillators corresponding to translation and rotation of the foundation. Veletsos and Meek (1974) used this result to obtain the properties of an equivalent single-degree-of-freedom (SDOF) oscillator which had the same time period and damping ratio as an SDOF system founded on linear elastic soil. By comprehensive numerical studies on the equivalent oscillator, their study was also extended into identifying various system parameters that could be used to assess the significance of soil-structure interaction effects.

The advent of numerical tools such as the finite element and boundary element methods in the 1970's enabled researchers to take up more complicated foundation configurations (such as embedded foundations and foundations on layered media) to calculate impedance functions. (Elsabee et al. 1977, Kausel and Roesset 1975). Gazetas (1991) summarizes the available frequency dependent impedance functions for different foundation shapes and configurations (including embedded foundations and arbitrarily shaped foundations), which were calculated over the years using various analytical and numerical techniques. After the 1985 earthquake, the significance of soil structure interaction effects on the seismic response and damage of structures in Mexico City was evaluated by Rodriguez and Montes (2000). Trifunac and Todorovska (1999) analyzed the nonlinear soil response effects. They tried to figure out the relation between the number of heavily damaged buildings and severity of shaking as well as crack density in water pipes as a variable for defining the strain level in the soil. Hayashi et al. (1999) performed several studies about 3 reinforced concrete structures with damaged shear walls in Hyogo-ken Nanbu earthquake that struck in 1995. They performed studies such as performing site inspections with micro-tremor measurements of structures, assessment of input motions and analysis incorporation with SSI. A simple soil-structure interaction model, which cares not only the soil-structure interaction but also the

interaction between footings, was suggested by Kocak and Mengi (2000). Initially, they offered a model for layered soil conditions; and then, based on the layered soil model, they created a finite element model for 3D SSI analysis. Estorff and Firuziaan (2000) introduced a general coupled boundary element/finite element formulation for investigating dynamic soil-structure interaction including nonlinearities.

2. SEISMIC SOIL-STRUCTURE INTERACTION

The effect of a dynamic soil–structure interaction depends on the stiffness and mass properties of the structure, the stiffness of the soil, and the damping characteristics of both soil and structure. The dynamic soil–structure interaction consists of two interactions, namely, kinematic interaction and inertial interaction. The kinematic interaction is the result of the stiffness of the structure, while the inertial interaction is the result of the mass of the structure. The kinematic interaction is explained with the help of Figure 2. In Figure 2a, the massless mat foundation restrains the vertical movement of the ground motion because of its flexural stiffness. As a result, the mat foundation moves differently than the free field ground motion (that is, the ground motion is away from the foundation). Also, the nature of ground motion in the close vicinity and below the foundation is changed from that of the free field ground motion because of this action. This interaction of the foundation with the ground motion is called the kinematic interaction. Similar examples of kinematic interaction are shown in Figure 2 (b and c). In Figure 2b, a vertically propagating shear wave is restrained by the embedded foundation. In Figure 2c, the axial stiffness of the slab prevents the incoherent ground motion produced below the foundation due to the vertically propagating shear wave. The kinematic interaction can also induce rotational movement in a foundation, as shown in Figure 2d for vertically propagating purely S waves.

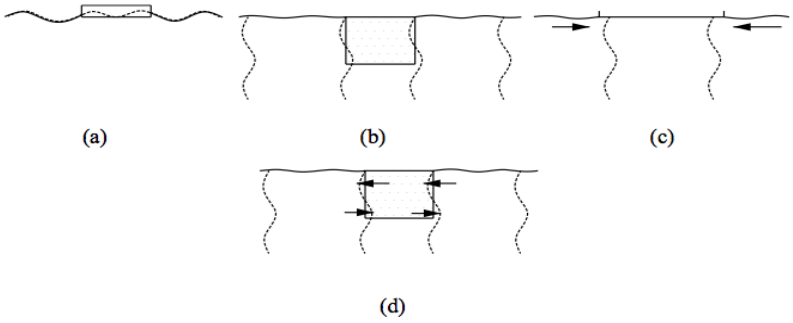

Figure 2. Kinematic interaction: vertical motion modified (a), horizontal motion modified(b), incoherent ground motion prevented (c) and rocking motion introduced (d).

3. NUMERICAL APPLICATION

3.1. Model Configuration

In this study, a two-dimensional finite element package program (commercially available as PLAXIS) for modeling of soil-structure interaction problems was used. Boundary conditions, prescribed loads, displacements and fixities were specified. The structural model could be simulated in stages, according to the sequence of construction proposed in the field. Displacements at nodes and stresses at elemental stress points anywhere within the model could be obtained.

The configuration of modeling used for multistory concrete building is shown in Figure 3. The model indicates geometry, boundary conditions and loading conditions applied to the model.

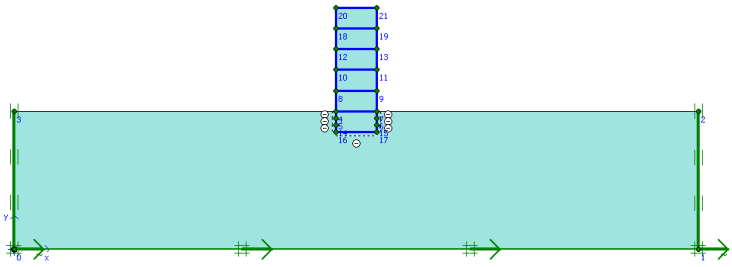

Figure 3. Screenshot of geometry model for a random case

3.2. Material Characteristics

The plate element was used to model concrete structure and its properties are given in the table below. Plates are structural elements used to model slender structures in the ground with a considerable flexural rigidity (or bending stiffness) and a normal stiffness. Plates can be used to model the influence of walls extending in z-direction. Modeling of facing units poses additional challenges. But, an indirect account of this behavior was provided for in the model by assigning axial stiffness to the elements used for modeling the vertical section of each facing unit. This prevented the modeled facing units from attracting any significant axial load.

Table 1. Plate properties

Parameter	Symbol	Value	Unit
Normal stiffness	EA	5.106	kN/m
Flexural rigidity	EI	9000	kNm^2/m
Poisson's ratio	ν	0.15	-
Rayleigh damping	α and β	0.01	-

3.3. Soil Characteristics

The program contains five different soil models including the Mohr-Coulomb and linear elastic model are available. In this study, Mohr-Coulomb soil model is preferred and its properties are given in Table 2.

Table 2. Constant soil properties

Parameter	Symbol	Value	Unit
Young's modulus (constant)	E_{ref}	30000	kN/m^2
Poisson's ratio	ν	0.33	-
Rayleigh damping	α and β	0.01	-
Dilatancy Angle	ψ	0	degree
Strength Reduction Factor in the Interface	$R_{inter.}$	1	-

Interface elements are used in order to model soil-structure interaction effect. Figure 4 shows how interface elements are linked to soil elements. The related interface elements are specified by five pairs of nodes when applying 15-node soil elements whereas three pairs of nodes for 6-node soil elements.

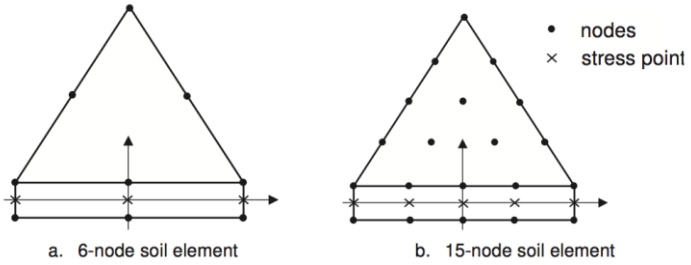

Figure 4. Distribution of nodes and stress points in interface elements and their connection to soil elements

To perform finite element analysis, a finite element mesh has been created and the boundary conditions and material properties are assigned. (Figure 5) This feature enables the automatic generation of a random mesh of triangular elements.

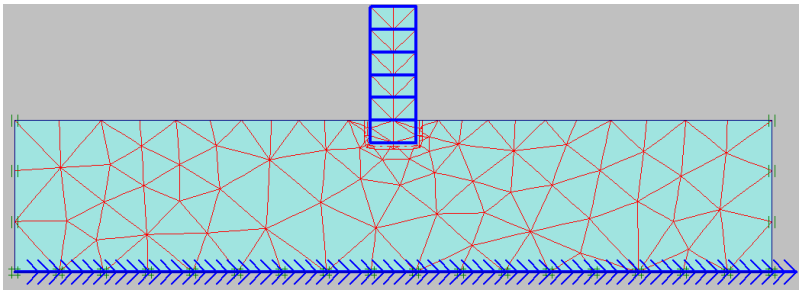

Figure 5. Generated mesh at initial condition for a random case

3.4. Earthquake Characteristics

A real accelerogram of 1989 - El Centro Earthquake recorded by the USGS in Imperial Valley is used for this study. It is contained in the standard Strong Motion CD-ROM (SMC) format, which can be recognized and interpreted by PLAXIS. (Figure 6)

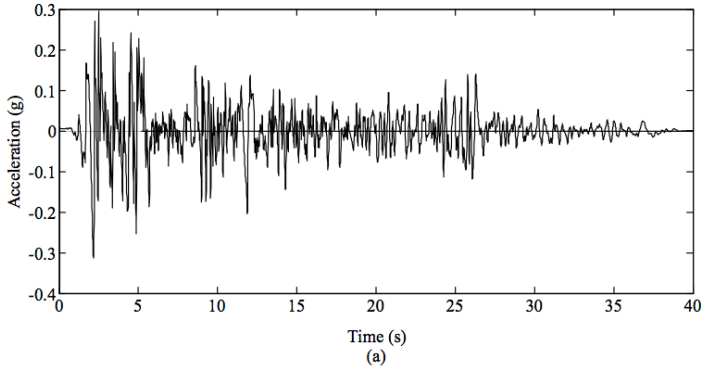

Figure 6. Real time accelerogram of Imperial Valley - El Centro Earthquake

3.5. Case Study Parameters

The input parameters selected for this parametric study can be divided into two groups, namely as soil parameters, concrete and geometry parameters. Soil parameters include cohesion, friction angle and unit soil weight and geometry parameters include foundation depth and height of building. Concrete weight is also included in the input parameters. Three values for each input parameters were selected in accordance with the ranges specified in the literature. These input values are presented in Table 3.

Table 3. Case study parameters

	Soil Parameters			Concrete and Geometry Parameters		
Parameter	Cohesion	Friction Angle	Unit Soil Weight	Concrete Weight	Foundation Depth	Height of Building
Unit	kPa	degree	kN/m^3	kN/m/m	m	m
Values	5	16	14	7.5	1	9
	15	24	18	10	2	12
	25	32	22	12.5	3	15

4. RESULTS

Maximum relative horizontal displacement refers to the difference between maximum horizontal displacements at the top and the bottom of the building. As can be seen from the interactions plot, all input parameters (for soil, geometry and material) have substantial effect on maximum relative displacement. The soil parameters (cohesion, friction angle and unit soil weight) have inversely proportional effect on relative displacements, which literally means that the increase in the soil parameters leads to smaller displacements. Concrete weight and height of building parameters have directly proportional effect whereas foundation depth has inversely proportional effect on relative displacements.

Another point that attracts the attention is the relation between height of building (h), foundation depth (d) and maximum relative displacement. (Figure 7 and 8) For the value of h=9 m, which corresponds to 3-story building, the increase in foundation depth from 2 meters to 3 meters does not effect the displacement values significantly. Likewise, while foundation depth (d) is 3 meters, increasing the height of building from 12 m to 15 m does not produce a considerable change in the displacements. In the light of aforementioned points, one can conclude that constructing a deeper foundation after a certain amount of depth (e.g. increasing the amount from 3 meters to 4 meters of depth) may not provide a considerable help to reduce displacement values. Yet, more intensive research needs to be done in order to strengthen this point of view. Therefore, a further study might be done by

- Increasing the dimension of the program using more inputs in the analysis. The other possible inputs of soil and structure might have a significant effect on the behavior as well.
- Expanding the geometry input by adding more than one type of soil and by using more realistic topographic surface profile.
- Using different earthquake inputs in order to investigate the effect of seismic characteristics such as magnitude, frequency, duration etc.
- Performing the analysis with the use of structures with different geometries.
- Using more than one structure with different material characteristics.

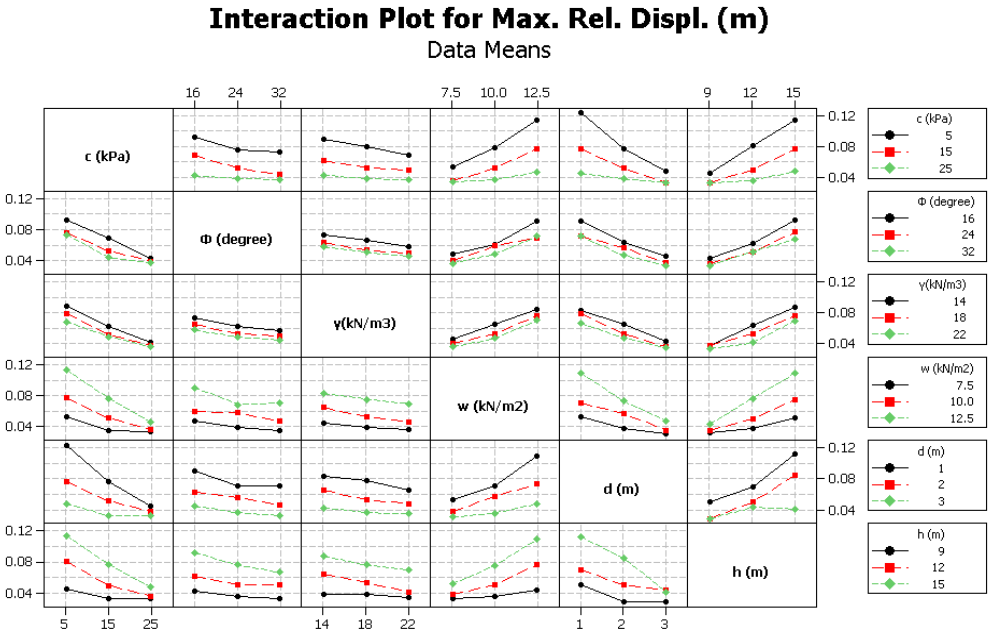

Figure 7. Interaction plot for maximum relative displacement

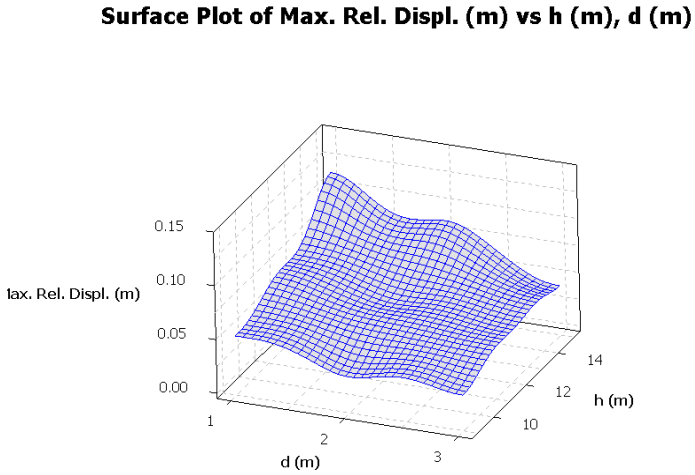

Figure 8. Surface plot of maximum relative displacement vs. height of building and foundation depth

5. CONCLUSION

The significance of soil effects on seismic behavior of structures was not well known by researchers until recently. Recent studies on interaction effects between soil and structure foundations indicated that soil does not behave like a fixed base rather it has a substantial effect on the behavior of structure. In this study, the importance of this effect has been investigated with the use of finite element method based software PLAXIS. The input parameters are generated in accordance with the literature on the purpose of getting suitable results. Several runs have been performed in order to test the accuracy of the program.

Some reference points on which we wanted to calculate the displacement have been marked on the geometry model of the frame structure. A sample earthquake recorded by the USGS is used for the analysis. Water pressure is neglected.

729 case studies have been performed so as to obtain displacement outputs. The results for failure cases in which factor of safety is less than 1 have been eliminated. The results are visualized and the interactions between parameters are illustrated graphically. For all input variables, a significant relation in maximum relative horizontal displacement was observed.

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