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Benefits of Soft Soils on the Seismic Response of Tall Buildings Using Three-Dimensional Numerical Soil-Structure Interaction Analysis

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Abstract: International seismic codes based on previous studies state that softer soils show higher ground response than harder ones regardless of the effect of soils on the structure's new properties. Previous studies on most were divided into studies carried out by structural engineers focusing on the structure mainly and modeling the soil as springs or performed by geotechnical engineers focusing on the soil only and modeling the structure as a generalized SDOF or simple frame. Most of the previous studies used the Mohr-Coulomb soil model which is not appropriate as it misses a lot of main characteristics like stress and strain dependency. In the Current study, different earthquakes with different frequency contents and amplitudes were applied on high-rise buildings ranging from 20 to 80 floors, supported over piles or raft foundations inside different soils being modeled by Hardening soil with a small strain model which is appropriate for seismic behavior. Piles abruptly changes the response of towers such that the response of the 20-floor tower on a raft was the same as forty floors tower on piles. Soft soil enhances the dynamic properties of structures which decreases the effect of soft soil and in some cases, it controls.

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Keywords: Dynamic soil-structure Interaction (SSI); soil-structure Interaction for seismic design; Soil effect on Tall-building; Soil Nonlinear time history Analysis; Foundation effect on soil-structure Interaction

1. Introduction

The construction of high-rise buildings is one of the indicators by which a country's success is measured. One of the most important loads that these structures must account for is seismic force. It is generally accepted that earthquakes do not kill people; earthquakes kill people when seismic loads hit structures. The rupture of the fault causes the earthquake. The fault creates multiple waves that propagate into the underlying rock below the structure and then rise through the floor to the structure. It is now common practice to apply seismic forces to the structure floors, moving down the structure until they reach the fixed support of the model. Usually, the soil effect is considered by multiplying the bedrock earthquake by the soil factor. The soil factor is typically derived from previous site response analysis studies and reported in the code.

Many studies were carried out on the topic of soil-structure interaction due to seismic load. Each of the previous studies covered the subject from a different perspective. Geotechnical discipline usually modeled the soil deeply with special software or with an experimental model, but they modeled the superstructure only as a generalized SDOF system, MDOF stick model, multi-bay and/or multi-levels 2-D frames, or very simple 3-D frames. On the other hand, structural discipline in general used to model the soil as a group of springs, dashpots, and sometimes masses. Foundations, especially deep foundations, which are used to support tall buildings were not usually modeled in previous studies, or they would adopt a few numbers of piles. The Mohr-Coulomb model was used in the vast majority of previous studies to model soil. Mohr-Coulomb loading and unloading path coincide at the same point i.e., does not include hysteretic loop., besides it lacks important features like shear, compression hardening, stress and strain dependency and dilatancy is not working on it until the shear surface is reached. Modeling of soil in many cases was, as a sequence of a few assumed random layers, if the sequence of these layers is changed, results might differ.

The selection of used seismic time history records was normally based on El Centro time history and other time histories with their actual magnitude. Previous studies in general, monitored results at a few points on the surface of the ground, normally using a group of response spectrum curves.

The main characteristic of previous studies can be summarized as follows and their associated studies as references are mentioned based on the item number in Error! Reference source not found. to

Table (3:

a) **For structure:**

1. Studies that treated the structure as a stick model with a generalized single degree of freedom, single stiffness, and single mass, based on the fundamental anticipated mode and disregarding higher modes.
2. Studies that took into account the two extremes of slender and short structures.
3. Studies that took into account the damping as a single modal damping ratio.
4. Studies that took the structure's elastic linear behavior into account, neglecting the structure's inelastic behavior.
5. Many studies cited do not incorporate realistic configurations of structures, particularly tall buildings with shear walls.

b) **For foundations:**

1. Studies that did not consider footings at all.
2. Studies that did not take the kinematic influence of the foundations into account.
3. Studies that did not take footings' filtering effect into account.
4. Studies that took into account single pile models.
5. Studies that took into account simple pile caps of three, four, or five piles.
6. Studies that considered the footing mass.
7. Studies that did not take damping of foundations into account.
8. Studies that did not take inelasticity of footing into account.
9. Study looked at the effects of structural embedment utilizing the soil's basement.

c) **For the soil:**

1. Studies that represent the soil as a single spring and dashpot.
2. Studies in which soil layers were assumed randomly.
3. Studies disregard the mass of soil.
4. Studies that did not take radiation damping.
5. Studies that did not simulate soil nonlinearity in general.
6. Studies that deal with nonlinearity using an equivalent linear method.
7. Study that proves that depending on the kind of soil and the intensity of the seismic excitation, soil nonlinearity behavior will not occur along the depth of the soil; instead, it will be concentrated at a certain depth.
8. In experimental testing, the surrounding layered container used to fill the soil during the test, which symbolizes the soil border condition, may impact the soil's overall behavior.
9. The article asserts that because the size of the soil grains, especially the clay, cannot be scaled down, the soil used in a very small-scale prototype, such as in a centrifugal test, is seen as rocks and boulders by piles and foundations.
10. Older soil models, such as Mohr-Coulomb, and linear and nonlinear Hypoplastic models were used in previous numerical models. The new hardening soil with a small strain model is the one that is advised to be utilized with seismic Analysis.
11. [1], [2]and [3] included the notion of modeling soil as a single macro-element for deep foundations.

d) **For excitation:**

1. Several investigations used a single or more random seismic excitations—typically the El Centro earthquake.
2. Studies include a certain intensity.

e) **Analysis and findings**

1. Studies in which the seismic force was applied to the structure rather than the bedrock as it should have been.
2. Studies in which only one location on the structure was used to capture the response.

Simple models were typically used. However, full numerical models were challenging to be handled. Some approaches took into account the substructure approach; other models consider successive coupling scheme as in [4] and [5], and other models model the adjacent soil close to the structure only using the finite element method, the far soil was modeled using the boundary element method, as in [6].

Table (1): References for each clause from a-1 to b-9

Reference no	Clause no												
	a-1	a-2	a-3	a-4	b-1	b-2	b-3	b-4	b-5	b-6	b-7	b-8	b-9
Kramer, S.L. [7]	✓		✓	✓	✓		✓				✓	✓	
Kaynia, A.; Kausel, E [8]	✓		✓	✓			✓	✓	✓		✓	✓	
Maheshwari, B.K., et al. [4]	✓		✓	✓			✓	✓	✓		✓	✓	
Ghannad, M.A.; Jahankhah, H. [9]	✓	✓	✓			✓	✓			✓	✓	✓	
Nakhaei, M.; Ali Ghannad. [10]	✓		✓			✓				✓	✓	✓	
Cai, Y.X.; Gould, P.L , et al. [5]	✓		✓	✓	✓	✓	✓				✓	✓	
John P. wolf [11]				✓		✓	✓					✓	
Rosenblueth, N.M.N, et al. [12]				✓		✓	✓					✓	
PÉREZ-HERREROS, J. [1]						✓	✓					✓	
Wilson, E.L. [13]								✓			✓	✓	
Chiou, J.S.; Hung, W.Y , et al. [14]		✓							✓		✓	✓	
Baker, J.W. [15]													✓
Syed, N.M.; Maheshwari, B.K. [6]		✓						✓	✓				

Table (2): References for each clause from c-1 to c-10

Reference no	Clause no								
	c-1	c-2	c-3	c-4	c-5	c-6	c-7	c-8	c-10
Kramer, S.L. [7]	✓		✓	✓	✓				
Kaynia, A.; Kausel, E [8]	✓		✓	✓	✓				
Maheshwari, B.K., et al. [4]	✓	✓	✓	✓	✓				
Ghannad, M.A.; Jahankhah, H. [9]	✓		✓	✓	✓				
Nakhaei, M.; Ali Ghannad. [10]	✓		✓	✓		✓			
Cai, Y.X.; Gould, P.L , et al. [5]	✓		✓	✓	✓				
John P. wolf [11]	✓			✓	✓				
Rosenblueth, N.M.N, et al. [12]	✓			✓	✓				
PÉREZ-HERREROS, J. [1]	✓			✓	✓				
Wilson, E.L. [13]				✓	✓				
Chiou, J.S.; Hung, W.Y , et al. [14]		✓			✓				
Pérez-Herreros, J.; Cuira , et al. [2]									✓
Perez-Herreros, J. [3]									✓
Syed, N.M.; Maheshwari, B.K. [6]		✓					✓	✓	

Table (3): References for each clause from d-1 to e-3

Reference no	Clause no				
	d-1	d-2	e-1	e-2	e-3
Kramer, S.L. [7]			✓	✓	✓
Kaynia, A.; Kausel, E [8]			✓	✓	✓
Maheshwari, B.K., et al. [4]			✓	✓	✓
Ghannad, M.A.; Jahankhah, H. [9]	✓	✓	✓	✓	✓
Nakhaei, M.; Ali Ghannad. [10]	✓	✓	✓	✓	✓
Cai, Y.X.; Gould, P.L , et al. [5]			✓	✓	✓
Wilson, E.L. [13]				✓	✓
Syed, N.M.; Maheshwari, B.K. [6]	✓				

The objective of this study is to investigate an entire 3-D strip, which was selected carefully to represent the system from the deep rock to the surface of the soil and to include an actual tall building ranging from twenty to eighty floor-structures, thus combining both structural and geotechnical approaches. Modeling these tall structures on full 3-D models was not, to some extent, possible during this study. Actual deep foundations were modeled with reasonable pile distributions and lengths. The soil was modeled using an "advanced hardening soil with small strain" soil model proposed by T. Schanz, P.A. and Vermeer, P.G.and Bonnier that overcomes the aforementioned deficiencies of the Mohr-Coulomb model, which makes it more convenient for seismic analysis. The selection of the sequence of soil layers was avoided by using two extreme types of soil, soft and stiff, each in a different model. Any sequence of layers can be equated to a single big layer of soil. The selection of used seismic records was based on using different earthquakes with different frequency contents, that have had major effects on earthquake engineering study, and these earthquakes were scaled up and down to provide two extremely weak and strong seismic events. Results were monitored on a grid of points along and across the entire model in the forms of time history and response spectrum curves.

The study proves that avoiding the previous studies' flaws gives additional and/or different conclusions than previous results. Using different time histories with different frequency contents on selected models proves, that weak soil does not necessarily amplify earthquakes more than strong soil as stated on current codes. Measuring time history records on different levels of soil and super-structure proves that the concluding behavior of different soil type behavior based on the ground or free field response spectrum is not necessarily correct. The effect of modeling piles is obvious compared to other models that use raft foundations for twenty floor-towers.

2 Used Models and Selected Earthquake Records.

A range of tower heights was used in this study, including twenty, forty, sixty, and eighty-floor structures. Twenty-story towers with raft and pile caps over piles foundations were built to explore the behavior of two types of foundations. It is not suggested, and it is rarely done, to use a raft for higher constructions. Different heights of towers were modeled in two extreme types of soil, soft and hard soil. The hard soil can be either very dense sand or very stiff clay; nevertheless, because of its increased strength and stiffness, very dense sand was chosen. Clay, on the other hand, indicated the soft soil. Due to its immense weight, the eighty-story skyscraper was only modeled on the stiff ground.

2.1 Models' description

Nine structures in three dimensions PLAXIS simulations were carried out in the same way that is given in

Table (4

Table (4): Models that were employed in the research.

Number of Floors	20 floors	40 floors	60 floors	80 floors
Type of soil	Hard/ Weak	Hard/ Weak	Hard/ Weak	Hard
Type of Foundation	Raft/ Pilecap	Pile cap	Pile cap	Pile cap

To depict the tower in modeling, a five-meter-wide slice was taken from it. As indicated in Figure (1, the tower is 21 meters long. Figure (2 shows that the slice has two shear walls at its ends and another massive internal shear wall representing half of the core. The length of the edge walls is 2.5 meters, the core is five meters. The core wall and the other edge walls are separated by 5.5 meters. Error! Not a valid bookmark self-reference.. shows the thickness of various structural parts in various models.

Table (5): Structural elements thickness for different models.

	Edge wall thick.	Internal wall thick.	Slab thick.
20 floors	300 mm	700 mm	250 mm
40 floors	600 mm	1400 mm	250 mm
60 floors	900 mm	2100 mm	250 mm
80 floors	1200 mm	2800 mm	250 mm

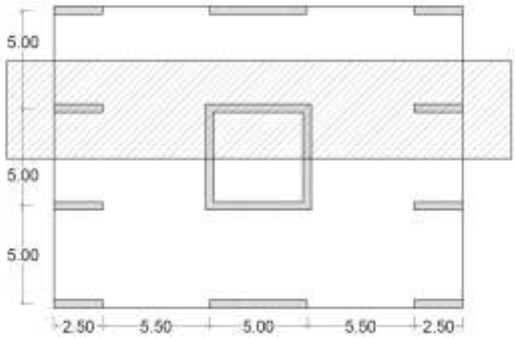

Figure (1): Plan of the used tower.

The soil block has the same model width as the structure and extends 110 meters to the right and left, giving it 241 meters. The soil block in the model was 60 meters deep. The huge dimensions of the soil were chosen to meet the dynamic nonlinear soil analysis criteria. The piles were modeled as squared sections with a 1-meter dimension to make the meshing process easier. The distance between piles was chosen to be 2.5 meters. The lengths of the piles were chosen to be 20 meters for 20 and 40 floors buildings and 30 meters for 60 and 80 floors buildings.

Figure (2): selected strip.

Because piles cannot be modeled as plane strain, 3-D models were used. Due to the largely required capabilities to run nonlinear time history for a comprehensive soil-structure interaction, solving a complete model was not attainable at the time of the investigation. As a result, a slice was chosen to depict the structure better. The five-meter slice was chosen for two reasons: first, the distance between walls was five meters, and second, the distance between piles was 2.5 meters. Figure (3 depicts an eighty-story skyscraper model.

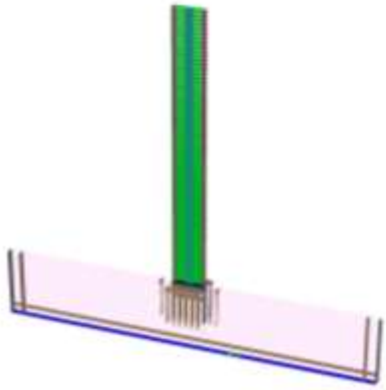

Figure (3): 80 floors piled foundation with soft soil PLAXIS model.

2.2 Soil Constitutive model

The soil model was one of the most important factors that is affecting the dynamic study. Mohr-Coulomb model Figure (4 is the basic soil model that considers the soil as linear elastic until it hits the shear yield surface, on which it remains perfectly plastic with no strain hardening and it does not consider compression hardening. In terms of cyclic loading, Mohr-Coulomb does not have a hysteretic loop if the load is removed and then re-applied since it has only one value of modulus of elasticity for both loading and unloading. Dilatancy in Mohr-Coulomb is only considered once the stress path hits the yield surface. CAM-clay Figure (5, created by the Cambridge team combines both shear yielding and compression yielding on one surface. The model allows hardening for the surface, which represent both shear and compression hardening. The model is based on critical state theory, with a failure surface that intersects the hardening surfaces. Cam-clay model has an error at the pre-consolidation point at the hydrostatic pressure line, since the strain vector has a deviatoric component. Modified CAM-clay Figure (6 avoids the conventional CAM-clay model by converting the surface into an ellipse. Figure (7 shows the hardening of the modified CAM-clay model. Soft Soil Figure (8 and Soft Soil with Creep Figure (9 models consider compression hardening only with a shear yield surface having perfectly plastic with no hardening. The most advanced model is the Hardening Soil with a Small strain model Figure (10 is used in this study, in which both shear and compression hardening are included. The modulus of elasticity for soil is assigned with different values for different loading types, loading, unloading shear, or compression loading. The stiffness in this model is automatically incorporated as stress-dependent without assigning it manually. The model has dilatancy included before hardening. The triaxial test shows different stress-strain relationships in both Mohr-Coulomb and Hardening soil models as in Figure (11. Moreover, the hysteretic damping is captured due to the difference between the initial soil modulus and unloading/reloading soil modulus as in Figure (12.

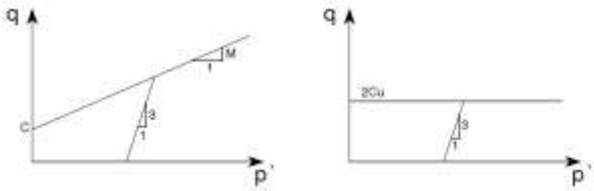

Figure (4): Mohr-Coulomb surface. [16]

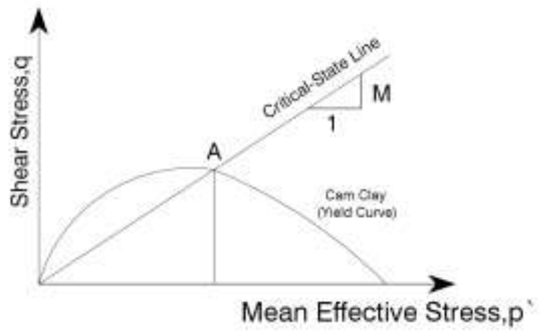

Figure (5): Relation between yield curve and critical state line.[17]

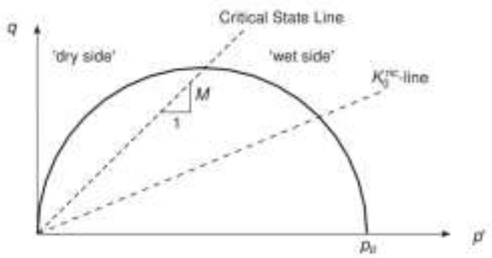

Figure (6): Modified Cam-clay model.[18]

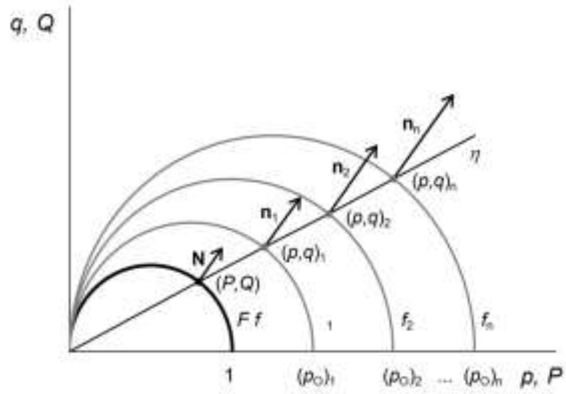

Figure (7): Modified Cam-clay Hardening.[19]

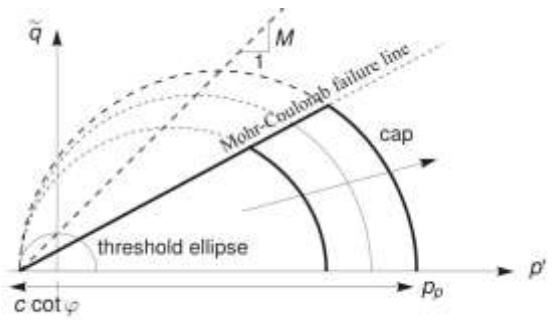

Figure (8): Soft soil model in p'-q plane. [18]

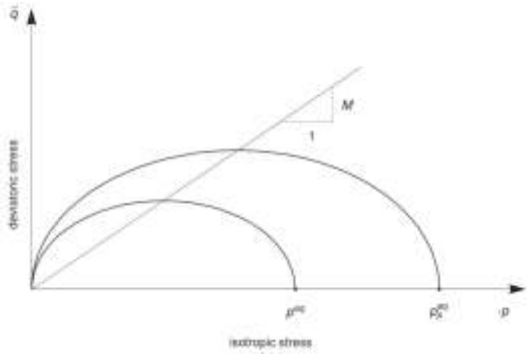

Figure (9): Soft soil with creep model. [18]

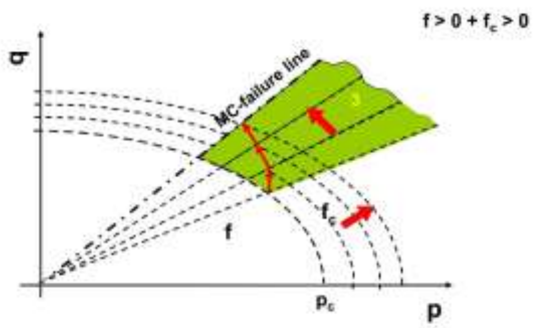

Figure (10): Shear and compression hardening. [17]

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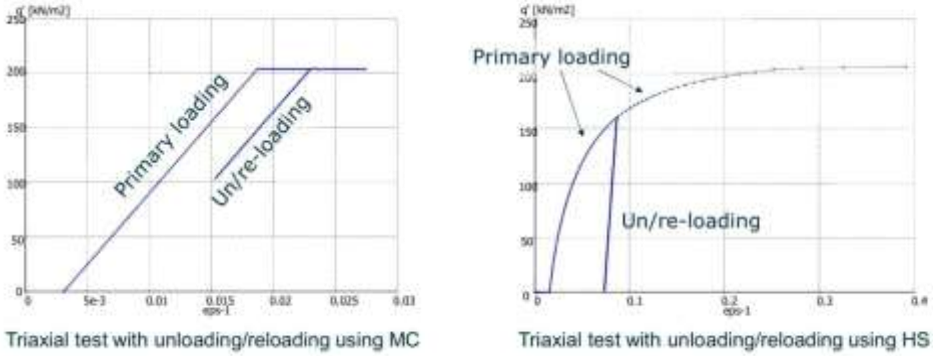


Figure (11): Triaxial test curve using both Mohr-Coulomb and Hardening soil model. [17]

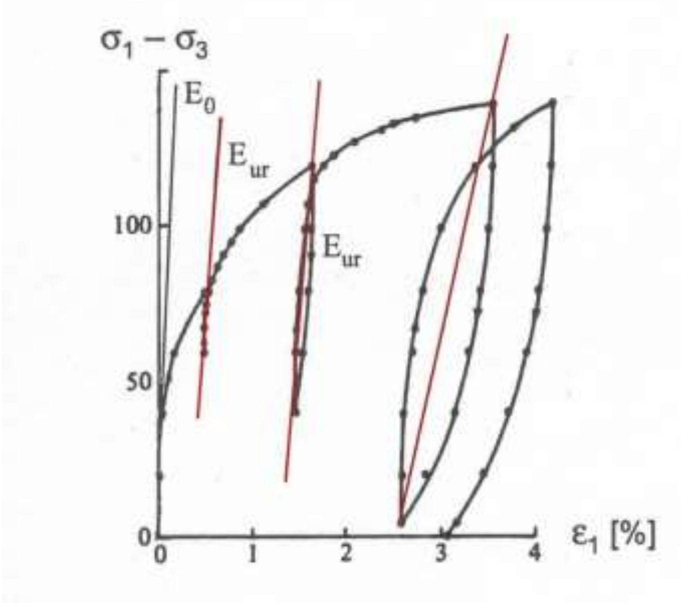


Figure (12): E_0 *and* E_{ur} values [20]

The parameters of two different soils for the Hardening soil with Small Strain model are given in Table (6.

Table (6): Soil definitions on used models.

Soil Type	Hard Soil	Weak Soil
Soil Name	VDenseSand	Clay
Soil Model	HS small	HS small
Gamma Unsaturated KN/m3	20	14
Gamma Unsaturated KN/m3	20	16
Rayleigh Alpha	0.09934	0.02457
Rayleigh Beta	0.8392E-3	0.2075E-3
E50 ref KN/m2	90,000	3000
E oed ref KN/m2	65,000	3000
E ur ref KN/m2	250,000	9000
C' KN/m2	1	1
Phi'	45	35
Psi	15	5
Gamma 0.7	0.10E-3	0.15E-3
G0 ref KN/m2	300,000	9000
Neu' ur	0.2	0.2
R interface	0.7	0.7
Initial method	K0	K0

2.3 Selection of an applied set of earthquake records.

Three earthquake records were selected to carry out this study; Imperial Valley earthquake in California, in 1940 (El Centro), Loma Prieta earthquake in 1989 and Northridge earthquake in California in 1994. Three-time histories are shown on **Figure** (13. All the selected time histories were first scaled to 0.15 g to unify all of them to match the amplitude of Zone 2 A as in UBC code. Each record was further scaled down to 0.05g to represent a weak earthquake and up to 0.3 g to represent a strong earthquake.

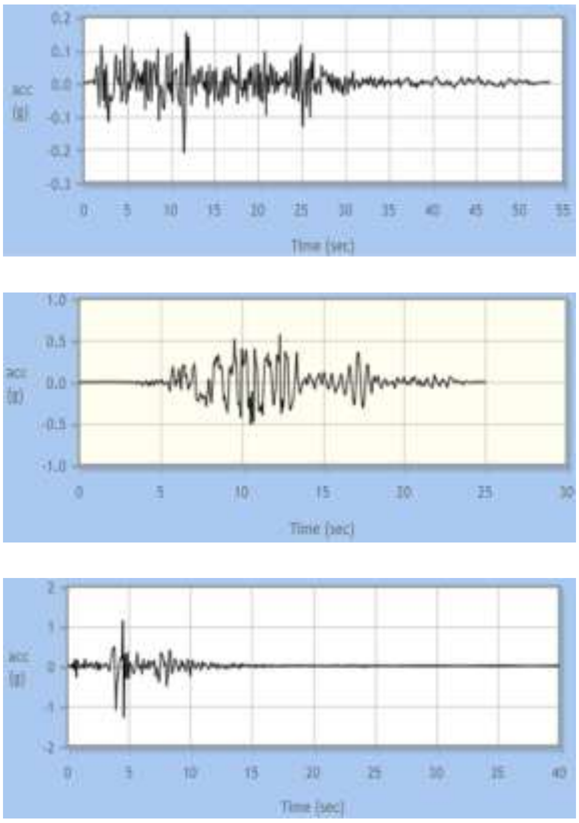


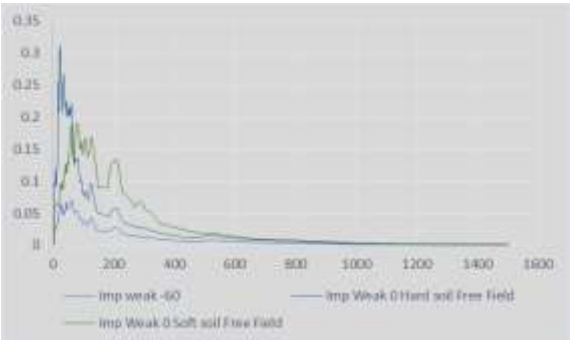
Figure (13): The Imperial Valley earthquake, the Loma Prieta earthquake, and the Northridge earthquake

3 Results

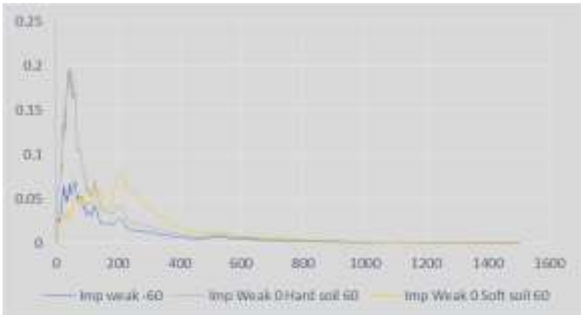
Response spectrum curves were constructed for different soil types, different earthquake types, magnitudes, and different tower heights.

Figure (14 gives response spectrum curves for selected weak Imperial Valley El Centro earthquake as a sample. It shows Input and output response spectra for El Centro earthquake with PGA of 0.05g for free field response, for 60, 40, 20-floors building on both piles and on raft foundation for both hard and soft soil compared with input response spectrum at -60 meter down the soil.

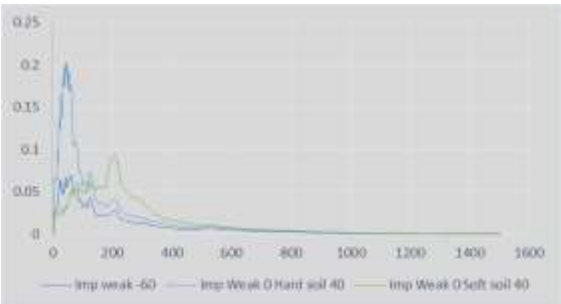
Time history curves were extracted from the software at different heights from the earthquake application point at the bedrock up to the tip of the structure for the 80, 60, 40 and 20-floors building for both soft and hard soil for three different earthquakes. Each earthquake was applied twice at the bedrock level each, with a small and large amplitude. The weak earthquake was selected to have an amplitude of 0.05g and the strong one has an amplitude of 0.30g. The maximum value of each time history at each level was selected to construct figures from Figure (15 to Figure (20. The target of that is to investigate how the peak value of the time response is being changed along the depth of the soil and the hieght of structure, and to study the effect of soft soil on different structures due to different earthquakes types and magnitudes.



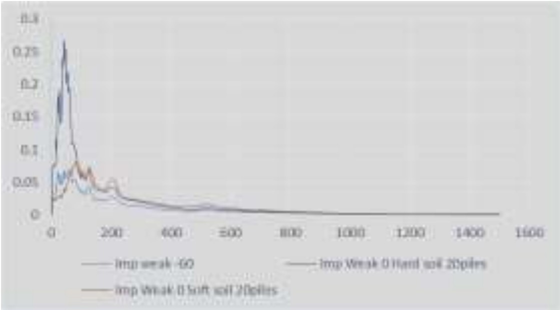
A



B



C



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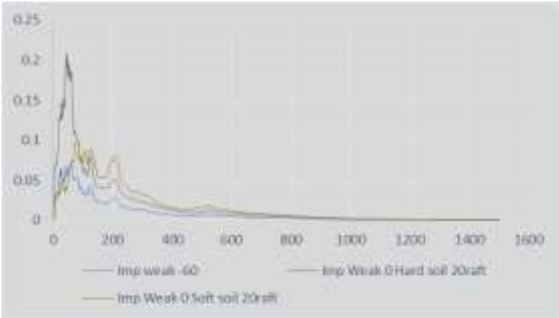


E

Figure (14): Input and output response spectra for El Centro earthquake with PGA of 0.05g. A) Free field response. B) 60-floors. C) 40-floors. D) 20-floors on piles and E) 20 floors on raft foundation for both hard and soft soil compared with input response spectrum at -60 meter down the soil.

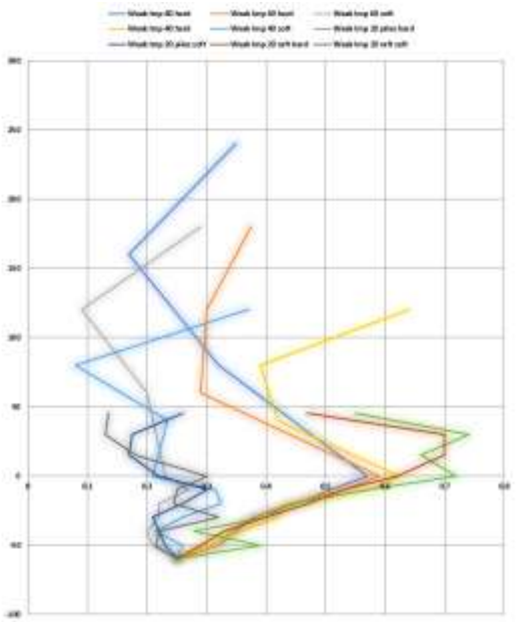


Figure (15): The maximum responses at different levels due to the weak El Centro EQ.

Note Horizontal axis is acceleration in m/sec^2 and vertical axis is level in meter.

In the figure, the legend of "Weak Imp 20 piles hard" for instance is as following:

weak Imp stands for: Imperial Valley – El Centro-earthquake with weak amplitude of 0.05g-PGA acceleration,

20 stands for: the number of floors of the tower,

Piles stands for: foundations type is piles and,

Hard stand for: strength of soil is hard.

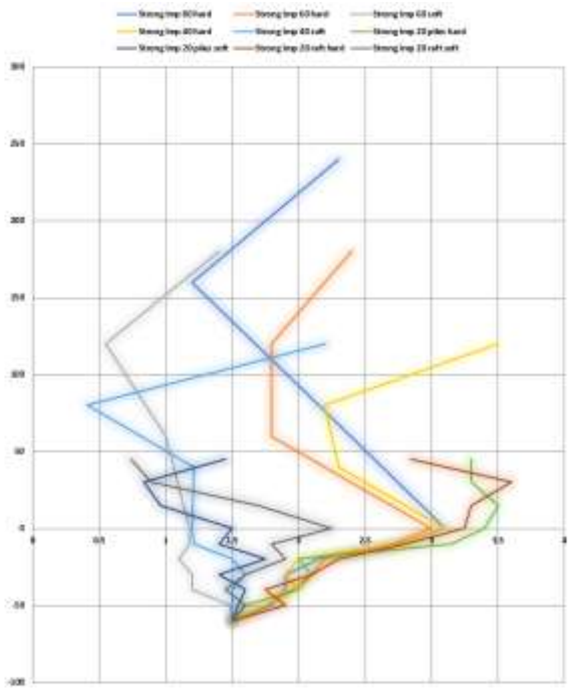


Figure (16): The maximum responses at different levels due to the strong El Centro EQ.

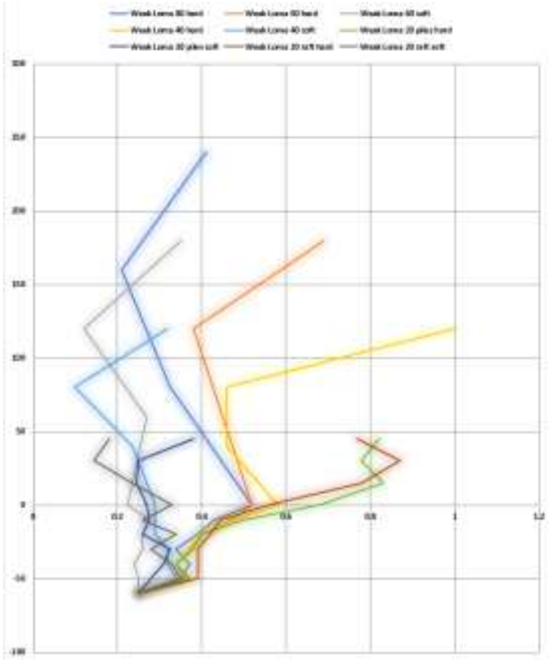


Figure (17): The maximum responses at different levels due to weak Loma Prieta EQ.

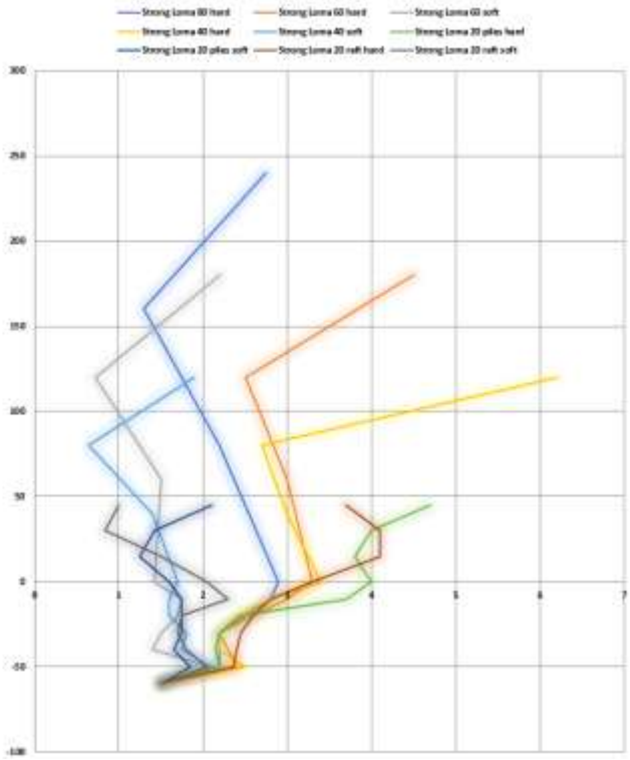


Figure (18): The maximum responses at different levels due to the strong Loma Prieta EQ.

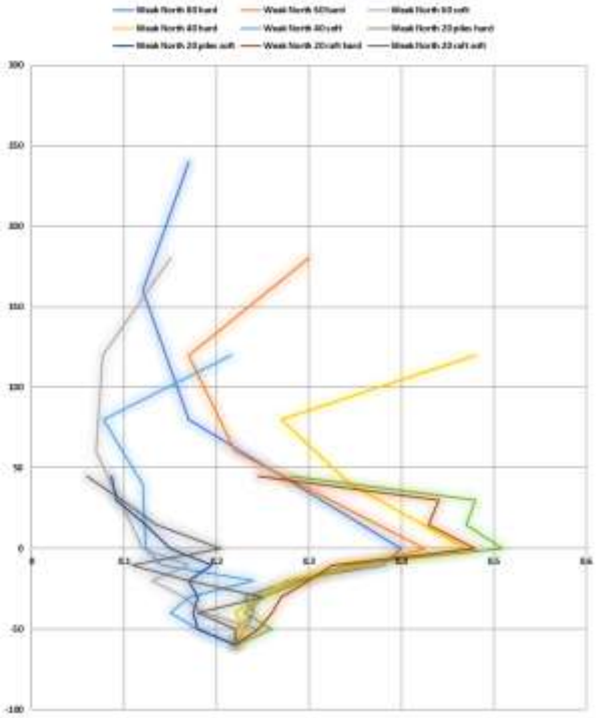


Figure (19): The maximum responses at different levels due to weak Northridge EQ.

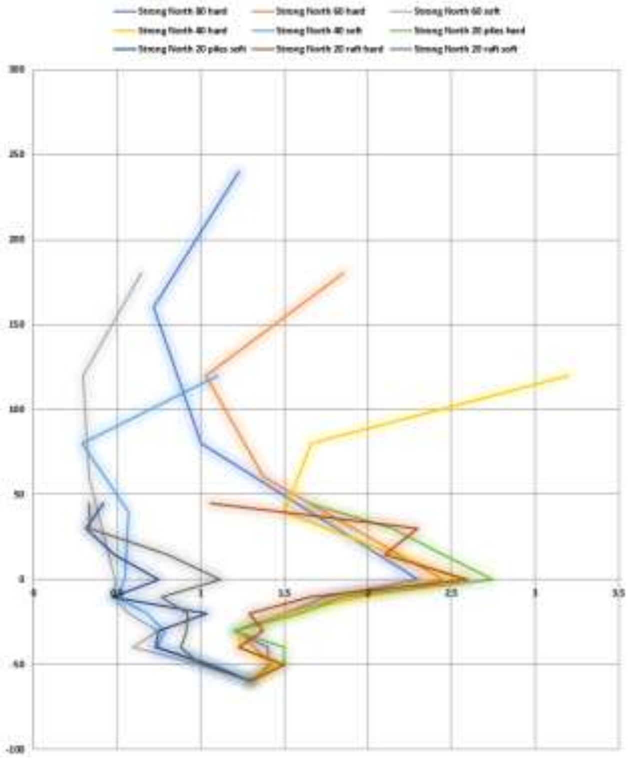


Figure (20): The maximum responses at different levels due to the strong Northridge EQ.

4- Discussion

4.1 Response Spectra curves and Peak Response History Values.

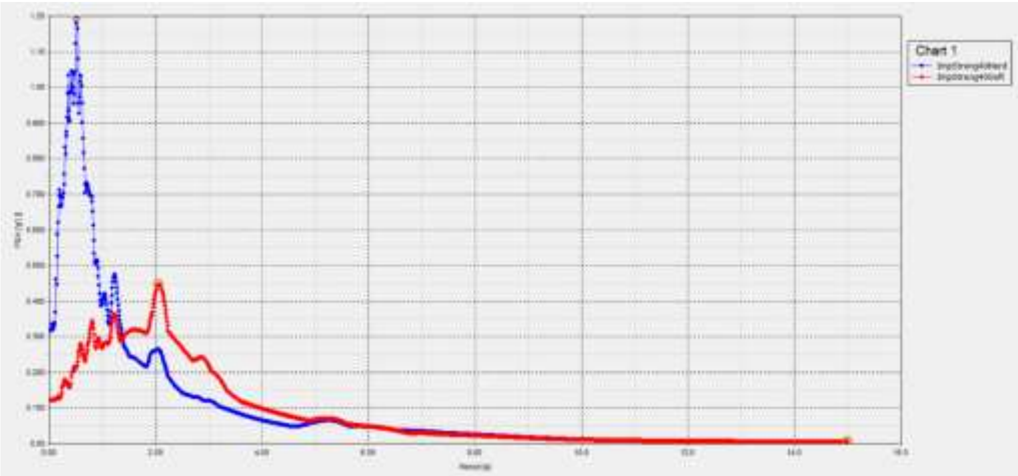
The response spectrum curves of the weak Imperial-Valley

Figure (14 reveal that the soft soil responds bigger than the hard soil does for a free field, twenty, forty, and sixty-floor structures, which meets with seismic codes like UBC97. However, as shown in Figure (15 to Figure (20

, the peak values of the acceleration time history along different levels of soil and structure demonstrate that hard soil creates a larger response on the superstructure, which appears to contradict the response spectra results for such structure periods.

To verify the previous result and to find its causes, a simple response spectrum curve for both hard and soft soil was re-plotted for a certain forty-stories tower due to Imperial Valley with a large amplitude as shown in Figure (21-a, which shows that softer soil gives higher response for this type of towers with a fixed based model which is 3.86 seconds. The time history of the acceleration of the same case was plotted at the upper floor of the tower which shows the opposite, that the harder soil gives a bigger response as in Figure (21-b, which means that the concluded result is valid, and the contradiction has a certain reason behind it. The reason will be investigated in the following paragraphs. Free vibration of the entire system was performed to find out the period of each system, and enter with the new system period on the constructed response spectrum.

a)



b)

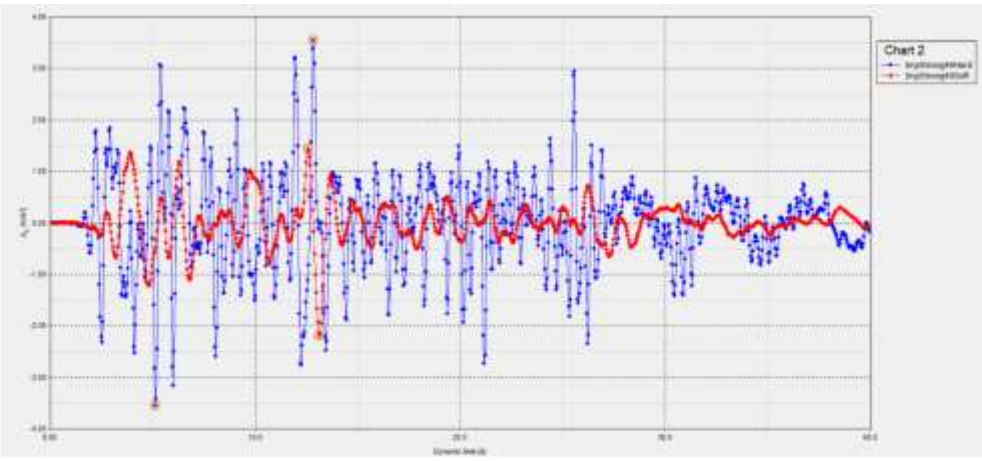


Figure (21 a) Response spectrum at the ground surface. b) Response history at the top of towers with different soil types.

4.2 Entire System Free Vibration.

The results were investigated, and a free vibration of entire systems of both soft and hard soil systems, including the tower, was researched to check if the full system period has been changed from the expected fixed-based model value and if it will affect the final results. Figure 22 shows the free vibration of the soft and the hard soil for a 40-floor tower. The period of the soft soil entire model– including structure and soil- was 9 seconds, but the hard soil tower period was only 4 seconds!

4.3 Application of Entire System characteristics in Response spectrum Curve.

Entering the previous response spectrum with 4 seconds for the hard soil-structure model intersecting the hard soil RS and 9 seconds for the soft soil-structure model intersecting the soft soil RS shows that the final response of the hard soil is much larger than the soft soil, as shown in Figure 22, ensuring that the result is valid. Figure 23, Figure 24, and Figure 25 show the periods of other models which also prove the same point that soft soil increases the total system period in a way that it can decrease the seismic effect even if soft soil by nature has a bigger response.

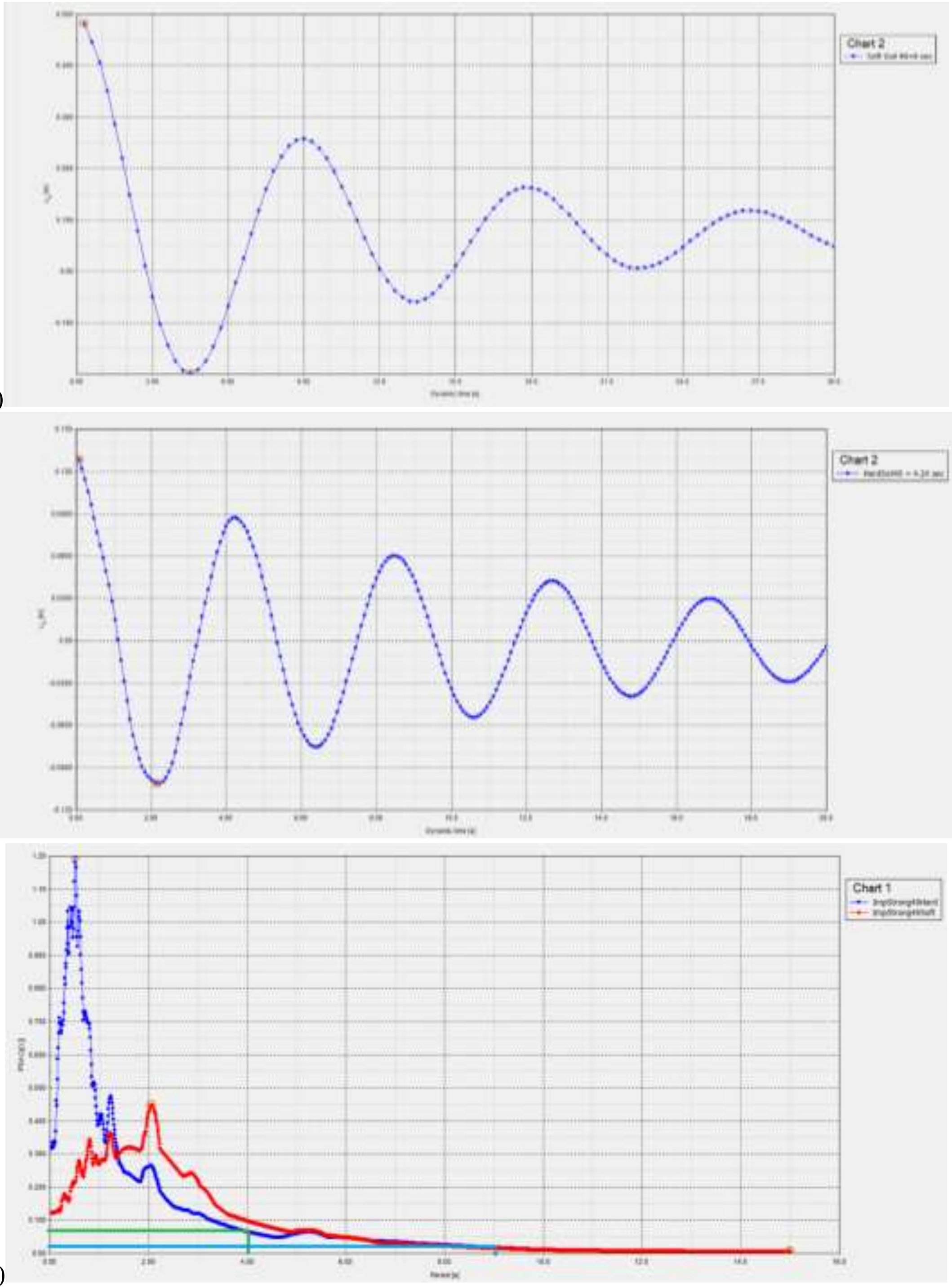
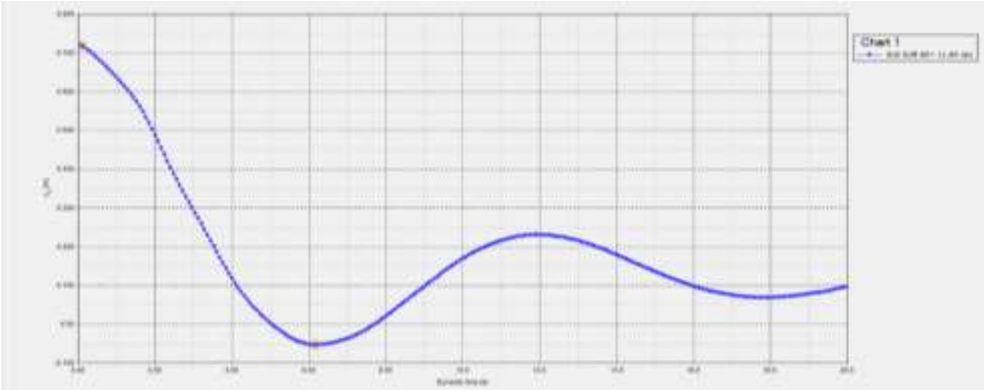
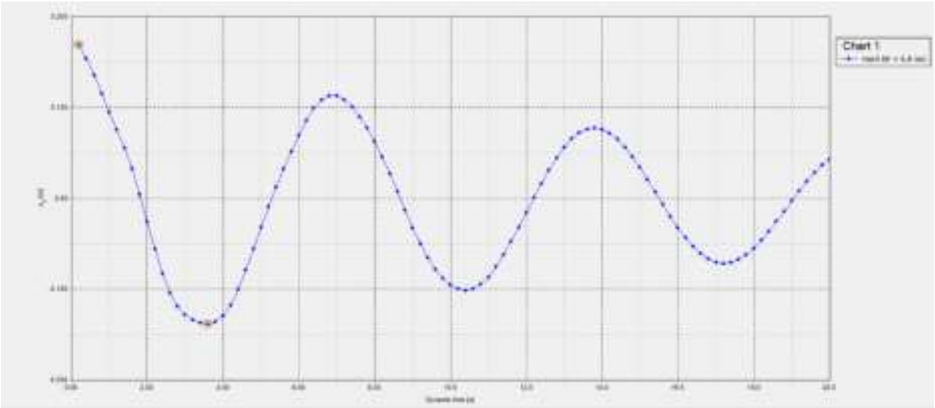
a)
b)
c)


Figure 22 a) and b) Free vibration of forty floors towers with different soft and hard soil c) Response spectrum for different soils with different periods.





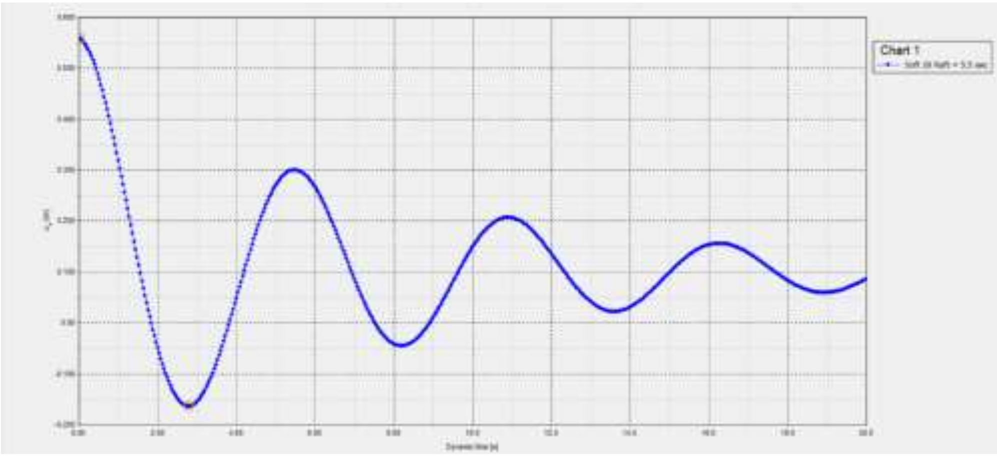
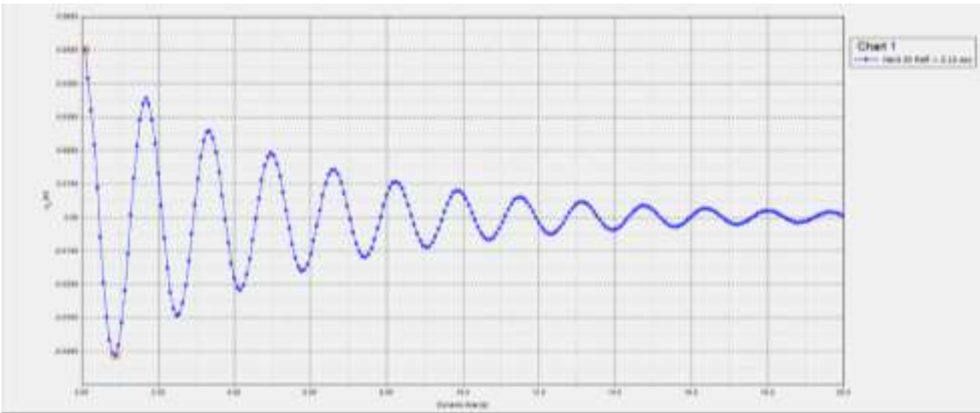


Figure 23 Free Vibration of 60 floors on soft and hard soil and 20 floors on a raft with soft soil.



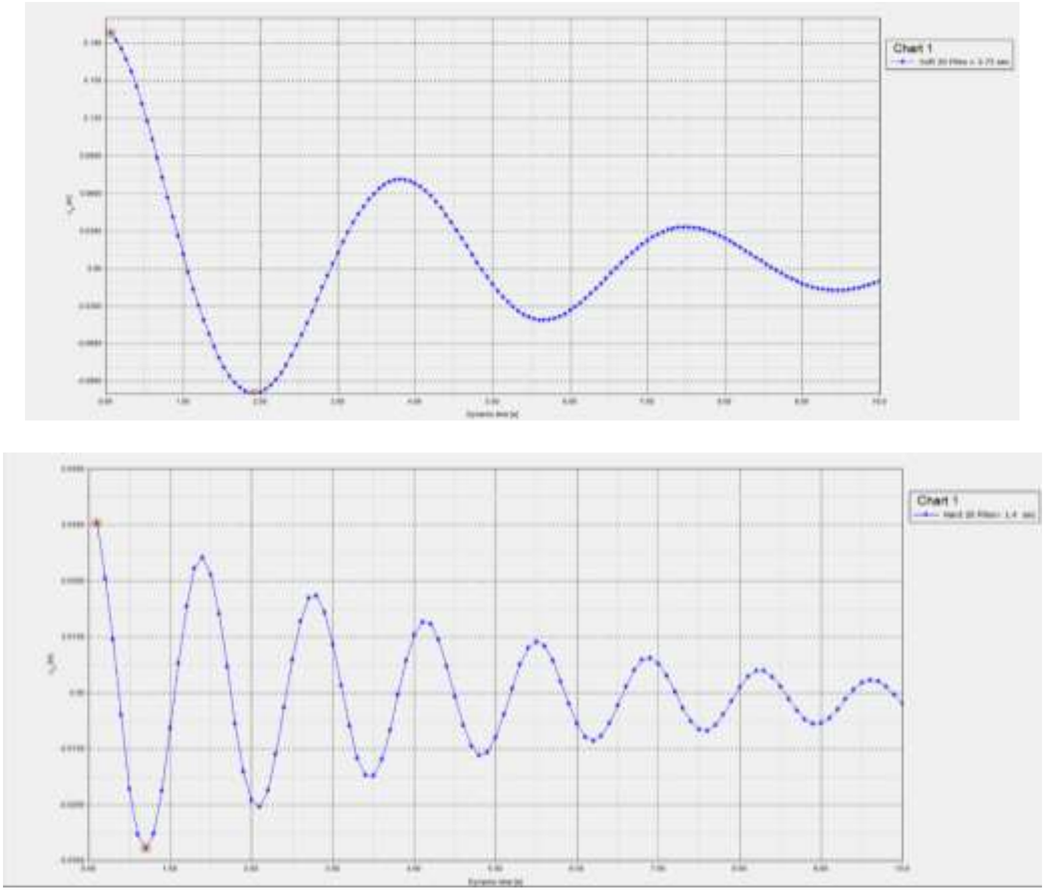


Figure 24 Free Vibration of 20 floors on a raft with hard soil and piles for soft and hard soils.

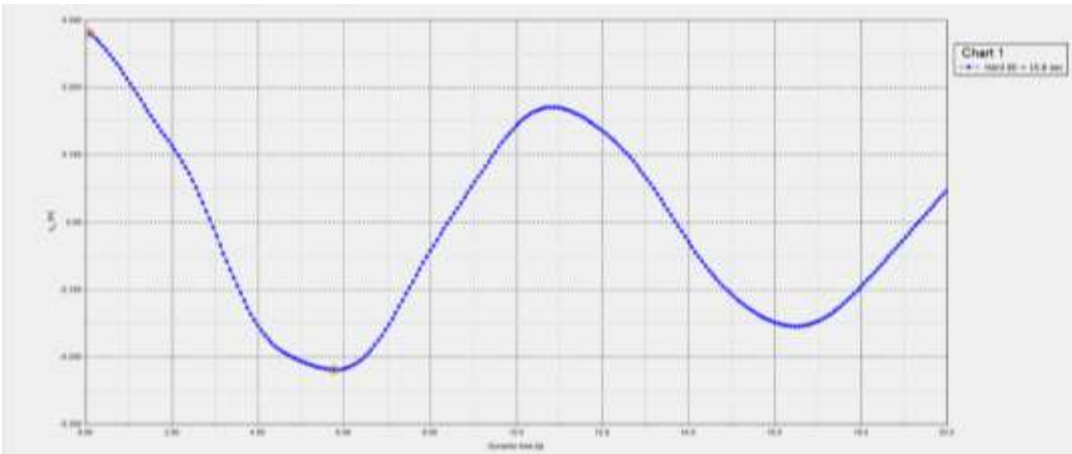


Figure 25 Free Vibration of 80 floors of hard soil.

Based on seismic standards, the standard procedure is to use various RS for different soils, but regrettably, the same period is used for forty-story buildings, ignoring the soil effect.

5. Conclusions

The Finite Element Method was used to simulate three-dimensional models of various tall structures over raft or raft on piles placed on hard and soft soil that was subjected to weak and strong three separate time history recordings to investigate the effects of each parameter on the response spectra curves at the ground surface and the time-history responses at the structure's roof The following were the outcomes:

3. Most response spectra curves show consistency with the current codes and literature, in which softer soils show larger responses than harder soils.
4. Response history of the superstructures constructed over softer soil shows lower responses for softer than harder soils.
5. The entire structure and soft soil system possessed longer periods, which is generally ignored in fixed-based models.

6. The period-lengthening effect on decreasing the structure response exceeds the soft soil effect of increasing the entire response spectrum curve.
7. Soft soil could enhance the entire response of towers constructed on it.
8. Solving based on earthquake response spectra on the ground surface using the fixed base models' periods and ignoring the soil effect in period lengthening gives misleading response results.

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