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3D EFFECTS OF DIFFERENTIAL SETTLEMENTS ON A SPECIAL MOMENT RESISTING FRAME DUE TO EARTHQUAKE

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SUMMARY

Nowadays, 3D effect of considering the soil behavior under spread foundations is an important subject during the seismic analysis and design process of buildings with tall moment resisting frames. The main structural purpose of this importance is the additional bending moments of structural elements originating from differential settlements. In addition in a geotechnical point of view the different values of subgrade reaction modulus during the earthquake must be taken into account. Although the importance of such a 3D analysis is clear but it's usually neglected because of some calculative limitations of ordinary computers and usual numerical soft wares.

In this paper, we will show a case study of 3D analysis of soil and structure together to achieve the realistic values of soil reaction modulus. The other main purpose of this study was to see if design forces of structural elements will change by assuming the soil layers or not. By considering the complete geometry of structure and the equivalent static loading of earthquake, the overall behavior of model will be discussed and the resulting bending moments in the structure will be illustrated.

Subgrade reaction modulus (Ks) will be calculated by dividing the interface area of soil and foundation into separated zones and using the obtained values of displacement and pressure in each zone.

Finally the Ks values will be illustrated and compared with the values obtained from the plate loading test results.

INTRODUCTION

Tehran is located in a high-earthquake-risk zone (Berberian [1]); the history of seismic activity in Tehran and its surrounding areas shows a high probability of a significant seismic event (Nowroozi [2]). Although Tehran has not experienced a major earthquake during this century, historical evidence suggests such an earthquake could happen soon. The human loss and economic damage of a major earthquake would be enormous. By contrast, minor earthquakes and tremors are relatively frequent in Tehran.

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Although standard codes for earthquake-resistant buildings have existed in Iran for many years, it was only after the new UBS was established for housing construction in 1989 that higher standards were adopted and rigorously applied.
There is a variety of restrictions and safety factors in the last version of Iranian standard code for seismic design of residential buildings with different type of structures. In a parallel way to design criteria, some ways for dynamic analysis are mentioned too.
It should be mentioned that there is a few geotechnical previsions in this standard and for some special problems like static and dynamic soil-structure interaction there is an obvious need to perform some additional studies.
For performing the 3D analysis of soil and structure together we have used a real professional project of structural design. The selected structure was a residential building of 24 stories in the northern province of Tehran. The structure is based on a steel moment resisting frame and the lateral stability is being achieved through the cooperation of a shear core with the steel frames.
The shear core is two U-shaped structures consist of six walls and in the intersection point of each two pair of walls, there is a column of boundary elements. The first three stories of the building are under ground level and then a retaining wall covers their perimeter. The basic geometry of concrete and steel elements of structure is illustrated in figure 1 and 2.

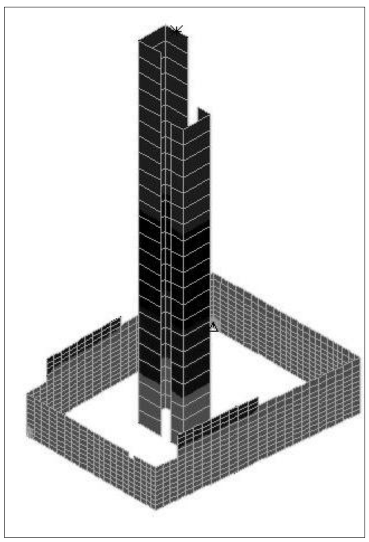

Figure 1: Concrete elements

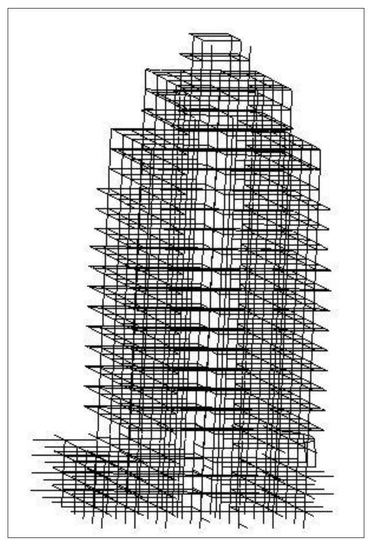

Figure 2: Steel elements

1. Materials and Loads

For performing the analysis first the situation of loading and also the assumed specifications of materials will be presented. It should be noted that there are two main categories of loads in the model; gravitational and earthquake loading.

1.1- Materials

All structural members are assumed to have a linear elastic behavior; in this way we have supposed the concrete to have an elastic modulus of $1.77\text{x}10^4$(MPa) and a Poisson coefficient of 0.3. Also we have used a value of 2500 kg/m^3 as the mass density of concrete. For the steel members we have supposed an elastic modulus of $2.00\text{x}10^5$ (MPa) and a Poisson coefficient of 0.3. The used value of steel mass density is 7850 kg/m^3.
For the soil we have used Mohr-Coulomb criteria for controlling the plastic zones under foundation. It should be noted that by using this criteria, we will be capable of controlling the stress in the soil mass and

also the soil behavior after its elastic threshold will obey the path which is being defined by plasticity parameters.
For the soil we have used cohesion of 30(kPa), friction angle of 30° and Poisson coefficient of 0.4. The elastic modulus of soil is assumed to be equal to 50(MPA).

1.2- Loads

All gravitational loads have been applied as a distributed pressure load on the floors and then the distribution process of load on the beams will be done automatically during analysis.
The earthquake loads on the structure have been calculated by using equivalent static theory. By using the seismic code of 2800 which is the Iranian standard for seismic analyze and design process of buildings, the equivalent static forces and moments have been calculated. It should be noted that the behavior coefficient of structure (R) is assumed to be equal to 11 which is presented by Iranian standards for buildings using special moment resisting frames and shear walls together. In addition to lateral forces, some torsion forces have been calculated either to assume the random movement of center of gravity in each floor. This forces and torsions could be seen in Table 1.

Table 1- Earthquake Loads Distribution

	Force (kg)	*Torsion-1 (kg.m)*	*Torsion-2 (kg.m)*
Gnd. FL.	*3,04*	*4,34*	*5,17*
1st FL.	*2,97*	*4,24*	*5,04*
2nd FL.	*7,53*	*10,76*	*12,80*
3rd FL.	*10,65*	*15,23*	*18,11*
4th FL.	*13,78*	*19,69*	*23,42*
5th FL.	*16,90*	*24,15*	*28,73*
6th FL.	*20,02*	*28,61*	*34,04*
7th FL.	*23,15*	*33,08*	*39,35*
8th FL.	*26,27*	*37,54*	*44,66*
9th FL.	*29,39*	*42,00*	*49,97*
10th FL.	*32,51*	*45,46*	*55,27*
11th FL.	*32,06*	*38,47*	*54,50*
12th FL.	*33,64*	*40,37*	*57,19*
13th FL.	*36,35*	*43,52*	*61,80*
14th FL.	*36,32*	*39,95*	*52,66*
15th FL.	*33,31*	*36,37*	*44,97*
16th FL.	*29,73*	*32,46*	*40,14*
17th FL.	*28,80*	*30,95*	*29,81*
18th FL.	*20,06*	*21,56*	*20,76*
19th FL.	*18,47*	*15,46*	*12,37*
20th FL.	*13,28*	*8,90*	*4,65*
21st FL.	*11,29*	*7,56*	*3,95*
Roof	*57,64*	*38,52*	*20,18*

2. Modeling

In this section firstly the model geometry will be discussed, then by illustrating the model in detail, some important finite elements methods which have been used to achieve to a precise stable model will be prompted.

3.1- Geometry

We have used the complete geometry of structure to build the finite elements model. Keeping away the effects of assumed boundary conditions in the general behavior of model, it was necessary to consider some proper dimensions for the soil block under the structure, and then a 110x290x380 meters block was used for modeling the underlying soil. The soil above the foundation elevation was neglected.

3.2- Used elements

Three kind of finite elements have been used to complete the model; 3D beams for steel frames, 3D shells for retaining and shear walls and also foundation and finally 3D solids for the soil volume.

All the shells used as walls and the foundation are modeled with their real thicknesses. It must be mentioned that all the steel beams and columns have been assumed with their real I and H sections which are used in the structure. The used 3D solid elements for the soil mass are with 21 nodes which will make the results more accurate and dependable.

3.3- Coupling the model

One of the major difficulties during the coupling process of such a complicated model is to fix the incompatible degrees of freedom. Constraint equations are used to fix the structural frame elements on the soil elements which are made of 3D solids and also foundation which is a 3D shell.

The main constraint equations are used for connecting the foundation nodes and soil surface, the structural frames and foundation nodes and finally the in plane nodes of each rigid diaphragm. Figure 3 shows the complete coupled geometry of the final model.

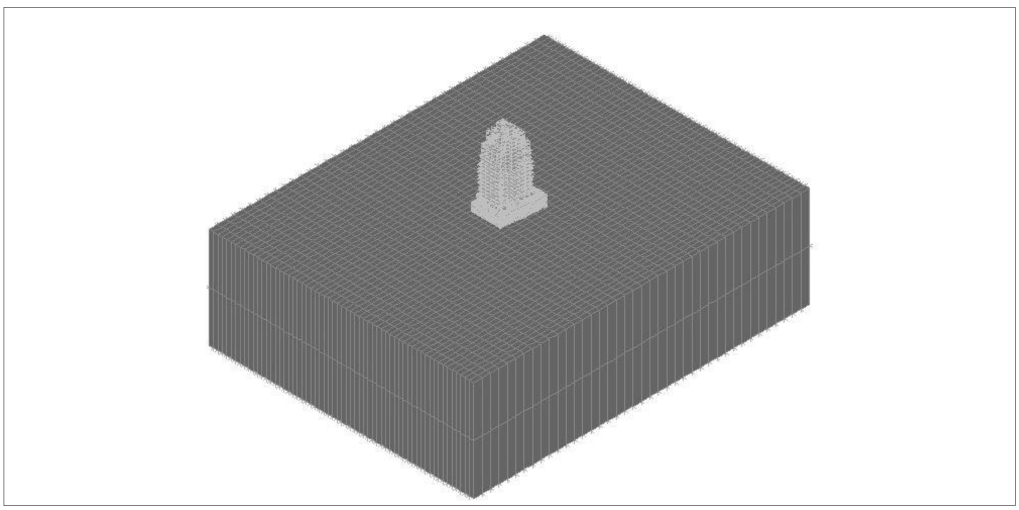

Figure 3: Complete geometry of the model

3. Analysis Results

Final analysis results could be divided in two main categories which are geotechnical and structural results. The most important geotechnical result is the distribution of different values of subgrade reaction modulus because of 3D behavior of structure and also the differences of this value for the gravitational and lateral loads.

In the other hand, the most important structural result is the redistribution of moments in the structural elements because of the differential settlements of foundation. These results will be discussed in the following paragraphs.

3.1- Subgrade reaction modulus

For calculating the subgrade reaction modulus two main parameters of output results have been used; the pressure under the different zones of foundation and also settlements. Figure 4 and 5 shows some examples of the used pressure and settlement contours which have been used for calculating the K_s values.

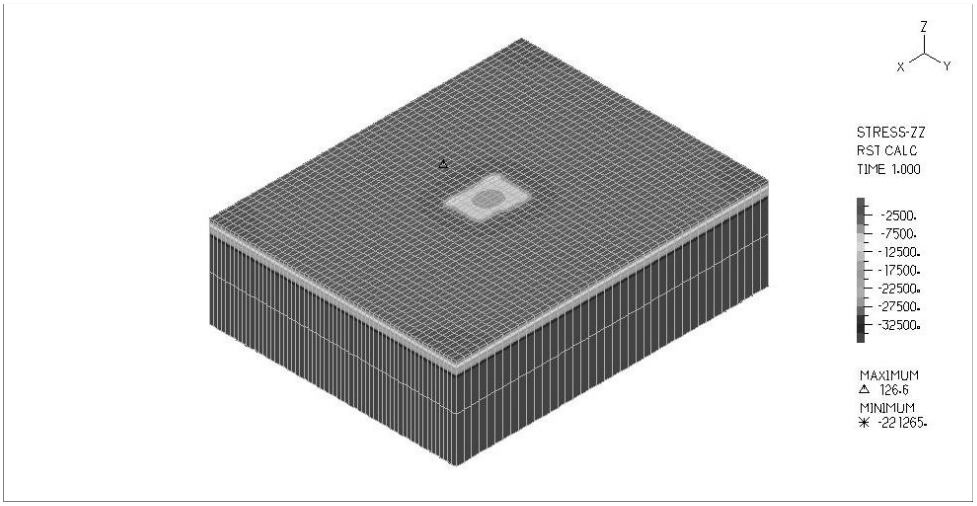

Figure 4: Pressure under the foundation

As it could be seen in displacement and stress contours, we can see that the soil underlying the foundation could be divided in four separate zones. It should be noted that, the resulted values of pressure and displacement in each zone are completely different in two analyses. In the other word there are obvious differences between static and equivalent static behavior of a foundation beneath such a structure.

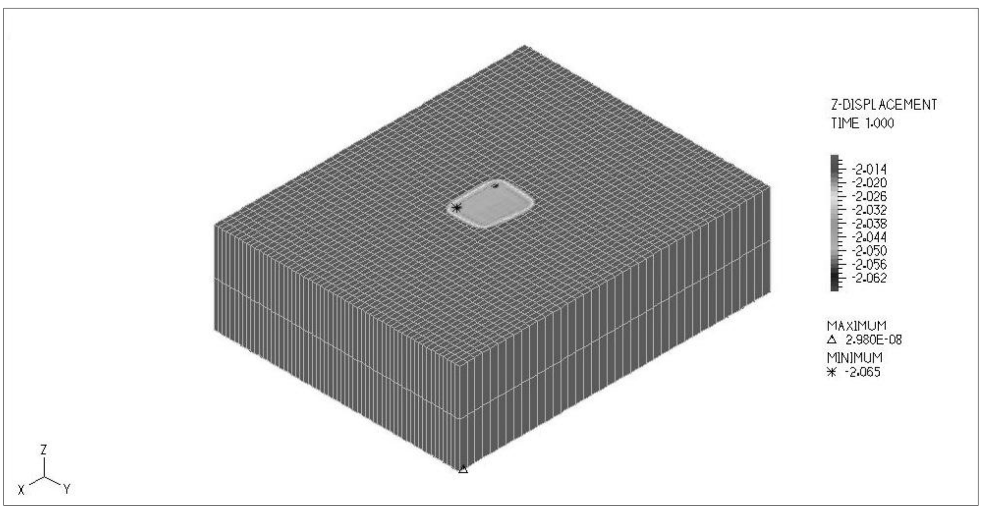

Figure 5: Settlements under the foundation

By assuming the different zones of the soil under the foundation like figure 6, the calculated values of K_s will be as shown in table 3 and 4.

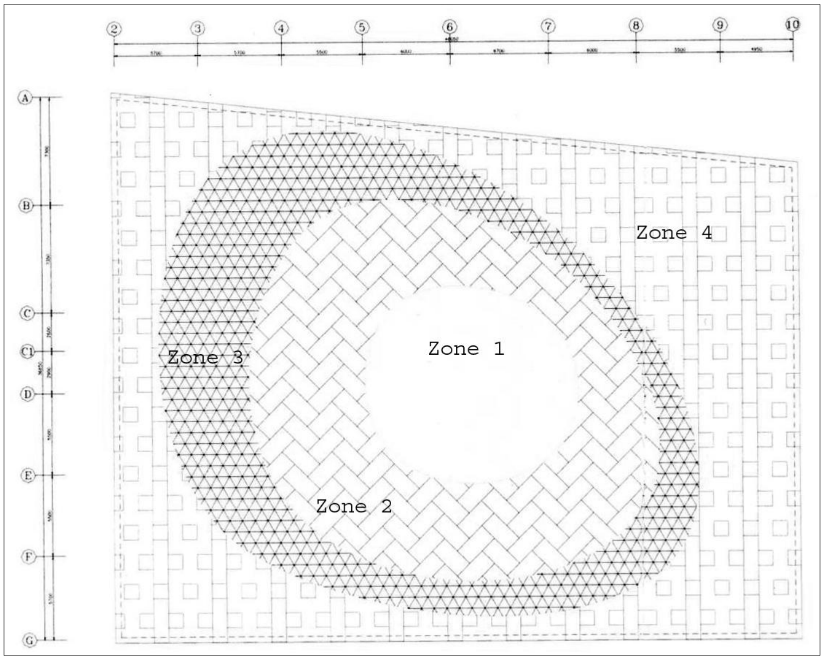

Figure 6: Selected zones of Ks under the foundation

Table 2- Ks for Gravitational Loads

Zone	*Pressure(kg/cm^2)*	*Settlement(cm)*	*Ks(kg/cm^3)*
4	*1.25*	*1.6*	*0.78*
3	*0.90*	*1.6*	*0.56*
2	*0.75*	*1.5*	*0.5*
1	*0.67*	*1.5*	*0.45*

Table 3- Ks for Earthquake Loads

Zone	*Pressure(kg/cm2)*	*Settlement(cm)*	*Ks(kg/cm3*
4	*0.90*	*1.7*	*0.53*
3	*0.75*	*1.8*	*0.42*
2	*0.60*	*1.57*	*0.38*
1	*0.60*	*1.5*	*0.40*

All above mentioned results for K_s are different from the results obtained from plate load test which was around 1.5 kg/cm^3. In addition it should be mentioned that when we use the plate load test, it is impossible to estimate the values of subgrade reaction modulus during earthquake.

3.2- Redistribution of Forces in Structural Design

For achieving to a comparison between the resulted forces and the forces calculated by using regular methods of modeling the structures without taking the foundation into the account, we have chosen some frames in the structure. By calculating the ratio of redistributed forces after differential settlements of foundation we have seen that in some elements there is an additional moment of almost 8% in comparison with the obtained moments of usual analysis which means in the final design process with some regular software of structural design and without modeling the full behavior of soil and foundation together, all design loads must be multiplied with this ratio. It should be mentioned that the magnitude of this ratio will decrease in the upper floors of building. In the other word, the maximum additional redistribution of moments will occur in the first and second floor above the ground and ground floor, by moving to the top of the structure the ratio will lead to zero.

4. Conclusions

By using a 3D analysis of static and dynamic soil-structure interaction, we have seen the important effects of differential settlements of foundation on the final values of subgrade reaction factor and also the design moments in the structural elements.

As a basic conclusion we can say that there are significant changes in the values of Ks when the complete 3D geometry of structure is used. In addition the values obtained from plate loading test and geotechnical correlations may be completely different from the realistic values for mat foundations of tall buildings. In our case the calculated subgrade reaction modulus was about 50% of values obtained by correlations.

In the other hand the values of Ks will change during an earthquake, also these values are near to static case but the increase and decrease of Ks in each zone may be different, this difference is a function of location of shear walls and other lateral stabilization mechanisms.

As a structural point of view, we can say that there is an additional redistribution of moments in the down floors of building. The ratio of this redistribution in our case was even up to 10% of the original moments; resulting from ordinary analyses.

Finally we can say that the 3D analysis of soil and structure together is necessary for non-symmetric tall structures using a combination of moment resisting frames and shear walls as the lateral stability mechanisms.

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