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EFFECTS OF SOIL-STRUCTURE INTERACTION AND BASE ISOLATION ON SEISMIC PERFORMANCE OF FOUNDATION SOILS

Serdar SOYOZ[1], K. Onder CETIN[2,*], Haluk SUCUOGLU[3]

ABSTRACT

This study primarily focuses on structural induced liquefaction potential. Moreover, the effect of base isolation systems on both structural performance and liquefaction potential was studied including the soil-structure interaction effects. Four different types of structures and three different types of local sites were analyzed under two different input ground motions. It was mainly found that, depending on the structural type and for a certain depth, the liquefaction potential could be higher under the structure than the one in the free field. Besides decreasing the story drifts and shear forces in the structure, base isolation systems were very effective for decreasing liquefaction potential in the soil. It was also observed that soil-structure interaction leads to very significant changes in the response spectra.

Keywords: Structure Induced Liquefaction, Cyclic Stress Ratio, Soil-Structure Interaction, Base Isolation Systems.

INTRODUCTION

The current state of the practice in assessing the potential for liquefaction beneath a structure is to treat the soil as if it were in the free-field and ignore any effects of the building. This practice has developed since it is believed to be a conservative approach and easy to perform. However it was observed, after recent earthquakes (e.g. Kobe, 1995 and Kocaeli, 1999), that there could be no signs of liquefaction in the free-field but once one gets closer to foundation, structure-induced liquefaction could be observed.

According to Rollins and Seed, 1990, liquefaction occurs below the building before it occurs in the free field for (S_a/a_{max}) ratios greater than about 2.4 which basically means the buildings with a period between 0.1 and 0.5 sec.

[1] PhD Candidate. Department of Civil and Environmental Engineering, University of California, Irvine, E-mail: ssoyoz@uci.edu
[2] Assoc. Professor. Department of Civil Engineering, Middle East Technical University, E-mail: onder@ce.metu.edu.tr
[3] Professor. Department of Civil Engineering, Middle East Technical University, E-mail: sucuoglu@ce.metu.edu.tr

Liquefaction potential of free-field soils is different than those ones under structures mainly due to variability in stress conditions these soils are subjected to. The effects of structure can be seen on cyclic stress ratio, a measure of soil liquefaction demand, in foundation soils from different aspects.

An overview of the effects of soil performance on the structural performance during the Kocaeli Earthquake, 1999 was given by Bakir et al. (2002) and Sancio et al. (2002).

During an earthquake, foundation soils filter and transmit the shaking to the building and at the same time it has the role of bearing the building vibrations and transmitting them back to the depths of the ground. In other words the ground and the building interact with each other.

Veletsos and Meek (1974) and Veletsos and Verbic (1973) showed analytically that the modal values are different when a structure is analyzed with and without interactions with soil. Stewart et al. (1999) applied system identification tools to a vast number of seismic records obtained from real-life structures and verified the fidelity of the results obtained by Veletsos et al. Trifunac et al. (2001) and Luco et al. (1987 and 1988) observed the behavior of a structure under different levels of seismic excitations. According to Stewart et al. (1999), there was nearly no reduction in spectral acceleration values obtained from free-field and surface foundation motions as an average. However it is worth to note that there are cases for which there is a considerable reduction or sometimes increases in spectral accelerations due to soil-structure interaction.

Koutsourelakis (2002) presented non-linear stochastic dynamic analysis of a soil–structure interacting system. They determined the risk of damage to the system due to liquefaction under a wide range of earthquake intensities. Ganev (1998) pointed out that the response of the soil-structure system to the 1995 Hyogoken-Nanbu Earthquake had been strongly influenced by pore-water pressure build up in the saturated surface soil layers.

Decoupling of the super-structure from the soil, consequently from the adverse effects of the earthquake motion by using base isolation systems has become a very popular method. All the base isolated structures performed well during two big earthquakes: Northridge, 1994 and Kobe, 1995.

Nagarajaiah and Sun (2000) performed a study on the performance of base isolated USC hospital building during Northridge Earthquake from the recorded data. The seismic response and performance evaluation of the hospital building shows that base isolation was effective in reducing the response and providing earthquake protection. The peak roof acceleration was reduced to nearly 50% of the peak ground acceleration. The peak drift was <30% of the code specification, and the super-structure remained in the elastic range which would have not been the case if it were a fixed base structure.

Jangid and Kelly (2001) investigated the effect of near-fault motions on base isolation systems. They found out that there exists a value of isolation system damping for which the superstructure acceleration for a given structural system attains a minimum value under near-fault motion. Spencer and Nagarajaiah (2003) present a state-of-art review of structural control. They first present the application of structural control to real-life structures and bridges most of which are from Japan.

BACKGROUND OF THE ANALYSES

On the basis of above discussions, what was done in this study is to model the structure and soil together so that the soil-structure interaction could be taken into account. The effect of structure on the liquefaction potential could be observed by comparing the liquefaction potential in the free-field and under the structure. Also base isolated structures were analyzed to examine the effect of isolation systems both on structural performance and on liquefaction potential.

To model the whole system, the program FLAC which implements the finite difference method, was used. The soil is meshed and the structure is modeled by structural elements. Also the free field boundaries are used as lateral boundaries.

Two input motions were selected as Kocaeli (1999) and El-Centro (1979) Earthquakes. Three different types of soil strata were modeled. For this purpose mainly the bore-hole data from the Sakarya City was used. The sites were constructed so that each one had different periods (Table 1).

Four different types of structures were chosen with three different types of structural periods. The structures were modeled as three, four and six story structures. Also one more four story structure was modeled having the same structural period with the original four story structure with an additional 50% weight (Table 2). All types of structures were analyzed also by adding an isolation layer.

For soil site response analyses the most important parameter is the shear wave velocity of the soil layers. There are number of correlations between the V_s (shear wave velocity) vs. SPT. In this study V_s estimates from the procedure proposed in Seed et al. 1984 were considered; G_{max} can be correlated to mean effective stress and the SPT blow counts as:

$$G_{\max} = 20000.(N_1)_{60}^{0.333}.\sqrt{\sigma'_m} \tag{1}$$

After the determination of the G_{max}, V_s can be found as:

$$V_S = \sqrt{\frac{G_{\max}}{\rho}} \tag{2}$$

where ρ is the mass density of the soil.

Table 1 Natural periods of the Sites

	Natural Periods of the Sites
First Site	0.29 sec.
Second Site	0.42 sec.
Third Site	0.7 sec.

Table 2 Natural Periods of the Structures

	Natural Period of the Non-Isolated Structure	Natural Period of the Isolated Structure
3 Story Structure	0.32 sec.	2.1 sec.
4 Story Structure	0.43 sec.	2.6 sec.
4 Story Structure	0.43 sec.	2.6 sec.
6 Story Structure	0.65 sec.	2.9 sec.

NUMERICAL RESULTS

In very simple terminology, liquefaction can be triggered by shear stresses introduced to the soil and can be reduced by the vertical effective stress on the soil. Simplified methods to correlate liquefaction resistance to SPT blow count proposed by Seed and Idriss (1971). Ishihara (1977) considered the effect of site response in this simplified method. Refinement of the Seed-Idriss methodology in probabilistic sense was done by Cetin et al. (2004). Using these charts the cyclic stress ratio, CSR, $\frac{\tau_{ave}}{\sigma'}$ required for the liquefaction can be determined. τ_{ave} is the equivalent uniform cyclic shear stress induced by the earthquake and σ' is the vertical effective stress. The existence of the structure affects both the shear force and vertical stresses imposed to the soil relative to the ones in the free field. Because of the additional weight of structure vertical stress in the soil will increase and CSR will decrease. So it is important to determine how much the shear stress induced by the structure in CSR will increase.

The main purpose of base isolation is to reduce the level of acceleration imposed to the structure consequently the shear forces and relative displacements in the super-structure. Based on the short discussion on liquefaction above, it can be seen that the reduction in the level of shear stresses will not only prevent structural damage but also behave in the favor of liquefaction potential.

In this study, CSR vs. depth plots were obtained at four different points under the structure as can be seen in Figure 1. Typical plots were given in Figure 2.

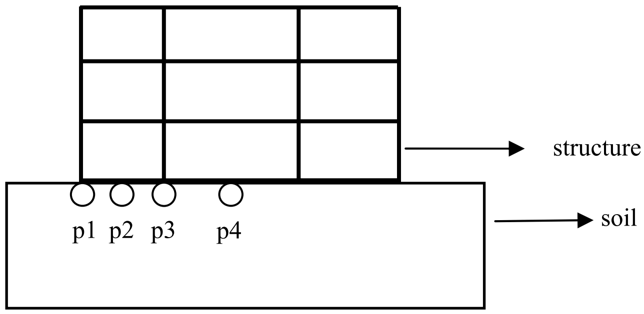

Figure 1 Points where CSR was plotted

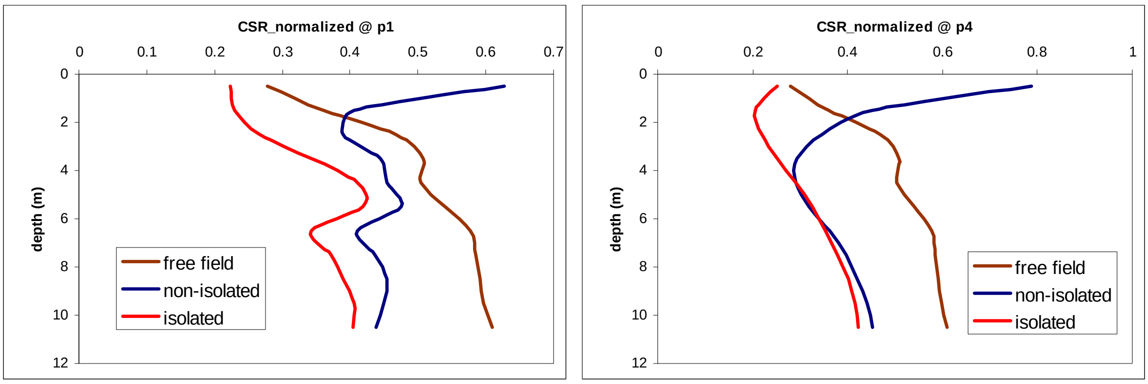

Figure 2.a CSR values under 4 story structure on second site for Kocaeli Earthquake

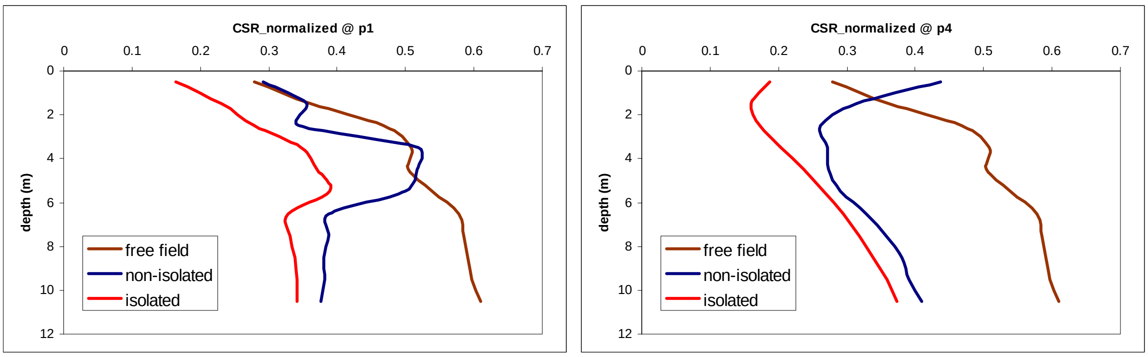

Figure 2.b CSR values under 6 story structure on second site for Kocaeli Earthquake

Depending on the type of structure CSR values under the structure differ. However for all the cases the CSR value under the non-isolated structure is greater than the CSR value obtained in the free-field. This is because the increase in $\tau_{\max}$ is greater than the increase in σ' induced by the structure giving a higher ratio of $\frac{\tau_{ave}}{\sigma'}$ under the structure than that one occurred in the free field. However after the first 2 m the CSR value turns out to be smaller than the CSR value in the free-field. So the ratio of D, depth up to which the CSR values are higher under the structure, and B, the width of the structure, then can be found approximately to be $\frac{D}{B}$=0.2.

Secondly it can be seen from Figure 2.b that CSR values under the structure are greater than the CSR values in the free field in the mid portions of the soil strata because of the K_α correction. It was observed that the α values for six story structure were much higher than the α values obtained for the other type of the structures. For the soil element in the free field there is no shear stress on the horizontal plane; however for soil elements under the edge of the structure static shear stress exists because of the loading of the structure. An α value can be obtained as $\frac{\tau_{static}}{\sigma'}$, in this study relationships between α and K_α, correction factor, proposed by Seed et al.1983 was used. In Figure 3 α values under 6 story structure can be seen.

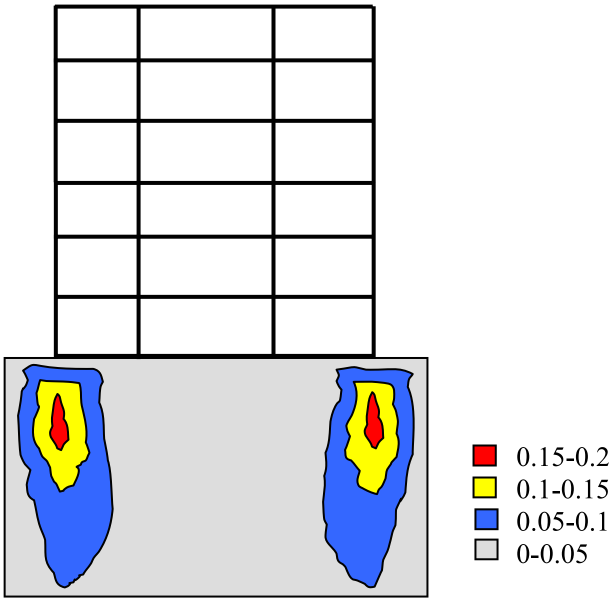

Figure 3 α values under 6 story structure

Another observation is that all these higher CSR values under the structure, which will potentially give rise to a higher probability of liquefaction occurrence, can be decreased by the base isolated structures. Simply because the $\tau_{\max}$ value on the soil elements induced by the structure is decreased and also σ' value is increased because of the additional isolation layer compared to non-isolated structures.

The liquefaction potential under the structure with a period range of 0.3-0.6 seconds was found to be greater than the one in the free-field; however for the structures having a natural period greater than 2 seconds which means for this study the base isolated structures, the liquefaction potential under the structure is lower than that one in the free field. This should not mean that base isolation is imposed as a first remedy to liquefaction; however it is just an effort to examine the effect base isolation to the structural induced liquefaction.

In literature, (e.g. Stewart et al 1999), the importance of soil-structure interaction is defined by the ratio of $\frac{h}{V_s.T}$; where h is the effective height which is equal to 0.7 of the total height of the structure, V_s is the equivalent shear wave velocity of the site and T is the natural period of the structure. In Figure 4 the plot of CSR vs. depth and $h/V_s.T$ is given. It can be seen that as this importance ratio increases CSR also increases.

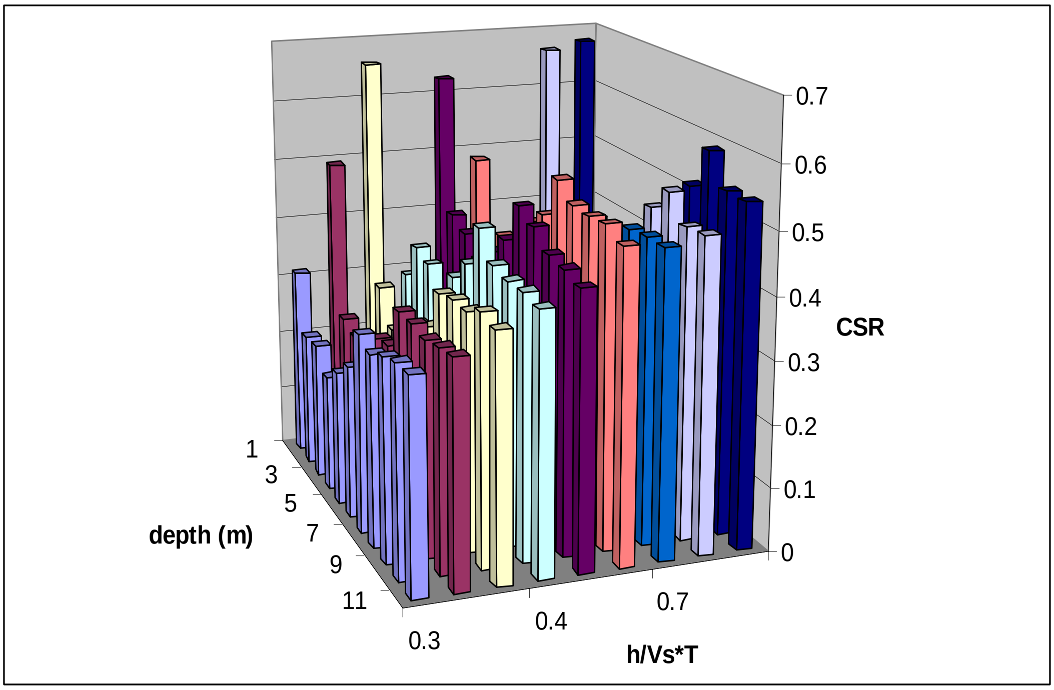

Figure 4 CSR-depth- $h/V_s.T$ plot for Kocaeli Earthquake

The isolators were found to be effective from structural point of view. Depending upon the types of the structure, site and the input motion the reduction in the structural response values can be decreased by a factor of 7-10 by use of isolation systems at an expense of large displacements concentrated in the isolation devices. An example of structural response values can be found in Table3.

Table 3 Structural response values of 4 story structure on the third site for Kocaeli Earthquake

	Non isolated	Isolated
Base shear obtained by FLAC (kN)	632	100
Relative Displacement on the first floor (cm)	1.52	0.23
Relative Displacement on the second floor (cm)	1.21	0.21
Relative Displacement on the third floor (cm)	0.92	0.16
Relative Displacement on the fourth floor (cm)	0.53	0.11

(Base displacement: 38 cm.)

To examine the effect of soil-structure interaction on response spectrum, motions under four different types of structures and the free-field motions were used. These four different types of structures were chosen to stand for different natural periods; namely, 3 story structure for 0.32 seconds, 4 story structure for 0.43 seconds, 6 story structure for 0.65 and the base isolated structure for 2.5 seconds.

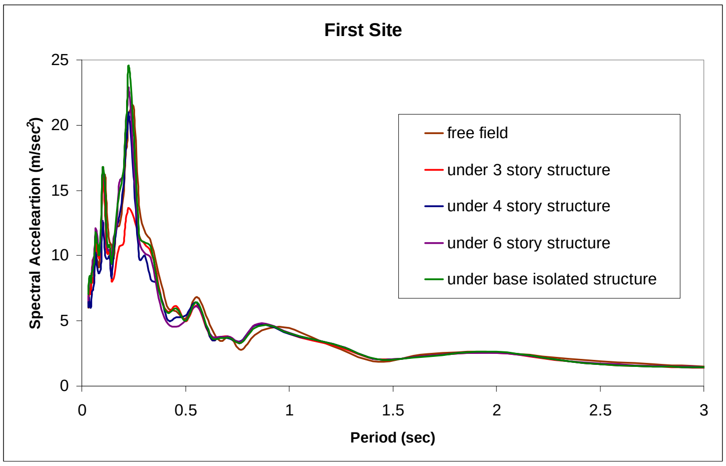

Figure 5.a Response Spectra for 5 % damping under Kocaeli Earthquake with the first site

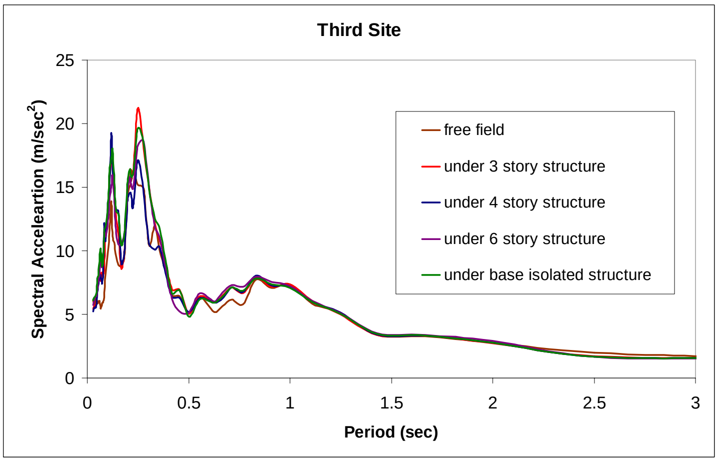

Figure 5.b Response Spectra for 5 % damping under Kocaeli Earthquake with the third site

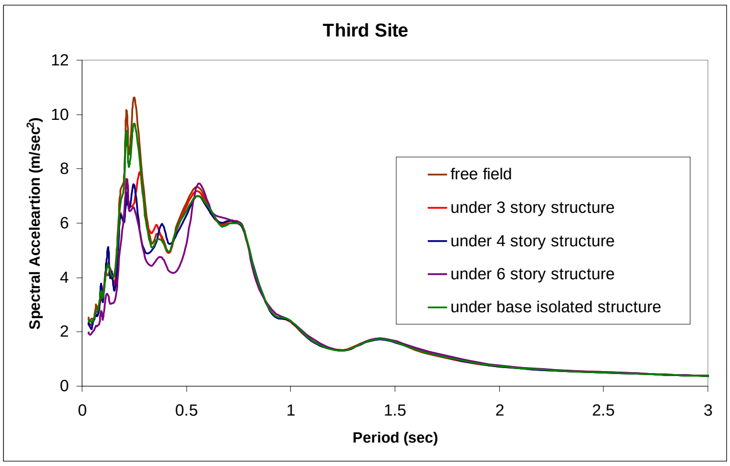

Figure 5.c Response Spectra for 5 % damping under El-Centro Earthquake with the third site

It can be seen from the Figure 5 that beyond a value of the period which is around 1 second, there is no difference in the response spectra obtained for five different cases. Additionally if the period of the structure is considerable high, in this thesis this is the case for base isolated structures, the spectral accelerations for all the periods are almost the same obtained for free-field motions and the motions under the structure.

It can also be observed that for some cases the spectral values obtained for free-field motion are higher and for some other cases the spectral values obtained for the motion under the structure are higher. The difference might be 1g, Figure 5.a. This observation does not depend only on the site characteristics or structural type. If the same type of structure and site are taken but only the input motion is changed, the spectral values will be different; values obtained for the motions under the structure might have lower or higher values than the ones obtained from free field motions (Figure 5.b- Figure 5.c).

CONCLUSIONS

- Dynamic response of a structure is defined by the interaction of underlying soils, earthquake shaking and super-structure itself.
- It was observed that for some cases there might be a 1 g spectral acceleration difference for specific periods between the response spectra obtained from the free field motions and the motions under the structure.
- The liquefaction potential under the structures was found to be greater than the one in the free field for the D/B ratio equal to 0.2. However after this level the liquefaction potential in the free field turns out to be greater.
- The liquefaction potential under the structures was observed to be affected by the structural type: For the six story structure the liquefaction potential of foundation soils was nearly equal to the one of free-field soils. This was mainly because the spectral acceleration level corresponding to the period of the six story structure is lower than the ones for other type of structures.
- Similarly for the six story structure, higher weight of the structure leads to a higher α value which makes the CSR values under the structure more critical than the CSR values in the free field, not close to the surface but in the mid portions of the site.
- The higher CSR values under the structure which can potentially give rise to liquefaction were reduced to a lower value than even the one obtained in the free field by using isolation systems.
- It can be concluded in scope of this study that the liquefaction potential under the structure will be higher if the structural period is lower than 0.6-0.7 seconds.
- The structural response values were observed to be decreased by a ratio of 7-10 by use of isolation systems.

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