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M. Tehranizadeh
Amirkabir University of Technology/ International Institute of Earthquake Engineering and Seismology, Tehran, Iran

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Effect of Soil Properties on Foundation Settlements Under Earthquake Loading

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M. Tehranizadeh
Amirkabir University of Technolgoy and
Member of Planning Council of Int-Inst. of Earthquake Engineering and Seismology
Tehran, Iran

ABSTRACT: An analytical study is carried out to predict the immidiate settlement of the structures during earthquake loadings. In this analysis a three dimensions mathematical model is used to investigae the behavior of the whole system consisting of soil - foundation and structure. The deformation of different points of the foundation as well as the other parts of the structure are calculated. The time acceleration record of Tabas earthquake was used as an earthquake type of loading. The effect of the main factors on the elastic settlement of the structure such as soil elastic modulus, foundation thickness, weight of the structure and number of floors are investigated. The variations of the total and differential settlements versus different parameters are plotted and some clear results are concluded concerning the settlement behavioral of soil - structure interaction during earthquake loadings.

1-INTRODUCTION

In order to study the behavior of a foundation during earthquake loadings it is necessary taking into account the whole system consisting of soil, foundation and structure.

Since during an earthquake, besides static loads, the horizontal and vertical loads due to ground motions are applied to the structre, the vibration of the system in this condition must be considered. The stresses and strains for all parts of the system can be calculated by writing the equations of motion.

The availability of high capacity micro - computers and the advanced dynamic analysis methods have caused to evaluate the behavior of these complicated systems more easily and accurately.

In this study a three dimensional model, capable of analysing this system under earthquake loadings is used. As it is shown in fig.1 the different part of the system are appropriately meshed and deformations of the elements as well as the foundation of the structure are determined.

2- Methods of analysis soil - structure interaction

There are different methods for analysing soil - structure interaction, some of them are too complicated and difficult to be used. In an overall review, they can be categorized into two main groups, namely: direct and substructure methods.

In the direct method a significant part of the soil around the embdded structure is modeled while the free field motion at the fictious bounder is applied to the system. This method would even allow certain non - linear material laws of the soil to be taken into account.

In the substructure method the nodes of the dynamic model located along the embdment on the soil - structure interface are indicated as circles. The free field response of the site (without any embdment) is calculated first. Then the unbounded soil is analysed as a dynamic system. The force - displacement relationship of the degrees of freedom of these same nodes, which will be in contact with the structure, is determined. These so - called dynamic - stiffness coefficient of the soil can physically interpreted as a generalized spring, a spring dashpot - system. Finally the structure supported on this spring - dashpot system is analyzed for a loading case which depends on the free field motion.

Since the direct method is used in this study, it is described in more details in this section. As it is shown in fig.2 the specified part of the soil around the structure are modeled together with the structure, and the dynamic stiffness matrices of the soil and structure are determined and the basic equation of the system in the ranges of desired time is written as below:

$$\left[\begin{array}{c|c|c|c} [M_{ss}] & [M_{sb}] & & \\ [M_{bs}] & \begin{matrix}[M^{s}_{bb}] + [\bar M^{f}_{bb}] \\ [\bar M_{bb}]\end{matrix} & [\bar M_{bi}] & \\ & & \begin{matrix}[\bar M_{ii}] \\ [\bar M_{ri}]\end{matrix} & \begin{matrix}[\bar M_{ir}] \\ [\bar M_{rr}]\end{matrix} \end{array}\right] \begin{Bmatrix} \{r_s\} \\ \{r_b\} \\ \{r_i\} \\ \{r_r\} \end{Bmatrix} + \left[\begin{array}{c|c|c|c} [C_{ss}] & [C_{sb}] & & \\ [C_{bs}] & \begin{matrix}[C^{s}_{bb}] + [\bar C^{f}_{bb}] \\ [\bar C_{bb}]\end{matrix} & [\bar C_{bi}] & [\bar C_{br}] \\ & & \begin{matrix}[\bar C_{ii}] \\ [\bar C_{ri}]\end{matrix} & [\bar C_{rr}] \end{array}\right] \begin{Bmatrix} \{r_s\} \\ \{r_b\} \\ \{r_i\} \\ \{r_r\} \end{Bmatrix}$$

$$+ \left[\begin{array}{c|c|c|c} [K_{ss}] & [K_{sb}] & & \\ [K_{bs}] & \begin{matrix}[K^{s}_{bb}] + [\bar K^{f}_{bb}] \\ [\bar K_{bb}]\end{matrix} & [\bar K_{bi}] & [\bar K_{br}] \\ & & \begin{matrix}[\bar K_{ii}] \\ [\bar K_{ri}]\end{matrix} & [\bar K_{rr}] \end{array}\right] \begin{Bmatrix} \{r_s\} \\ \{r_b\} \\ \{r_i\} \\ \{r_r\} \end{Bmatrix} = \begin{Bmatrix} \{0\} \\ \{0\} \\ \{0\} \\ \{R_r\} \end{Bmatrix} \qquad (1)$$

in which the superscripts and subscripts used are as follows:

b- the nodes located on the soil - structure interface

s- the other nodes of the structure

i- the nodes located inside the soils' zone

r- the nodes locate on the soils' zone

g- the nodes belonging to the soil (excavation condition)

f- the nodes belonging to the soil (for natural ground without excavation)

The modeled zone of the soil is selected so that the forces on the outside boundary are dissipated. Thus the stress waves induced on the selected boundary are properly absorbed and no reflection interfers the system. In the equation (1), the [M], [C] and [K] are mass, damping and static stiffness matrices respectively. The characteristic matrix of the system in the soil - structure interface is equal to: $\left[k^s_{bb} + k^{-g}_{bb} \right]$.

The vector {r} represents deformations and the superscriptt denotes total motion of the system. The vector {R} shows the forces applied to the system. In this method the boundaries are considered far enough from the structure so that the free field conditions to be met there. In this case the following equations can be written:

$$\begin{aligned} \{\ddot{r}_i\} &= \{\ddot{r}_i^t\} \\ \{\dot{r}_i\} &= \{\{\dot{r}_i^t\}\} \\ \{r_i\} &= \{rf_r\} \end{aligned} \qquad (2)$$

substituting equation (2) in equation (1) results in:

$$\begin{bmatrix} [M_{ss}] & [M_{sb}] & [\overline{M}_{bl}] \\ [M_{bs}] & [M^s_{bb}]+[\overline{M}^g_{bb}] & \\ & [\overline{M}_{ib}] & [\overline{M}_{il}] \end{bmatrix} \begin{Bmatrix} \{\ddot{r}^t_s\} \\ \{\ddot{r}^t_b\} \\ \{\ddot{r}_l\} \end{Bmatrix} + \begin{bmatrix} [C_{ss}] & [C_{sb}] & [\overline{C}_{bl}] \\ [C_{bs}] & [C^s_{bb}]+[\overline{C}^g_{bb}] & \\ & [\overline{C}_{ib}] & [\overline{C}_{il}] \end{bmatrix} \begin{Bmatrix} \{\dot{r}^t_s\} \\ \{\dot{r}^t_b\} \\ \{\dot{r}_l\} \end{Bmatrix}$$

$$+ \begin{bmatrix} [K_{ss}] & [K_{sb}] & [\overline{K}_{bl}] \\ [K_{bs}] & [K^s_{bb}]+[\overline{K}^g_{bb}] & [\overline{K}_{il}] \\ & [\overline{K}_{ib}] & \end{bmatrix} \begin{Bmatrix} \{r_s\} \\ \{r_b\} \\ \{r_l\} \end{Bmatrix} = - \begin{Bmatrix} \{0\} \\ \{0\} \\ [\overline{M}_{ir}]\{\ddot{r}_f\}+[\overline{C}_{ir}]\{\dot{r}_f\}+[\overline{K}_{ir}]\{r_f\} \end{Bmatrix} \qquad (3)$$

The difference between the earthquake and other dynamic loadings is that in case of the earthquake the motion induced in the bedrock is transfered to the structure via the upper soil layers. The bedrock in fact is the lowest boundary of the soil layers beneath the structure and the soil is considered to be fixed at this level.

Having the recorded motion of the ground surface, the bedrock motion should be determined and the assumed model consisting of soil - foundation and structure for this motion can be analyzed.

In the most earthquakes' spectra, the propagated waves from the fixed horizontal boundary have not a considerable effect on the analysing results of the superstructures. Since the effective waves in the soil - structure interaction are surface waves which propagate near the ground level and dissipated with depth considerably, they would reflect from sides boundaries before reflecting from the lower boundaries.

The advantage of the direct method toward others is that in this dynamic analysis when using finite elements, there is no need to write any subroutine for modeling the soil. The soil behavior can be predicated satisfactory by having the parameters: ρ (specific mass), E (elastic modulus), G (shear modulus), ϑ (poissons' ratio) and ζ (damping ratio). In this method the variations of the soil properties in different directions as well as the irrugular shape of the soil - structure boundaries or any irregularity in the soil or structure can be applied and investigated easily. The only problem in this method is the dependency of some soil parameters, such as damping ratio and stiffness, to the exciting frequency which of course in case of low frequency vibrations is negligable.

3- The method and results of the study

In order to study the influence of different parameters on the elastic settlements of a mat foundation during eartquake loadings, a special system, as shown in fig.2, consisting of soil, foundation and structure is considered. This system has been analysed by finite elements method and the results are presented by a series of graphs.

In this study the acceleration - time records of eartquake in the bedrock has been used. The frame, shell and solid blocks are used to model the structure, foundation and soil respectively.

The modeled system is a seven stories building resting on a mat foundation. In this study the bending elements, four nodes elements (bending plane) and eight nodes elements (three dimensional) are used for the structure, foundation and soil respectively. The acceleration - time record of Tabas earthquake (fig.3, occured in 1977 in the eastern - north region of Iran) is applied to the system and the induced settlements of the foundation are calculated and plotted. The elastic settlement of the side columns as well as the differential settlements between two adjacent columns are determined and the effect of different factors on these settlements are investigated. The parameters are studied in this research are as follows:

1- The effect of the soil modulus on the elastic settlement

2- The effect of the foundation thickness on the elastic settlement

3- The effect of the weigth of the structure and number of floors on the elastic settlement

The variations of the elastic settlements are shown in fig. 4 to 6, 7 to 8, 8 to 9 and 1o to 12 versus soil modulus of elasticity, foundation thickness, weight of the structure and number of floors respectively.

4- Discussion of the results

According to the fig. 4 to 6, it can be seen that the increase in the soil elastic modulus results decrease in the elastic settlements during earthquake loading. This decrease under the side and corner columns are more significant than that under the internal columns. The rate of decrease in settlement decreases as the elastic modulus increases, so that it becomes negligable for stiff soils. This can be attributed to the behavior of the soil - foundation as a unit system. In fact in case of stiff soils the structure behaves as if located on a very thick foundation.

The effect of the foundation thickness on the elastic settlement is more clearly evident in fig.7 and 8. It can be seen that doubling the thickness of the foundation leads to a decrease of 30% in settlement. The decrease in differential settlement is even mrore due to increase of foundation thickness. Doubling the thickness of the foundation causes 50% decrease in differential settlement between two columns. It may be due to changes in the loading conditions from concentrated to a more uniform state beneath the foundation.

The increase in weight of the structure will lead to icreasing both total and differential settlements during earthquake. This increase for side columns are more significant than internal columns. As a result the differential settlement may increase more rapidly leads to local or general failure of structure. It is evident from the figures that doubling the mass of structure cause the differential settlement to increase 300% approximately.

It can be seen from Fig. 10 to 12 that increasing two floors to a five stories building would double the elastic settlements. The increase happen for both side and internal columns, but the rate of increase for internal columns is less than that for the side columns, The reason, besides increasing the surcharge, may be due to changes in the modes of vibrations of the structure in the new situation.

5- Summary and conclusion

The soil - structure interaction during earthquake loading was studied, by direct method. Tabas spectrum of earthquake was applied to the selected system consisting of soil - foundation and seven stories building, and displacements of different points beneath the foundation were caculated by finite elements method. The influence of different parameters such as soil modulus of elasticity, foundation thickness, weight of the structure and number of floors on the elastic settlements were studied and investigated.

According to the analysis' results, while the increasing soil modulus and foundation thickness result in decreaseing the elastic settlement, increasing weight of the structure and the number of floors lead to increasing the settlements during earthquake loadings. In connection with differential settlements it is evident that the increase in soil stiffness and foundation thickness, decrease differential settlement considerably, but the increase in weight and number of floors increases them which may cause the local or general failure of the structure.

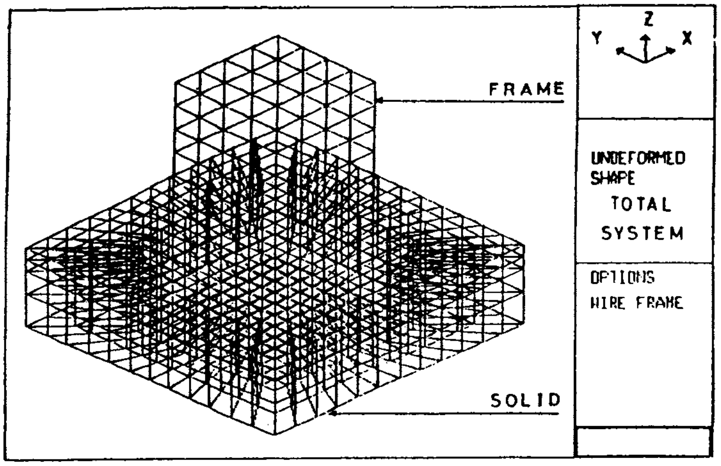

Fig.1-Three dimensional view of the soil-structure system

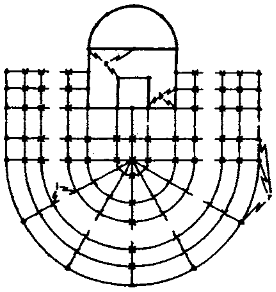

Fig.2-Soil-structure system with different nodes

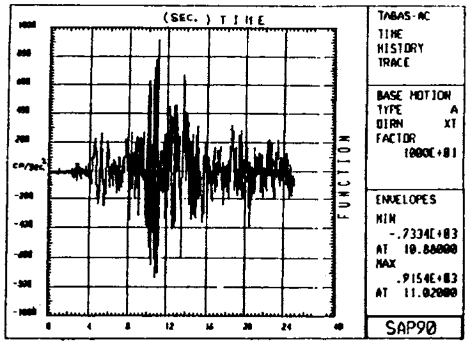

Fig.3-The acceleration-time record of Tabas earthquake

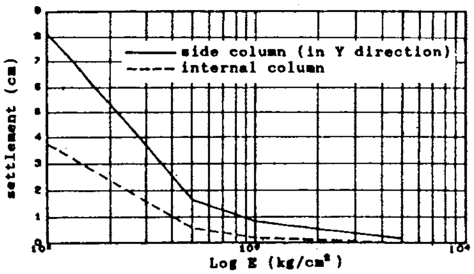

Fig.4-Settlements of the side and internal columns versus elastic siol modulus

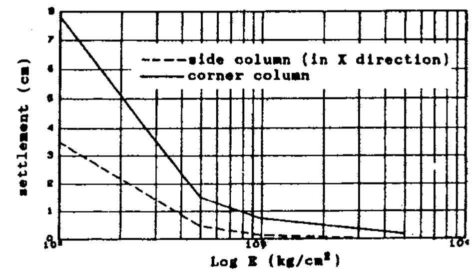

Fig.5-Settlements of corner and internal columns versus elastic soil modulus

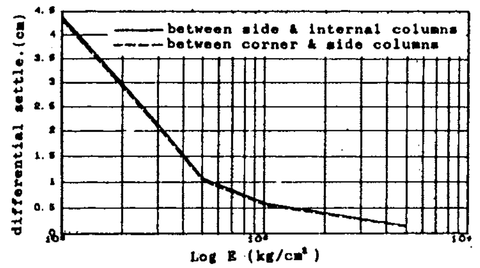

Fig.6-Differential settlements versus elastic soil modulus

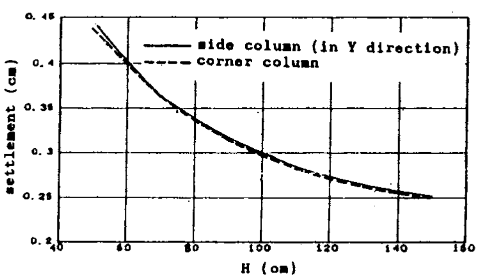

Fig.7-Settlements of side and corner columns versus foundation thickness

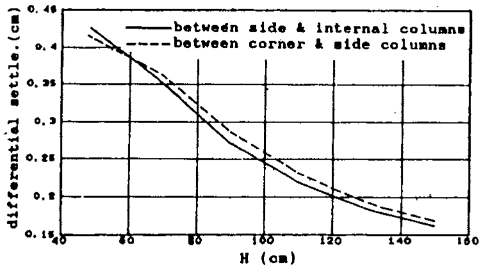

Fig.8-Differential settlements versus foundation thickness

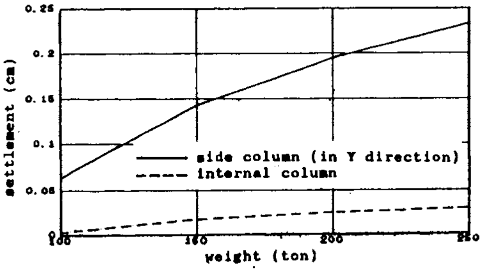

Fig.9-Settlements of side and internal columns versus weight of structure

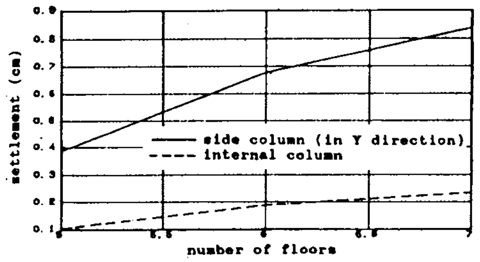

Fig.10-Settlements of side and internal columns versus number of floors

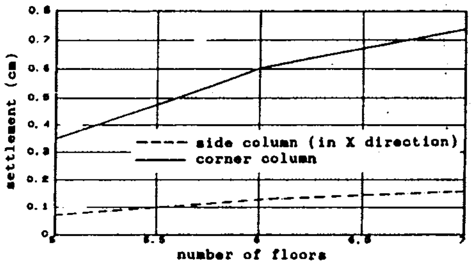

Fig.11-Settlements of corner and internal columns versus number of floors

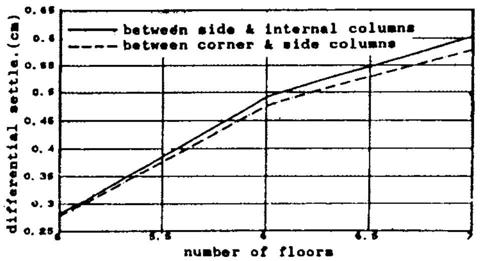

Fig12-Differential settlements versus number of floors

References

Bowles, J.E. 1982."Foundation analysis and design", McGraw-Hill

Kolar, V.& Nemec, I. 1989."Modeling of soil - structure interaction", Elsevid

Majid, K.I. 1982."An investingation into the behavior of complete structures resting on clay", Int. symp. on num.model in geomech.

Nelson, R.B.& Muki, Y. 1987."Dynamic response of structure", ASCE.

Wilson, E.L.& Habibullah, A. 1989. "SAP 90", computer and structure, Inc., Berkley, California

Wilson, E.L.& Habibullah, A."SAP SLT-A steel stress check postprocessor for SAP 90"

Wilson, E.L.& Habibullah, A. "SAP TIME-An interactive time history display postprocessor for SAP 90"

Wolf, J.P. 1985. "Dynamic soil - structure interaction", prentice - hall