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CONTRIBUTION OF SOIL-STRUCTURE INTERACTION TO SEISMIC RESPONSE OF BUILDINGS

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Buildings are susceptible to soil structure interaction effects due to the induced changes in the dynamic characteristics of soil during seismic excitation; particularly several buildings have been constructed on soft soil. Because of this detrimental effect, this paper aims at clarifying the soil structure interaction effect on the seismic response of buildings under strong ground motions to provide damage control and enhance the safety level of such buildings. An iterative dynamic analysis was performed using SAP2000 program to carry out three dimensional time history analysis of non-linear soil-foundation-building models under a great earthquake ground motions. The interaction between the soil and structure is represented by Winkler spring model and the damping effect of the soil is modeled by dashpots. The coefficients of springs and dashpots were based on medium soil profile underneath and along the embedded depth of foundation and calculated as recommended by Newmark and Rosenblueth 1971 [23].

A comparison of response for different building models subjected to three dimensional great earthquake ground motion shows that incorporating the soil structure interaction could have a detrimental effect on the building performance and overestimates the top displacements response. On the contrary flexible bases of buildings have noticeable effect on the structural behavior of buildings by providing pronounced reduction in the internal forces of superstructure response compared to the fixed base buildings. Also, the obtained results confirmed that the dynamic characteristics of soil structure system should be recommended for conservative nonlinear seismic response of the high building since it mitigates of earthquake hazards.

KEYWORDS: *Buildings – Soil-Structure Interaction – Flexible bases – Fixed base – Three dimensional Ground motions – Seismic Response – Time history analysis.*

1. INTRODUCTION

The seismic analysis of engineering structures is often based on the assumption that the foundation corresponds to a rigid block, which is subjected to a horizontal unidirectional acceleration. Such model constitutes an adequate representation of the physical situation in case of average size structure founded on a sound rock. Under such conditions, it has been verified that the free field motion at the rock surface, i.e., the motion that would occur without the building, is barely influenced by its presence. The hypothesis loses validity when the structure is founded on soil deposits, since the motion at the soil surface, without the building may be significantly altered by the presence of the structure. The dynamic characteristics of the structure, such as vibration modes and frequencies, are modified by the flexibility of the supports. Thus, there is a flux of energy from the soil to the structure, and then back from the structure into the soil, in a process that is known in seismic engineering as soil-structure interaction (SSI).

The load and deformation characteristics of the structural and geotechnical (soil) components of the foundations of structures can affect, and in some cases dominate, seismic response and performance. Recognizing this important fact, many structural engineers have included representations of foundation strength and stiffness in their seismic analysis models for many years. The modeling of the soil and structural parts of foundations inherently accounts for the interaction of the soil and structure. There are three primary categories of soil-structure interaction (SSI) effects. These include: (1) a soil and foundation flexibility effect, an introduction of flexibility to the soil-foundation system resulting in a change in the stiffness of the lateral-force resisting elements, which lengthens the fundamental response period of the model; (2) a foundation damping effect, dissipation of energy from the soil-structure system through radiation and hysteretic soil damping; and (3) a kinematic interaction effect, the filtering of the dynamic characteristics of ground shaking transmitted to the structure.

If the soil material can be considered linear then the SAP2000 program, using the SOLID element, can be used to calculate the one, two or three dimensional free-field motions at the base of a structure. In addition, a one dimensional nonlinear site analysis can be accurately conducted using the FNA option in the SAP2000 program. Under major structural elements, such as the base of a shear wall, massless elastic springs should be used to estimate the foundation stiffness (Clough and Penzien) [5].

The response to earthquake motion of a structure founded on a deformable soil will not be the same as if the structure were supported on a rigid foundation. The ground motion recorded on the base of the structure will be different from that which would have been recorded had there been no building. The practical importance of these effects on the properties of the soil structure system. In terms of the dynamic properties of the system, this dynamic coupling, or interaction between a building and the surrounding soil, will generally have the effect of (1) reducing the fundamental frequency of the system from that of the structure on a rigid base, and (2) dissipating part of the vibration energy of the building by wave radiation into the foundation medium. There will also be energy losses due to internal friction of the soil. Because of these effects, the response of a structure on a soft foundation to a give earthquake excitation will, in general, be different from that of the same structure supported on a rigid ground. It is the influence of a soil structure interaction on the response of structures to earthquake motion that is the general subject of this paper.

Observations of buildings during earthquakes have shown that the responses are influenced by their supporting media, especially when the soils are soft [20-23, 19]. For special structures, interaction effects can be important even for relatively hard soils since the relevant parameter is not the stiffness of the soil, but a dimensionless ratio of the stiffness of the building to the soil stiffness.

The Winkler foundation is a model that can be created in order to represent the stiffness and the dampening effects of the soil surrounding a pile shaft. The stiffness of the soil is represented with springs and the dampening effect of the soil is represented with dashpots. These are simple interactions existing in ABAQUS, which can be attached to each element of the pile, representing the soil that it is founded in. Different types of soil from hard clay to soft sand can be represented in this manner. [11]

Numerous analytical and experimental studies have been performed on the topic mentioned in the previous section, namely; soil structure interaction. Consequently, simplified procedures and computer codes have been developed. Many advances have been made on the topic mentioned above, some of which are summarized in the following section.

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. This interaction has been attracting the interest of researchers for the last half-century.

One of the first comprehensive studies belongs to Seed and Lysmer (1975) [18]. The drawbacks and the advantages of two methods which are still being used were examined. These methods are 1) representing the effect of the soil on the structural response by a series of springs and dashpots or 2) modeling the soil-structure system by finite element method. They pointed out the lack of rigorous numerical modeling and again the lack of database obtained from field cases which are no more concern thanks to powerful PC’s and recorded response data.

One of the ways to evaluate natural period of a soil structure system is to use micro tremor data. Similarly, Ohba (1992) [17] proposed a correlation between natural period of a structure as a function of its height which is a commonly used in practice. He also included the effect of stiffness of the soil on the natural period of the structure. The standard penetration test results were used to account for the stiffness of the soil. He concludes that increase of the height makes natural period of the structure longer, also this value gets longer as the stiffness of the soil gets smaller. Putting aside the changes in the level of acceleration because of the existence of the structure and considering the response spectra obtained from the free field motions and from the ones underneath the structure being equal, even this observation itself is enough to emphasize the effect of soil structure interaction.

A report was published by Architectural Institute of Japan after the Kobe earthquake, 1995 (1997). During this earthquake very many strong ground motion data were obtained in and around city of Kobe. Among them, there were some records which were simultaneously obtained at the foundation level and at the ground surface. After comparing them, it was concluded that the maximum accelerations on the foundation level are smaller. It was revealed in this report that the maximum accelerations on the foundation levels were 30% smaller than the ones in the free field.

In soil structure interaction field, few empirical studies have been performed due to limited availability of strong motion data from sites with instrumented structures and free field accelerometers. Recently, a comprehensive study was conducted by Stewart et al (1999) [16] using 77 strong motion data sets at 57 building sites which encompass a wide range of structural and geotechnical conditions. It was observed firstly in this study that there was nearly no reduction in spectral acceleration values obtained from free field and surface foundation motions, which was the primary important parameter controlling the structural response. However it is worth to note that there are cases for which there is a considerable reduction or sometimes increases in spectral accelerations. Also for the same site and same structure, different response of the structures and the level of acceleration were obtained under different input motions. For one earthquake the free field value of the peak ground acceleration was recorded to be greater than the one obtained from the surface foundation motions. For another input motion, the peak ground acceleration obtained from the surface foundation motions turns out to be greater. These kinds of observations lead to a conclusion that the interaction takes not only between soil and structure but also with the input motion itself.

However, Stewart et al (1999) [16] indicates that there is a high correlation between the lengthening ratio of structural period due to the flexibility of the foundation and structure to soil stiffness ratio. Typical soil structure interaction effects occur for the values of around 0.1–0.3 of stiffness ratios. For these typical values the lengthening in the period is around 1.1–1.5. However there are again some cases for which the stiffness ratio is around 1.5 and consequently lengthening in the period are around 4. Such a big difference in natural period results in completely different level of accelerations. As a general trend when the structure is stiff and the underlying soil is soft the soil structure effect gets important, on the other hand as the structural period gets longer and the stiffness of the soil under the structure gets higher soil structure interaction loses its importance. This extreme case can be a base isolated structure founded on a rock site which can be found in the data sets compiled by Stewart et al (1999). For these kinds of structures, it can be observed that there is hardly any soil structure interaction effect.

Chandler and Hutchinson (1987) [3] study the effect of soil-structure interaction on the coupled lateral and torsional responses of asymmetric buildings subjected to a series of historical free-field earthquake base motions. they show that for particular classes of actual buildings the equivalent rigid-base responses are significantly increased for structures founded on medium-stiff soils, and hence the assumption of the major building codes that a conservative estimate of response is obtained by considering the structure to be fixed rigidly at its base is shown to be inconsistent with the presented dynamic results. It is shown that foundation interaction produces greatest amplification of torsional coupling effects for structures subjected to a particular class of European strong-motion earthquake records, identified by similarities in their spectral shape, for which the vibrational energy of the ground motion is distributed approximately uniformly over the range of frequencies which are of interest for real structures. They recommend that provision be made in the torsional design procedures of building codes for the increase in the coupled torsional response due to soil-structure interaction as indicated in this study. Such provision should be based on the results of comprehensive parametric studies employing a wide selection of earthquake records and accounting for expected variations in localized soil conditions.

Sikaroudi and Chandler (1992) [4] represented a detailed parametric study on torsional coupling in earthquake-excited asymmetric buildings including the effects of soil-structure interaction. They found that for short and long period structures, torsional provisions based on analyses of rigidly based buildings also suffice for those supported on flexible foundations. However, for intermediate height buildings with moderate or large eccentricity, increased torsional loadings must be specified to account conservatively for the accentuation of the combined lateral-torsional response for such structures when supported on moderately flexible and very flexible foundations. Some recommendations for implementing such provisions in building codes have been outlined.

Chang et al. (2008) [8] extract the dynamic parameters of an irregular building superstructure considering both torsional coupling (TC) and soil–structure interaction (SSI) effects. They show that the decrease in value of the modal frequencies will be overestimated if the SSI effects are neglected.

The behavior of piles has been studied extensively using both laboratory tests and theoretical studies. A comprehensive review of such research can be found in Stewart et al., (1994)[9]. Both the finite difference and finite element methods have been used in the analysis of soil pile interaction. In presence of single piles, the system is usually analyzed as a Winkler foundation in which the soil is represented by either elastic springs (Broms et al. (1964b)) [6] or a series of nonlinear springs (Byrne et al. (1984))[7]

Ghosh and Masabhushi (2000) [10] used a dynamic centrifuge test on layered soils to trace the transmission of the acceleration traces through the layered soil. They show that in general there was larger amplification in soil of higher relative density and lower pore pressure generation. But the structural response is greatly influenced by the layering and a localized hidden soft patch in a dense soil can be dangerous if it is not detected in routine site tests and the shear force attracted by the building base can be 1.5 times more than what it would have been designed for.

El Ganainy and El Naggar (2009) [14] conclude the following conclusions:

(1) The proposed assemblage of a moment-rotation hinge, shear hinge connected in series with an elastic frame member can simulate the rocking and horizontal responses of shallow foundations under cyclic loading with good accuracy.

(2) It is important to accurately simulate the soil squeeze out phenomenon when analyzing the response of shallow foundations subjected to cyclic rocking action. It affects the amount of hysteretic damping resulting from the moment-rotation response.

The effect of this phenomenon can be included in the model by assigning an appropriate energy degradation factor. More comparisons with experimental results are needed to quantify the variation of this factor with different parameters involved in the footing model

The designer must ensure that the magnitude of such deformations would not be structurally or operationally detrimental. Although this philosophy has been applied to the design of earth dams and gravity retaining walls, its practical significance for foundations might be somewhat limited in view of the large values of the coefficient of friction at soil–footing interface and the passive−type resistance often enjoyed by embedded foundations.

Separation and uplifting of the foundation from the soil would happen when the seismic overturning moment tends to produce net tensile stresses at the edges of the foundation. The ensuing rocking oscillations in which uplifting takes place involve primarily geometric nonlinearities, if the soil is competent enough. There is no detriment to the vertical load carrying capacity and the consequences in terms of induced vertical settlements may be minor. Moreover, in many cases, footing uplifting is beneficial for the response of the superstructure, as it helps reduce the ductility demands on columns.

Housner (1963) [13] and many others have reported that the satisfactory response of some slender structures in strong shaking can only be attributed to foundation rocking. Deliberately designing a bridge foundation to uplift in rocking has been proposed as an effective seismic isolation method. Moreover, even with very slender and relatively rigid structures, uplifting would not lead to overturning except in rather extreme cases of little concern to the engineer. In soft and moderately-soft soils much of what was said above is still valid, but inelastic action in the soil is now unavoidable under the supporting edge of the uplifting footing in rocking. At the extreme, inelastic deformations in the soil take the form of mobilization of failure mechanisms, as discussed below.

Martin and Lam (2000) [12] illustrate with an example of a hypothetical structure containing a shear wall connected with a frame how dramatically different are the results of analyses in which inelastic action in the soil is considered or is ignored. With inelastic action (including uplifting) the shear wall “sheds” some of its load onto the columns of the frame, which must then be properly reinforced; the opposite is true when linear soil foundation behaviour is assumed. Thus, computing the consequences of “plastic hinging” in shallow foundation analysis may be a necessity.

Baidya [15] conclude that shallow foundations are often of a form that is highly vulnerable to damage from differential horizontal and vertical ground movements during earthquakes. It is therefore good practice even in quite low structure, especially those founded on soft soils, to provide ties between column pads. In the absence of a more realistic method an arbitrary design criterion or such ties is to make them capable of carrying compression and tension loads equal to 10 percent of the maximum vertical load in adjacent columns. However, it may be possible to resist some or all of these horizontal forces by passive action of the soil, particularly for light buildings. The designer may also have a choice between providing the tie action at the bottom floor level (in tie beams or in the slab) or at some other position in relation to the foundations.

2. SOIL BEHAVIOR UNDER CYCLIC LOADING

The effect of earthquake loads on a soil element can be represented by a complex shear stress time history □(t), acting after a previous loading history. Depending on the level of the considered earthquake motion and the dynamic properties of the soil-structure system, the soil shear strain level induced by the seismic event can vary. Consequently, models of different complexity should characterize the soil. Typical gross distinctions can be made between soil behavior at pre-failure and at failure conditions. In the first case, further distinctions are made among the so-called «small-strain region», the «medium strain region» and the «large strain region». Distinction can be easily understood by considering the schematic soil behavior as reported in Figure 1, which shows typical relationships existing between shear stiffness or damping ratio and the shear strain level. At small strains, soil stiffness and damping ratio attained their maximum and minimum values, respectively.

Soil response can be adequately represented by a linear model. At medium strains, soil shows a clear nonlinear behaviour but the response under cyclic loading is stable (i.e. no plastic volumetric strains or pore water pressure is detected). In this strain range soil behaviour can be represented by linearly equivalent models. Finally, at large strains shear-volumetric coupling is apparent and the effect of the number of cyclic loadings cannot be neglected. In this case, elastoplastic effective stress models could be opportunely used to simulate soil behaviour. Several parameters affect both initial shear strain and damping ratio and their strain dependency. (D'Onofrio and Silvestri (2001) [24]

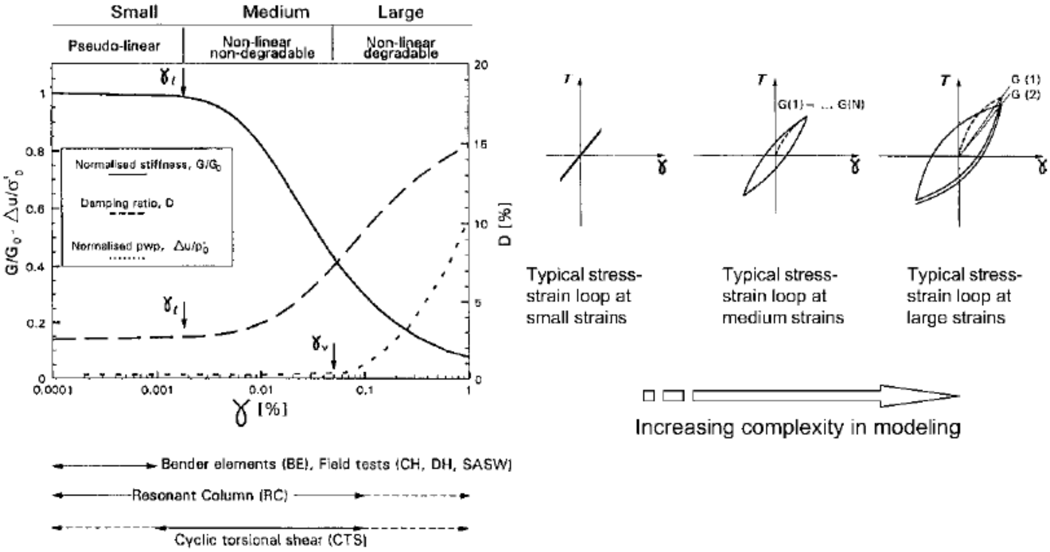


Figure 1: Typical variation of the soil response under cyclic loading at increasing strain level in terms of shear modulus and damping and stress-strain loops.

3. DESCRIPTION MODELING OF BUILDINGS

To study the effect of soil structure interaction on the building subjected to earthquake three models will be exam. A three stories, six stories, and twelve stories buildings will subject to a 0.25g earthquake in X (from left to right) , Y(from north to south) , and Z (from down to up) directions.

Building is 12x12 m plan and 3m story height, each story contains a beams (frame element) 25x70 cm 4 m spacing in both directions (X, and Y directions) and height of the story is 3.0m, slab thickness 14 cm (shell element) and column 65x65cm (the buildings are symmetrical in X, and Y direction to avoid the effect of torsion to give pure effect of the soil structure interaction only).

Different kinds of foundation will be used, fixed base for control case with fixed support and so the effect of the earthquake will affect purely shaking the superstructure only and the SSI with no effect on the buildings. The second kinds of foundation is the isolated foundation tied together by a tie beam in level of the foundation in both directions (ISO tie), (the exterior footing with thickness 1.0m 2.00x2.00m and the interior footings with thickness 1.20m and 2.40x2.40m), and a raft foundation with projection 1 m around the buildings (raft). Two types of levels will be checked at 2.5 m from ground level (-2.5), and 4 m from ground level with reinforced concrete retaining walls (-4). All displacements and forces found in the different elements of different models are for time history load only not for the combination loads dead and time history.

Figure (3) demonstrates the components of the building that under consideration. As shown in figure the building is symmetry in all direction in plan shape and in stiffness of the elements (column and beams) to avoid the effect of the generated shear due to torsion unsymmetrical.

Table 1 describes the different types of cases of bases that will be studied; the symbols will be used to brief the names of the five cases of bases.

Table 1: The brief and description of the studied model of buildings

symbol	brief	Description
Case (1)	FB	Fixed base
Case (2)	ISO tie (-2.5)	Isolated square footing with ties in the 2.5m from ground level
Case (3)	ISO tie (-4)	Isolated square footing without ties in the 4.0m from ground level
Case (4)	Raft (-2.5)	Mat foundation thickness 1.00m at 2.5m from ground level
Case (5)	Raft (-4)	Mat foundation thickness 1.00m at 4.0m from ground level

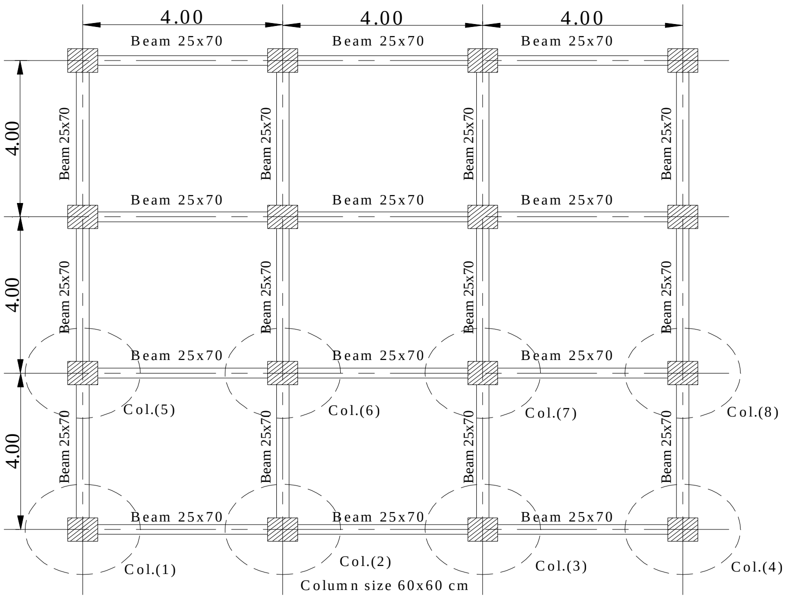


Figure (2): typical plan of the 3, 6, and 12 stories model building

4. MODELING OF SOIL – STRUCTURE INTERACTION

The soil contact with the different elements of the building under ground level (foundations, ties, and column) based on springs and dashpots was thought to provide sufficient accuracy for the application at hand and, thus, was the approach adopted in this study. The coefficients of the springs and dashpots were calculated using the expressions described and recommended by Newmark and Rosenblueth (1971)[23].

In Table (2), *G* is the small strain shear modulus of the soil, *r* represents the plate radius, and ν and ρ are the Poisson’s ratio and mass density of the soil, respectively. When a noncircular foundation is considered, an equivalent radius must be defined in order to use these equations. In the present study, the equivalent radius was obtained by equating the area of a circular plate to the square plate and solving for *r*. These constants were introduced to the spring-dashpot model developed in SAP2000 and in MATLAB. These coefficient is represented the medium soil (as an Egyptian soil).

Table (2): Values of stiffness and damping coefficient of soil parameters

DIRECTION	STIFFNESS	DAMPING	MASS
Vertical	$K = \frac{4Gr}{1-\nu}$	$1.79\sqrt{K\rho r^3}$	$1.50\rho r^3$
Horizontal	$18.2Gr\frac{(1-\nu^2)}{(2-\nu)^2}$	$1.08\sqrt{K\rho r^3}$	$0.28\rho r^3$

r = Plate radius; *G* = shear modulus; ν = Poisson's ratio; ρ = mass density

Source: Adapted from "Fundamentals of Earthquake Engineering, by Newmark and Rosenblueth, Prentice-Hall, 1971[30]

The SAP2000 program has the ability to solve the multi-support, soil-structure interaction problems using this approach. At the same time, selective nonlinear behavior of the structure can be considered.

The springs and dashpots were used in x, and y direction with a small values of confessions that given for the properties of the soil in horizontal direction, but the properties of the soil is different in z direction that the values of confessions of springs and dashpots were big that that given in horizontal direction

Figure (2) illustrates the brief discussion of the node connection of the building and soil interaction. It can be seen the springs in the three directions and dashpots (X, Y, and Z directions).

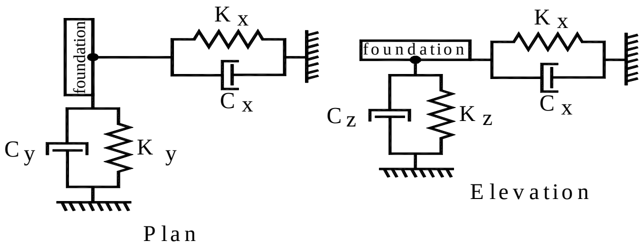


Figure (3): Typical soil structure interaction joint (springs and Dashpots in X, Y, and Z directions)

5. INPUT LOADINGS

A time history analysis was carried out using El Centro earthquake and ten models are excited by three orthogonal components of seismic motion which has maximum acceleration 0.25g (Figure (4))

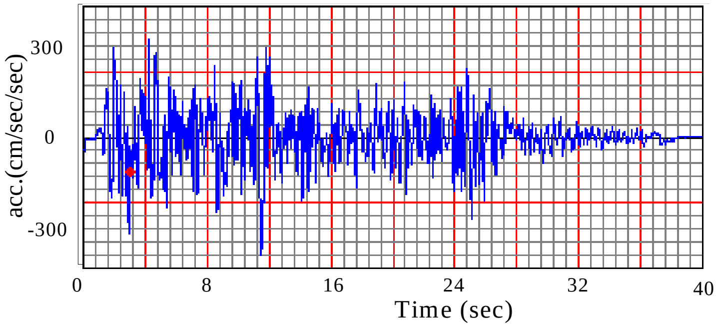


Figure (4): El Centrio model vibration

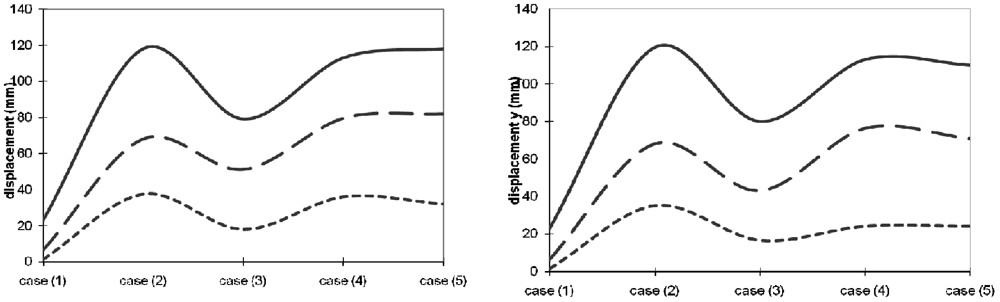
6. RESULTS AND DISCUSSION

6.1. Time History of displacements

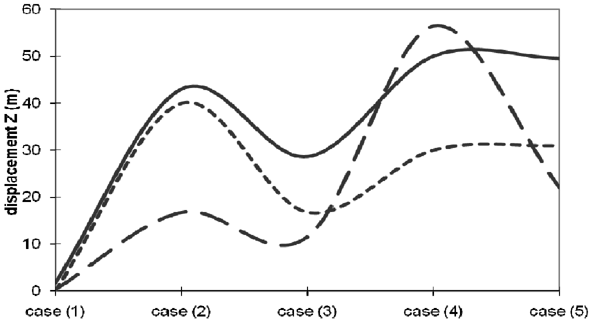
Figure (5) describes the top displacement at level of different building height (3, 6, and 12 stories) with different types of bases. The control case was the FB case to show the effect of soil structure interaction. Figure (5-i) shows the displacement in X-direction for different building heights with different types of bases, it can be seen in the case of three stories the displacement in ISO tie (-2.5), and ISO tie (-4) are equal with respect to the FB case. For the ISO tie (-2.5) and raft (-2.5) the displacements in x direction equal 20 times the displacement in case of FB. The displacements equal to twice times the FB in case of ISO tie (-2.5), and raft (-4) bases. For the displacement in Y-direction the relation between displacement in different cases of base and FB are the same like displacement in X-direction. The displacements in X, and Y direction for the different cases of bases in the three stories model equal half values in the case of six stories cases in the same cases of bases, but in case of twelve stories model the displacements in X and Y directions equal to nearly 1.5 times the displacement in six stories model.

Figure (5-ii) shows the displacement in Y-direction for different building heights with different types of bases, it can be seen in the case of twelve stories. For the ISO tie (-2.5), raft (-2.5), and raft (-4) the displacements in y direction equal 5 times the displacement in case of FB. The closet case in displacement with FB case was ISO tie (-4) (nearly 3 times the displacement of FB case). In case of six stories model the displacements in X and Y directions equal to nearly 10 times the displacement in FB case. The displacements equal to 20 times the FB case in both directions (X,Y) in three stories building model, but the closest case is to FB case is ISO tie (-4) and the maximum case of displacement with respect to FB case was ISO tie (-2.5).

Figure (5-iii) illustrates the displacement in Z direction of the different model in different cases of bases. For twelve stories building the maximum displacement in Z direction equal to nearly 28 times the displacement in case of FB in the case of raft (-2.5) and raft (-4), but the minimum displacement was recorded in case of ISO tie (-4) base (nearly 11 times the displacement in FB case). The maximum displacement in z direction was recorded for six stories building (more than 200 times the FB case), but the minimum case was ISO tie (-4) (nearly 38 times the FB displacement). For three stories building the displacement in Z direction was more than 600 times the displacement in the FB case.



i) Displacement in X-direction ii) Displacement in Y-direction



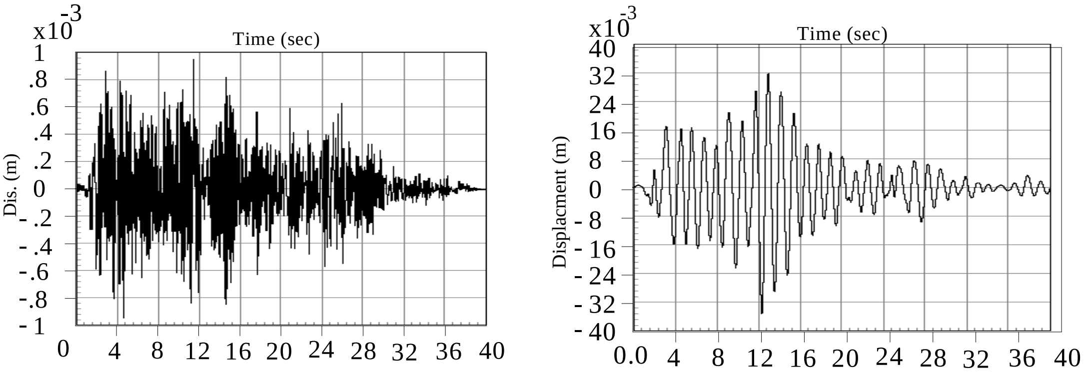
iii) Displacement in Z-direction

⋯⋯ three stories - - - six stories ▬ twelve stories

Figure (5): Top displacement in X, Y, and Z direction for different types of bases

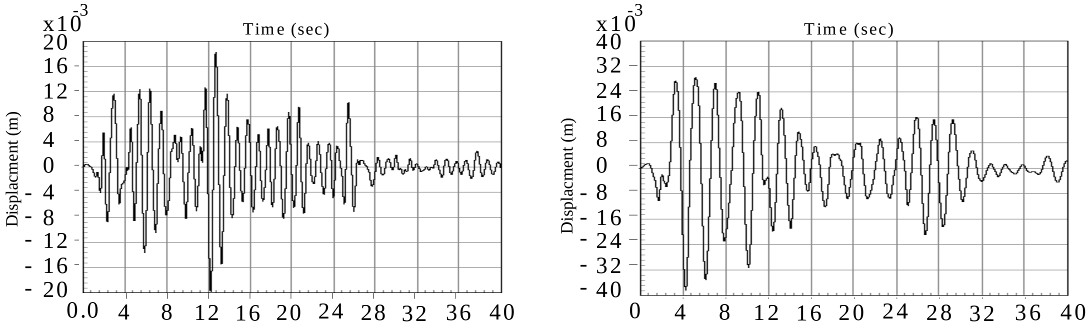
Examples of time history response of the top displacements for the two models (3-stories and twelve stories) in comparison with the original case (fixed base) are shown in Fig. (6-13). It can be seen that separation of the soil (fixed base condition) under large dynamic load, leading to amplification of high frequencies mode of building vibration. From the superstructures top displacements time history in 3-stories model, it can be clarified that the soil structure interaction effects in reducing the top displacement response and the top displacements time history is characterized by large peak displacement which is associated with short duration impulse of high frequency like spikes. The soil structure interaction would significantly increase the displacements for three models. The contribution of soil structure interaction to top displacement can be comparable to the height of building whereas this effect is detrimental with the fixed base conditions.

From top displacement time history stories models 4 and 5 as shown in Fig. (10-13) it can be seen that the soil effects on building response. The top displacement reaches 10cm after 10sec. for consideration the soil structure interaction and this effect is ignored for fixed base assumption. The top displacement time history for case 5 (twelve stories with raft -4) show the response nature strong excitation three and four cycles of large displacement response with the amplitude of displacement. The displacement time history for model a (raft (-2.5)) displays slightly attenuate after peak response and the time history high frequency spike.



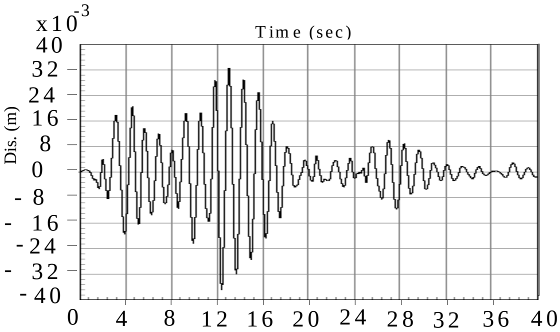
Fixed base

Isolated tie foundation at level-2.5



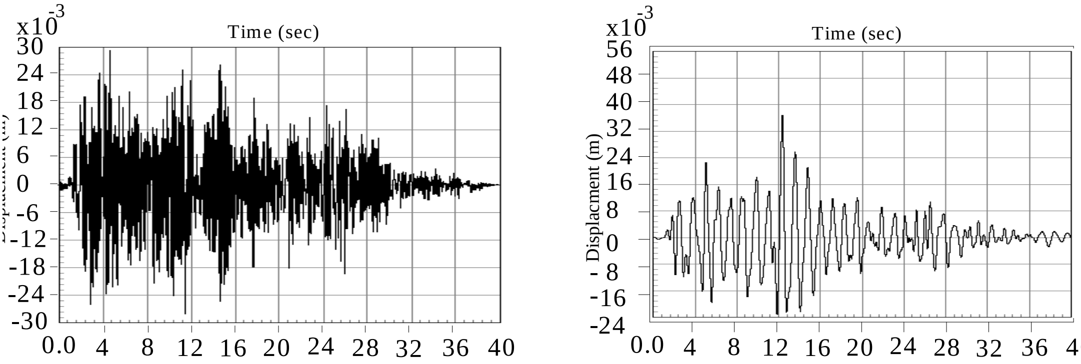
Isolated tie foundation at level -4 (retaining wall model)

Raft foundation at level-2.5

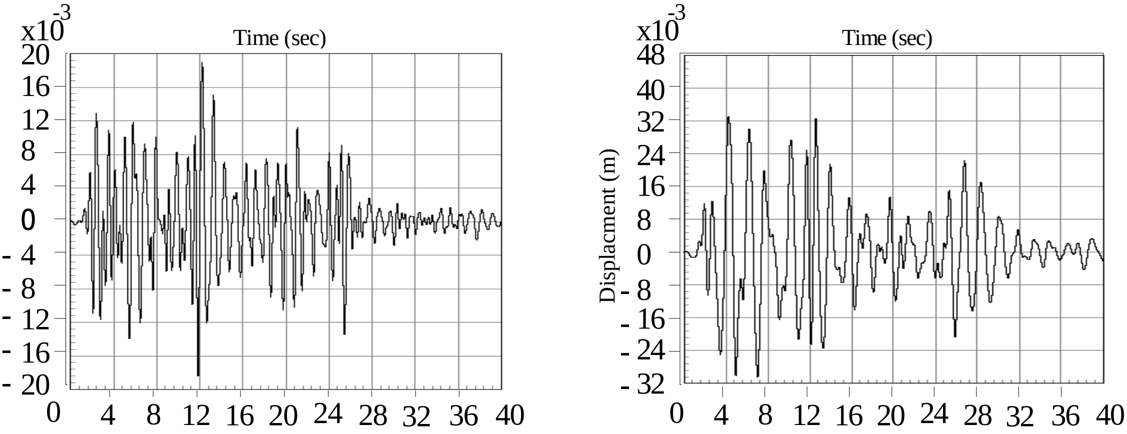


Raft foundation at level-4

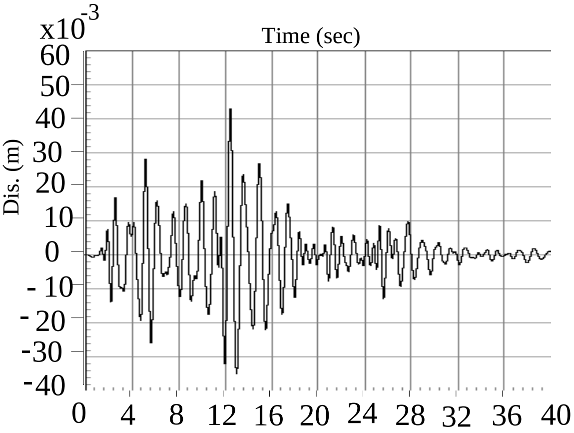
Figure (6): Time History of Top displacement X-direction 3 stories



Fixed base   Isolated tie foundation at level-2.5

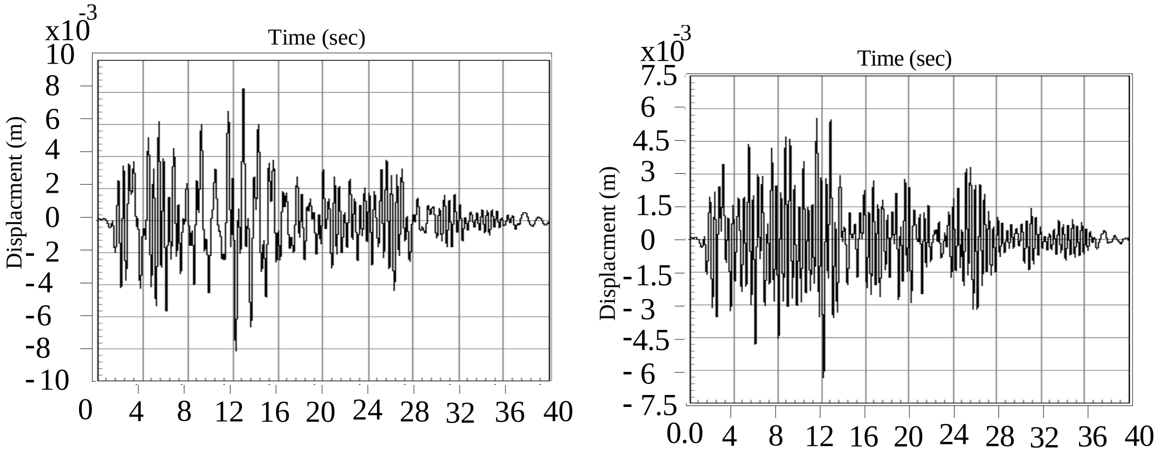


Isolated tie foundation at level -4 (retaining wall model)   Raft foundation at level-2.5

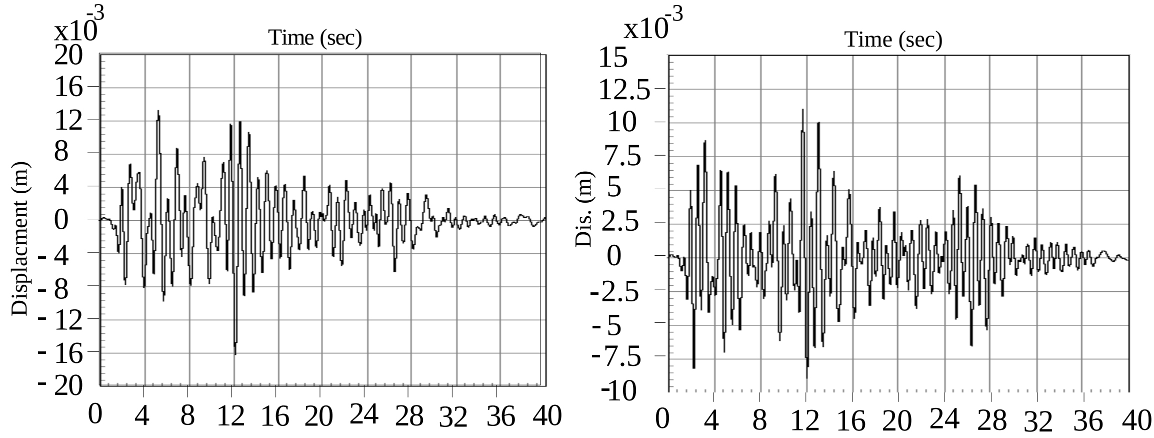


Raft foundation at level-4

Figure (7): Time History of Top displacment Z-direction -3 stories

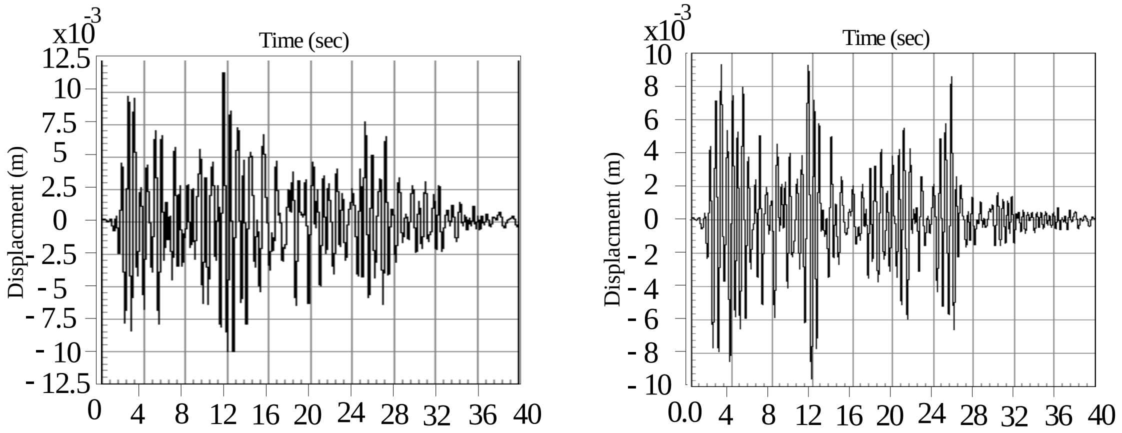


Isolated tie foundation at level-2.5 Isolated tie foundation at level -4 (retaining wall model)

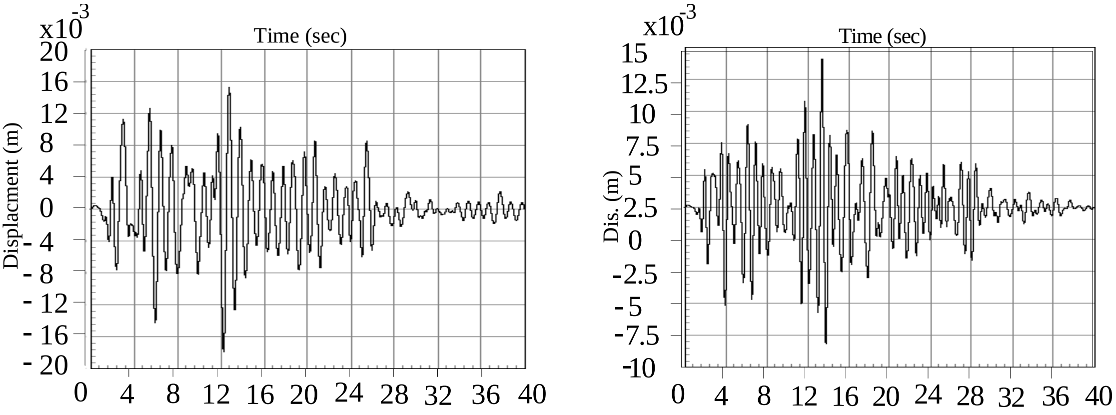


Raft foundation at level-2.5 Raft foundation at level-4

Figure (8): Time History of foundation displacment X-direction -3 stories



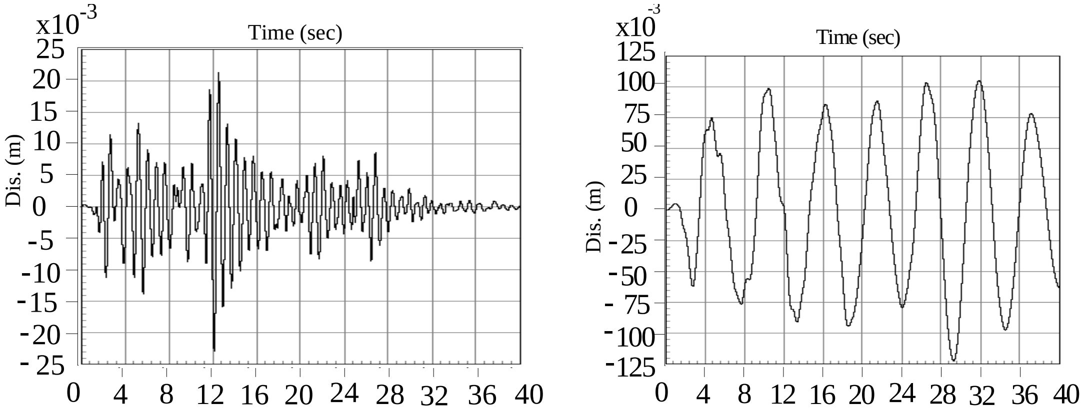
Isolated tie foundation at level-2.5 Isolated tie foundation at level -4 (retaining wall model)



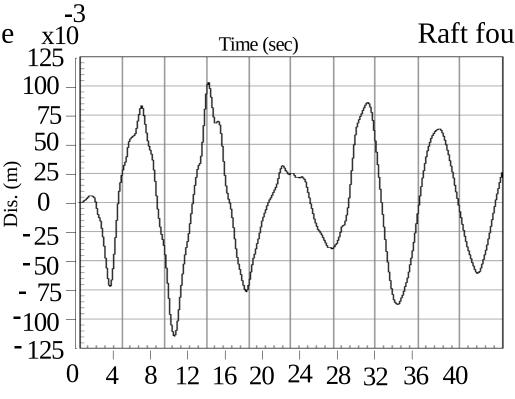
Raft foundation at level-2.5 Raft foundation at level-4

Figure (9): Time History of foundation displacment Z-direction -3 stories

Time history response of top displacement in case (3) of isolated base foundation with retaining wall round the building perimeter is shown in Fig. 6 it is illustrated from fig. 6 that the retaining wall round the building provides pronounced reduction in top displacement response compared to the other cases. It can be concluded that the retaining wall is effective in controlling and improving the building performance.

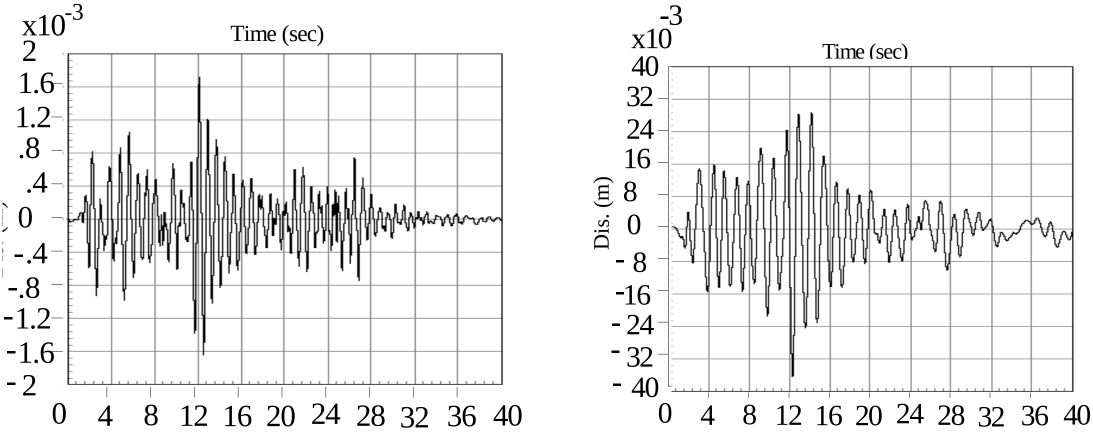


Fixed base Raft foundation at level-4

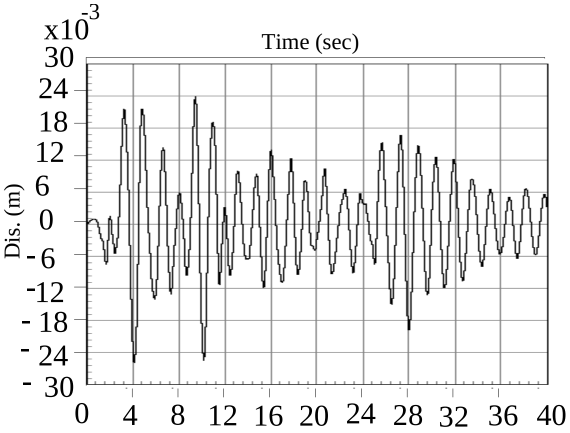


Raft foundation at level-2.5

Figure (10): Time History of top displacment X-direction -12 stories

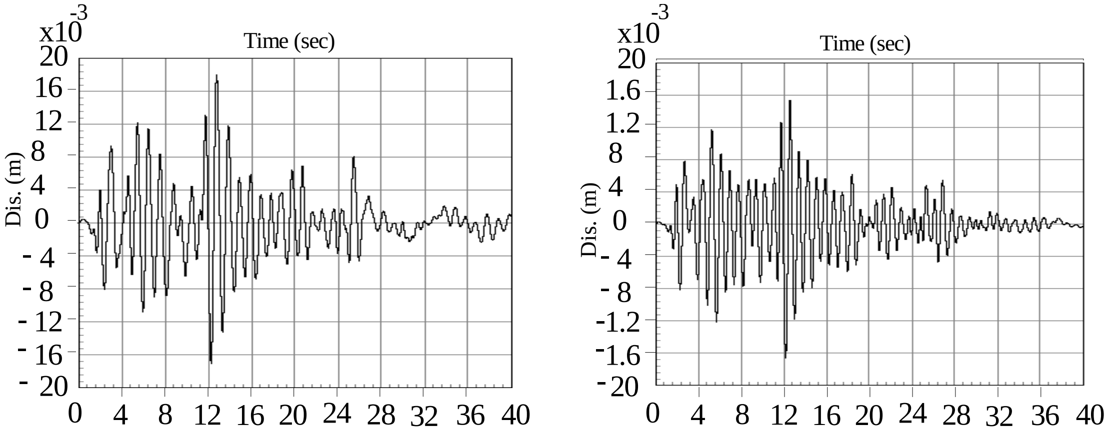


Fixed base Raft foundation at level-4



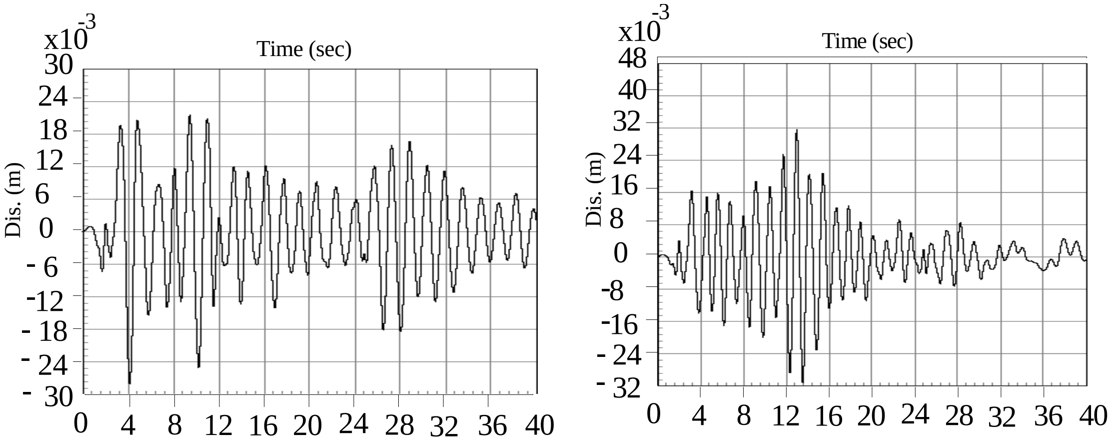
Raft foundation at level-2.5

Figure (11): Time History of top displacment Z-direction -12 stories



Raft foundation at level-2.5 Raft foundation at level-4

Figure (12): Time History of foundation displacment X-direction -12 stories



Raft foundation at level-2.5

Raft foundation at level-4

Figure (13): Time History of foundation displacment Z-direction -12 stories

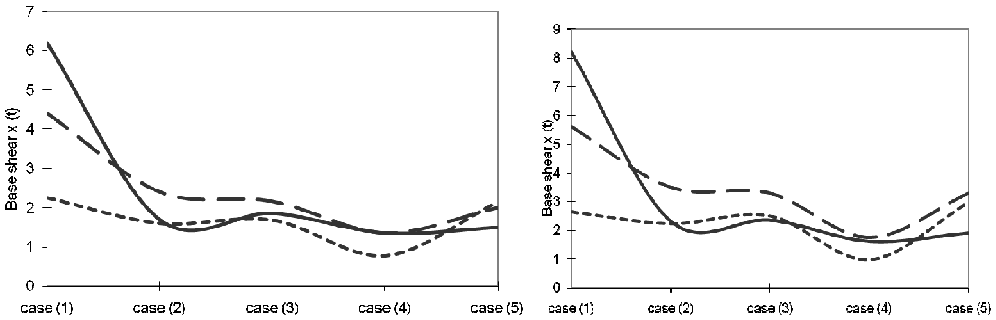
6.2. Time History of Base Shear

Figure (14) and figure (15) show the base shear in X and Y directions for column 1 to 8 in different heights models and different bases cases.

For column (1 to 8) base for different cases of bases shear in X and Y directions nearly equal to 1/3 times the base shear in FB case in twelve stories building model, but the most minimum base shear with respect to FB case was the raft (-2.5) cases for columns (6), and (7) (nearly 0.125 times in base shear in X direction and 0.167 times in base shear in Y direction).

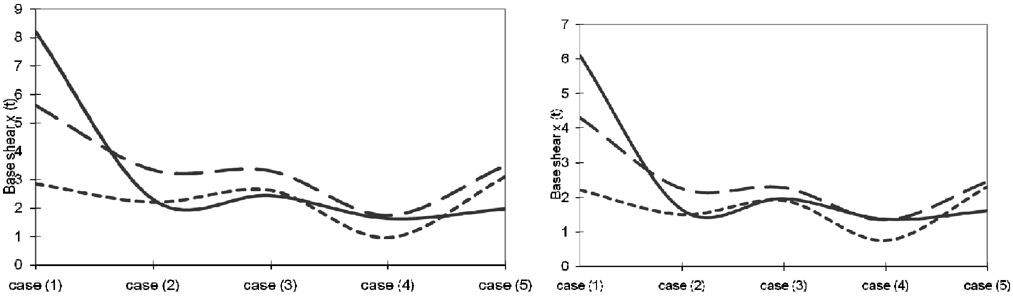
For column (1 to 8) base shear for different cases of bases in Y direction nearly equal to 1/2 times the base shear in FB case in six stories building model, but base shear for different cases of bases in X direction nearly equal to 1/3 times the base shear in FB case. The most minimum base shear with respect to FB case was the case raft (-2.5) cases for columns (1-8), (nearly 0.167 times in base shear in X direction and 0.25 times in base shear in Y direction).

For column (1 to 8) base shear for different cases of bases in Y direction nearly equal to 1/2 times the base shear in FB case in three stories building model, and base shear for different cases of bases in X direction nearly equal to 1/2 times the base shear in FB case. The most minimum base shear with respect to FB case was the case raft (-2.5) cases for columns (1-8), (nearly 0.33 times in base shear in X direction and 0.5 times in base shear in Y direction).



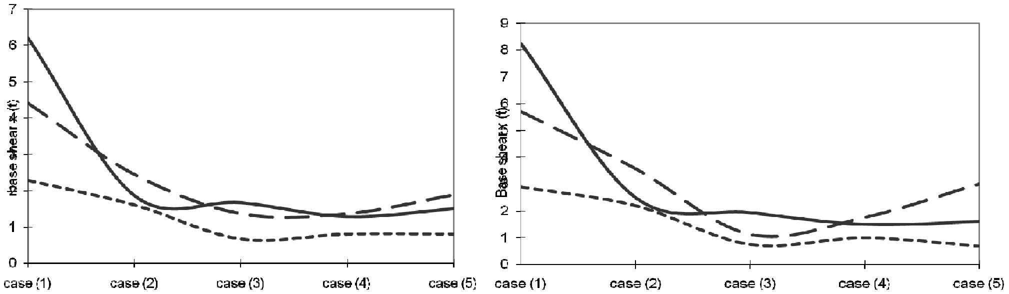
i) Base shear col. (1)

ii) Base shear col.(2)



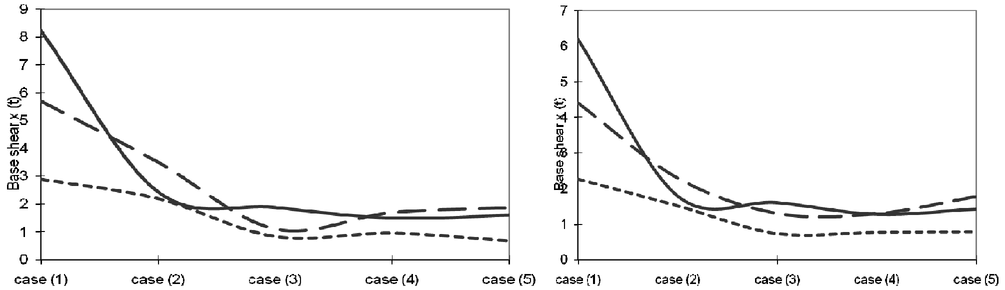
iii) Base shear col.(3)

iv) Base shear col.(4)



v) Base shear col. (5)

vi) Base shear col.(6)

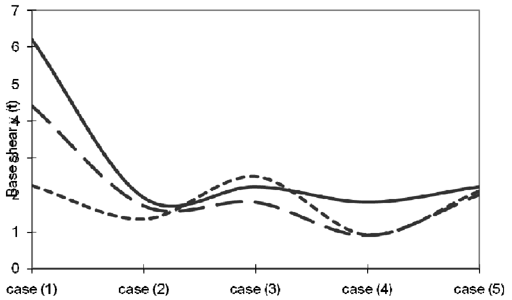


vii) Base shear col.(7)

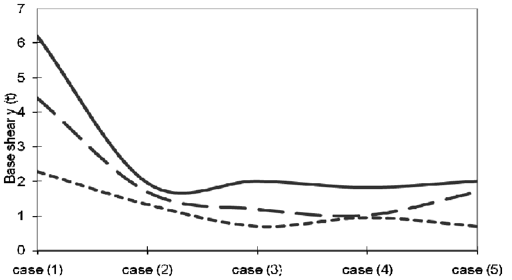
viii) Base shear col.(8)

.... three stories - - - six stories ▬▬ twelve stories

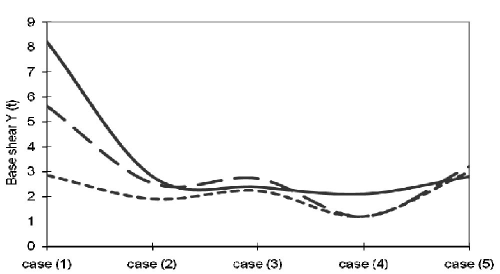
Figure (14): Base shear in X-direction for different elements in three six and twelve stories building



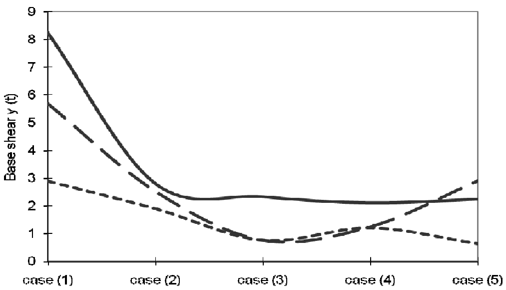
i) Base shear col. (1) ii) Base shear col.(2)



iii) Base shear col.(3) iv) Base shear col.(4)



v) Base shear col. (5) vi) Base shear col.(6)

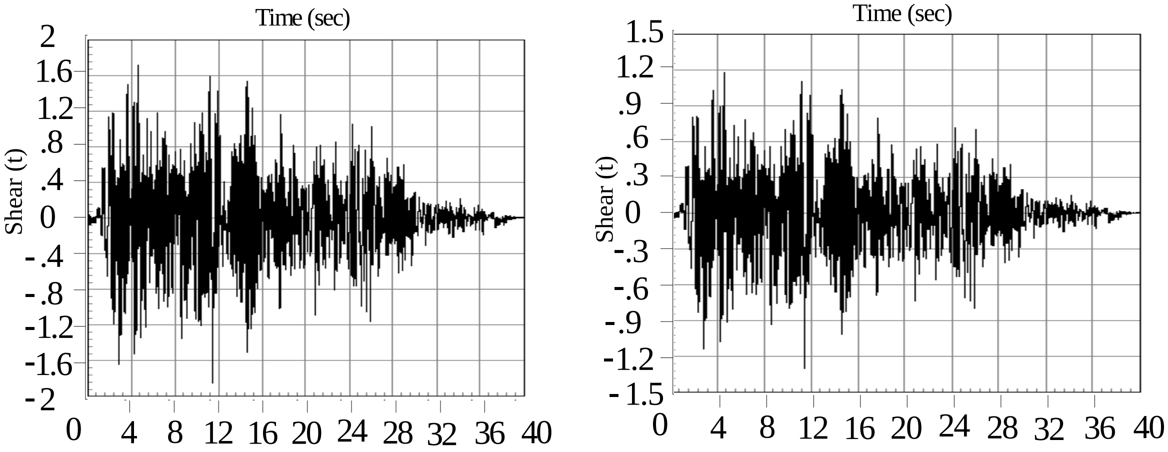


vii) Base shear col.(7) viii) Base shear col.(8)

······· three stories – – – six stories —— twelve stories

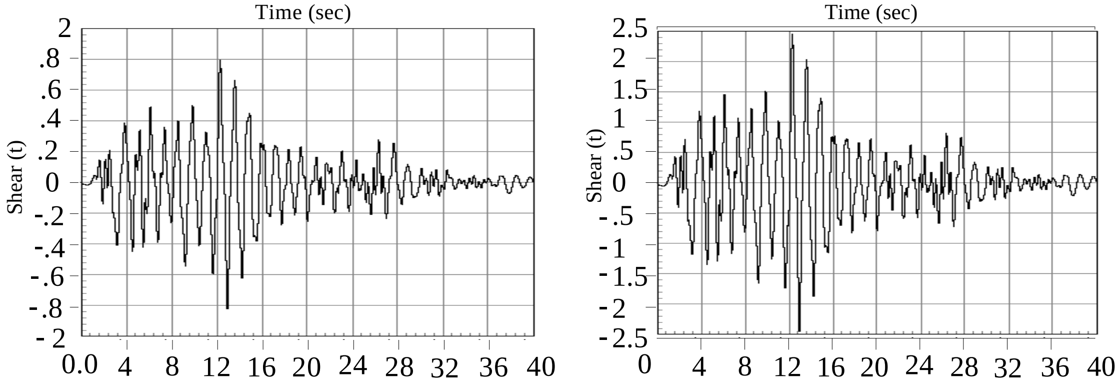
Figure (15): Base shear in Y-direction for different elements in three, six and twelve stories building

The soil structure interaction influence on the building base shear time history study for different cases of base as shown in fig (16-17). It is appeared that the base shear schemes in the case of fixed base shear has high frequency content compared with that of flexible bases. The flexible bases result in decreasing the induced base shears. The contribution of flexible bases in reducing base shears reduces 70% and 30% of that fixed high and short building respectively.



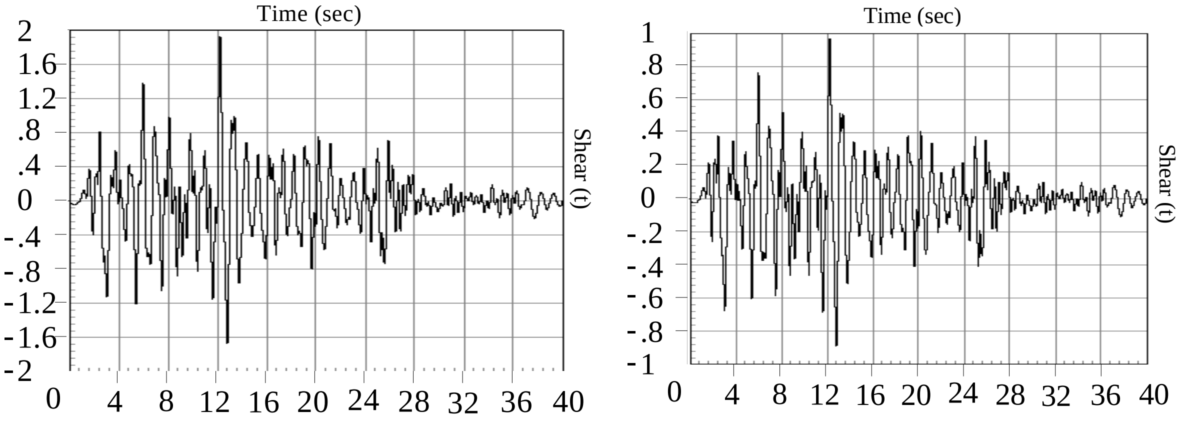
Col (1) Col (6)

Fixed base



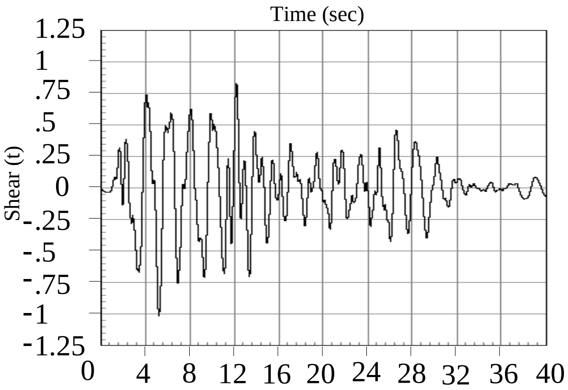
Col (1) Col (6)

Isolated tie foundation at level-2.5

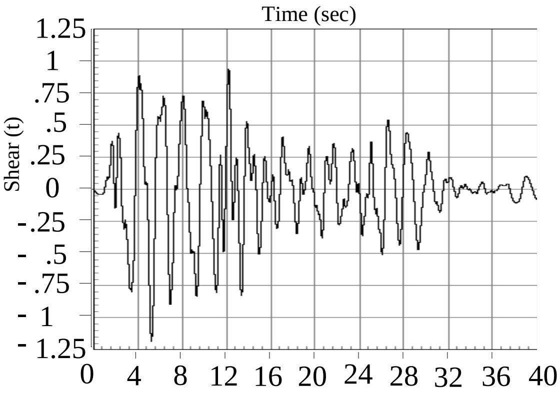


Col (1) Col (6)

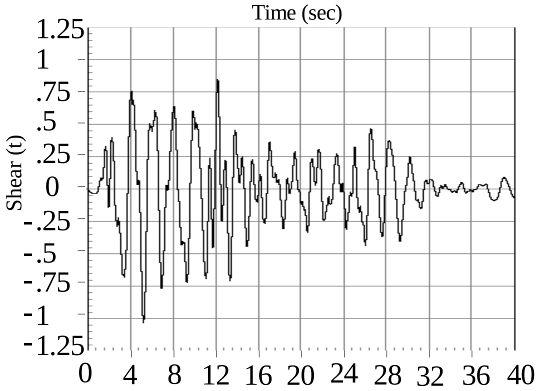
Isolated tie foundation at level -4 (retaining wall model)



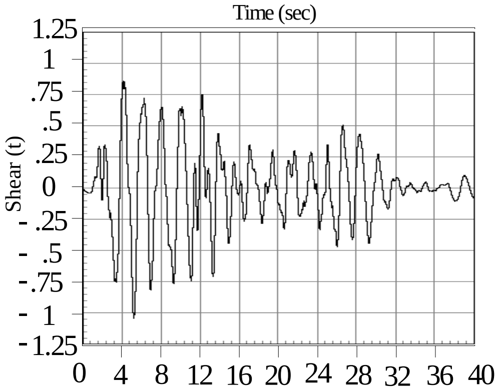
Col (1)



Col (2)

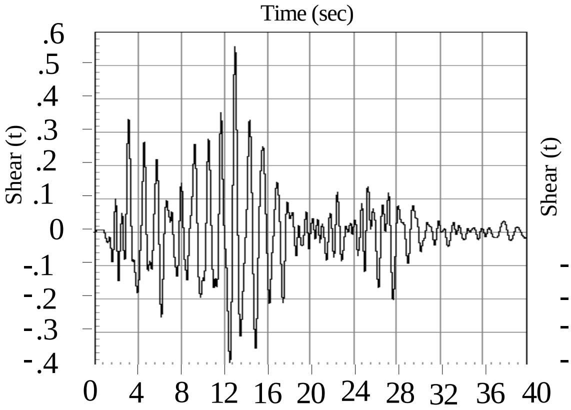


Col (5)

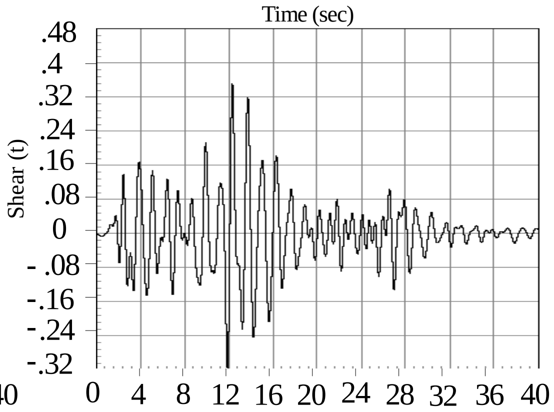


Col (6)

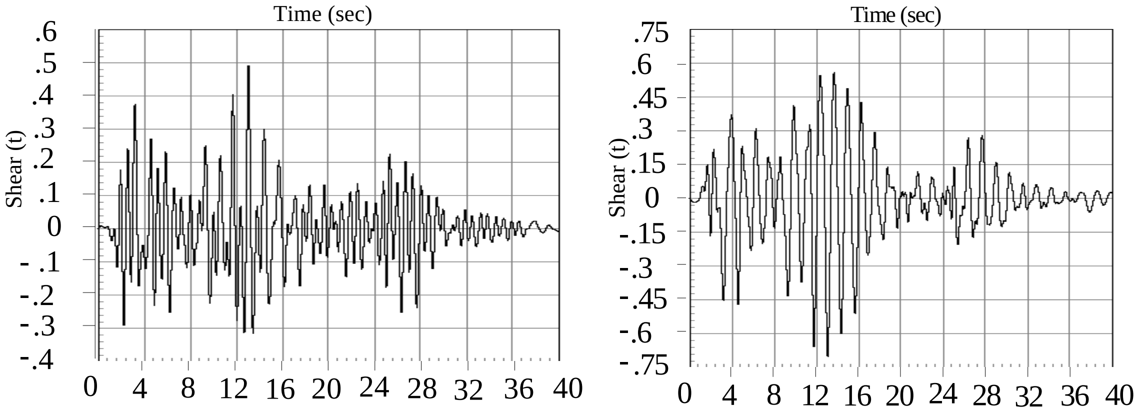
Raft foundation at level-2.5



Col (1)



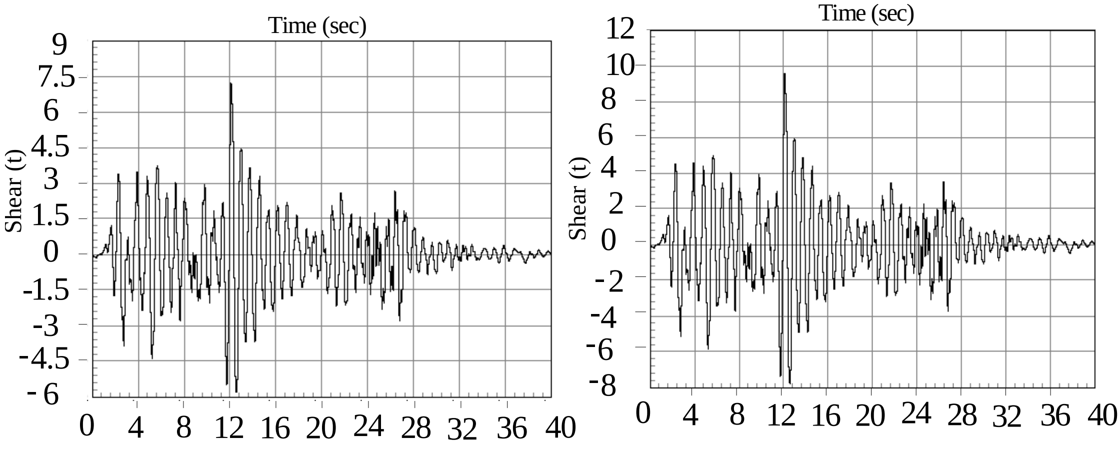
Col (2)



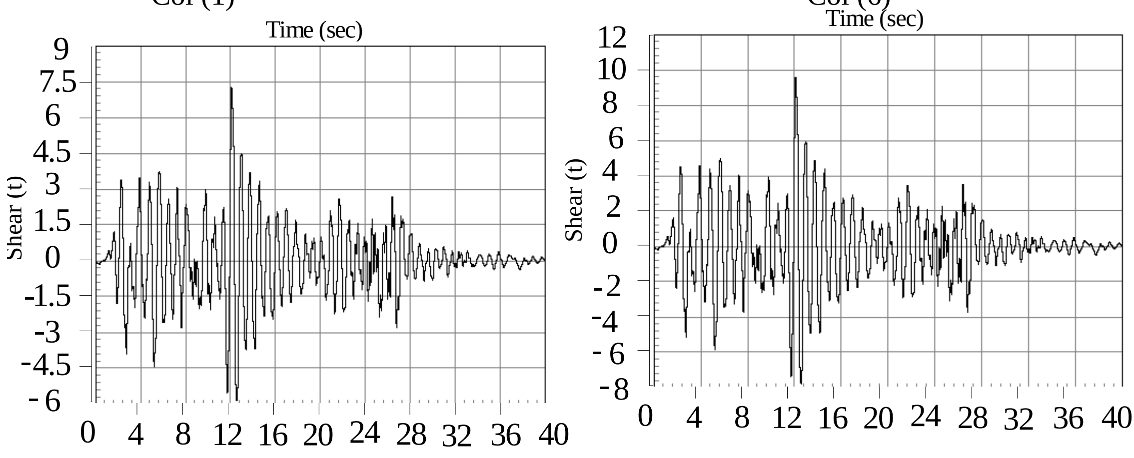
Col (5) Col (6)

Raft foundation at level-4

Figure (16): Time History of Base shear X-direction -3 stories

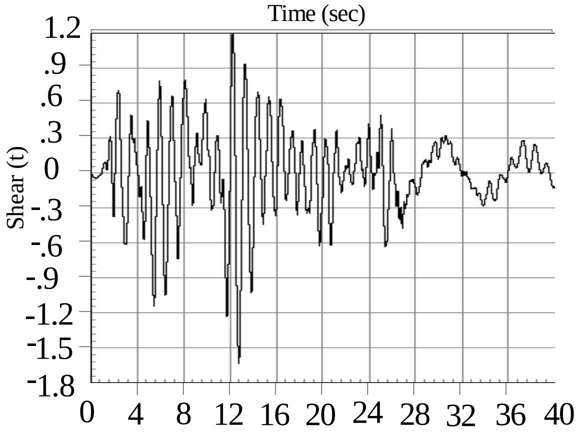


Col (1) Col (6)

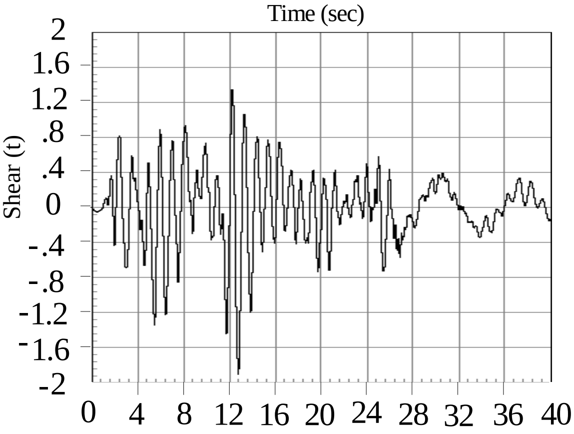


Col (5) Col (6)

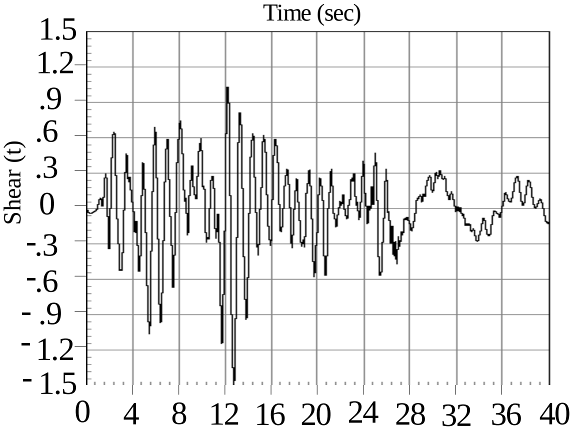
Fixed Base



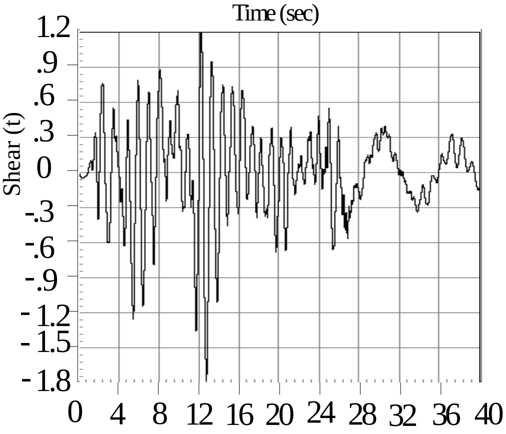
Col (1)



Col (2)

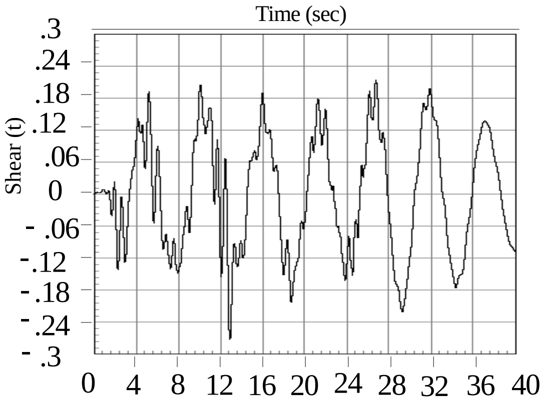


Col (5)

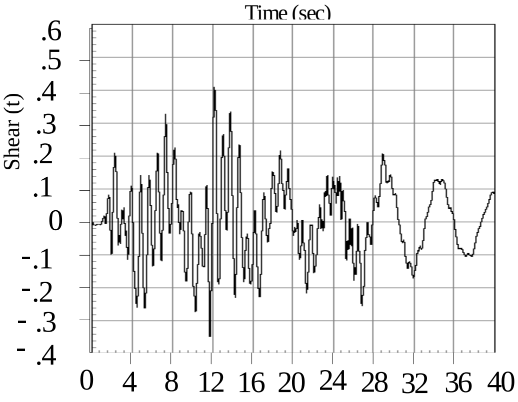


Col (6)

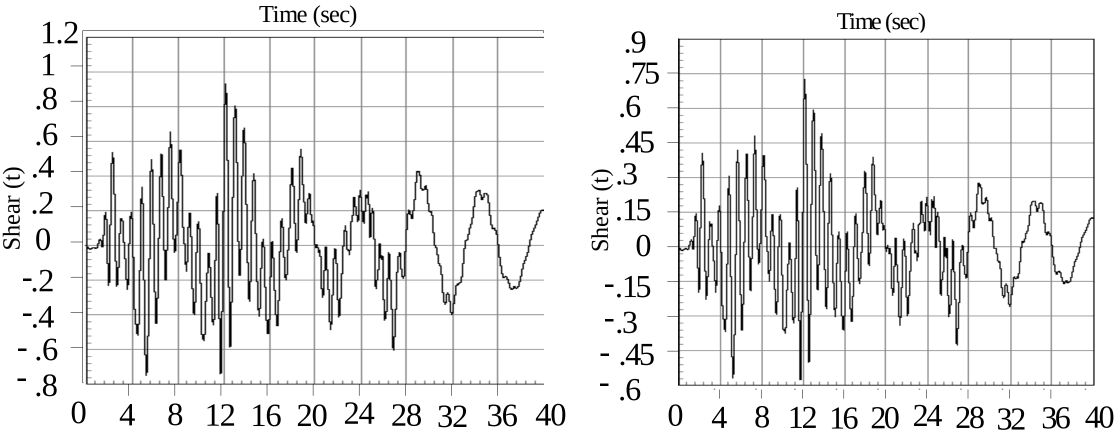
Raft foundation at level (-2.5)



Col (1)



Col (2)



Col (5)

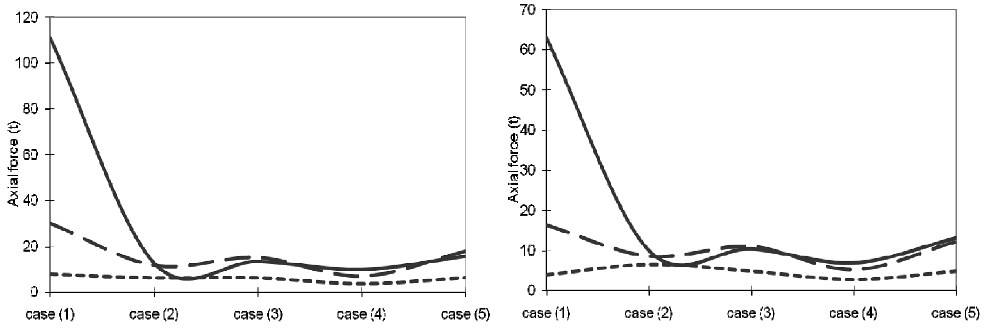
Col (6)

Raft foundation level (-4)

Figure (17): Time History of Base shear X-direction -12 stories

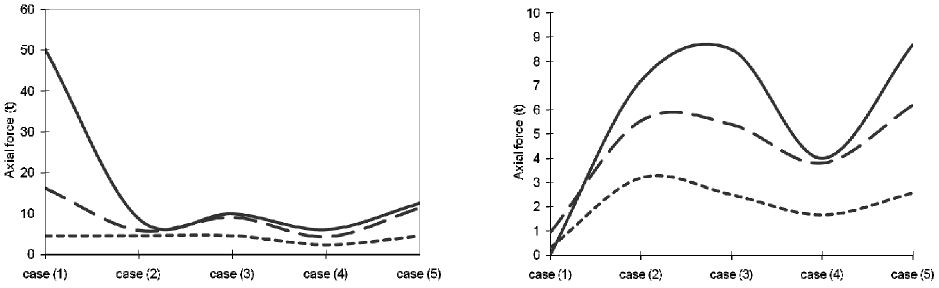
6.3. Time History of Axial Force

Figure (18) shows the axial forces in different element of the different models as a result of time history analysis only in different cases of bases. The axial forces in columns (6-8) in case of FB were equaled to axial forces in cases of different bases. The axial force in columns (1-2-3-5) in different cases of bases equal to 1/2 the axial force in FB case. For column (4) (end corner column) the axial force in different cases of bases equal to nearly 5 times the axial force in FB case for three, six and twelve stories building models. For column (5, and 7) the axial force in different cases of bases equal to nearly 12 times the axial force in FB case for twelve stories building model. In twelve stories building model column (1 – 2 – 3 – 8) recorded a very small value of axial force with respect to FB for all cases of bases (nearly equal to 6 times smaller than its values in different cases of bases).

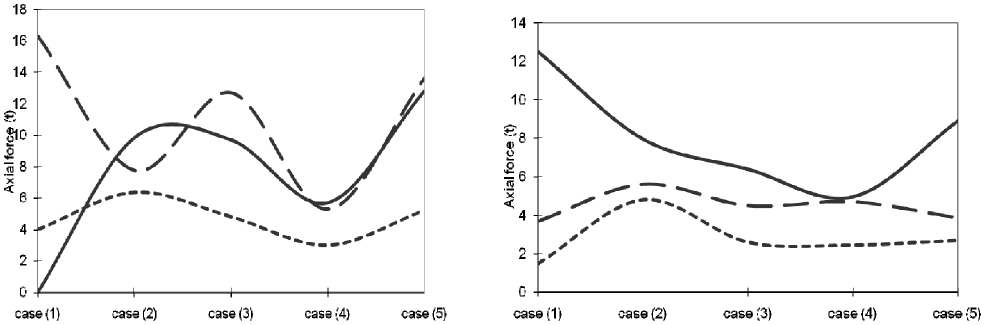


i) Axial force col. (1)

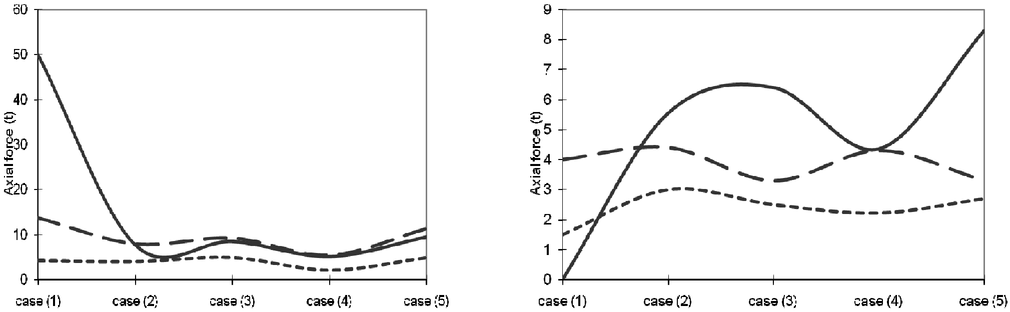
ii) Axial force col.(2)



iii) Axial force col.(3) iv) Axial force col.(4)



v) Axial force col. (5) vi) Axial force col.(6)



vii) Axial force col.(7) viii) Axial force col.(8)

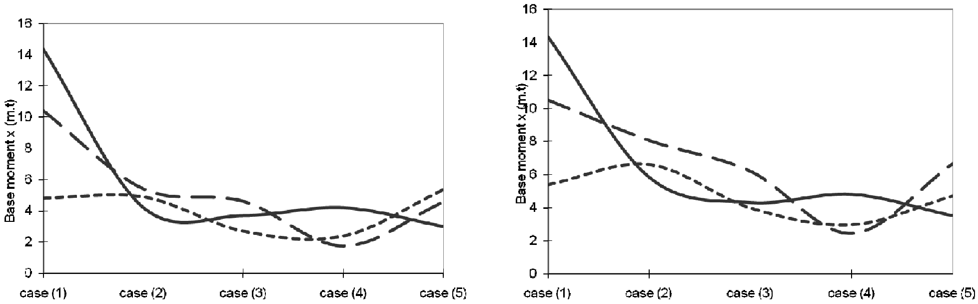
⋯⋯ three stories - - - six stories ▬ twelve stories

Figure (18): Axial force in Z-direction for different elements in three, six and twelve stories building

6.4. Time History of Moments

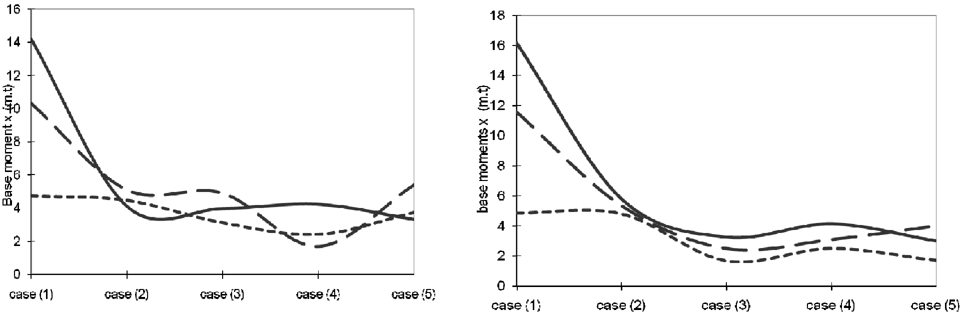
Figure (19) and (20) show the base moments in X and Y direction for 3, 6, and 12 stories building models in different cases of bases. The base moment (X and Y directions) in twelve stories building model for columns (1- 2 – 3 – 4 – 5 – 6 – 7 - 8) in different cases of bases equal to nearly 1/3 times the moment in FB case, but for columns (5 – 6 – 7 – 8) the base moments in cases of bases Raft (-2.5), and Raft (-4) in both direction equal to nearly 1/5 times the base moments of FB case. The base moment (X direction) in six stories building model for columns (1-8) in different cases of bases equal to nearly 1/3 times the moment in FB case, except columns (2), and (3) in cases ISO tie (-4), Raft (-2.5) and Raft (-4) bases in Y direction equal to 1/5 times the base moment in FB case.

In the three stories building model the base moments in X and Y directions are nearly equals for all columns in all cases of bases except for bases ISO tie (-4), Raft (-2.5) and Raft (-4) the base moments equal 1/2 times the FB moment.



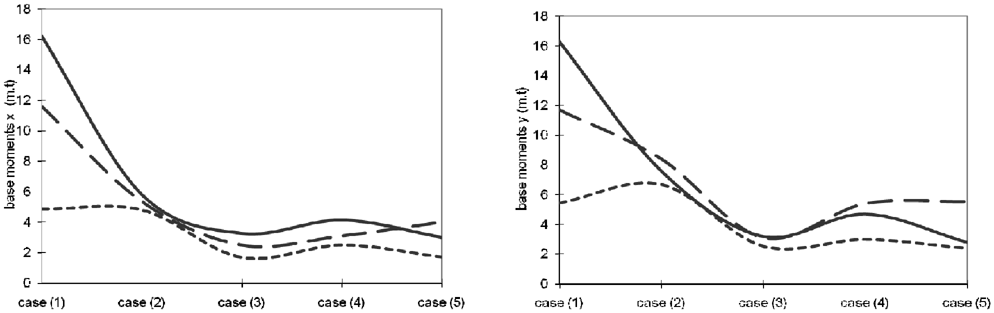
i) Base moment col. (1)

ii) Base moment col.(2)



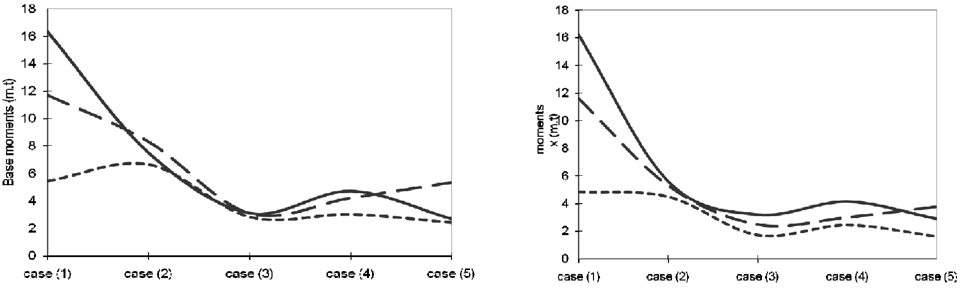
iii) Base moment col. (3)

iv) Base moment col. (4)



v) Base moment col. (5)

vi) Base moment col. (6)

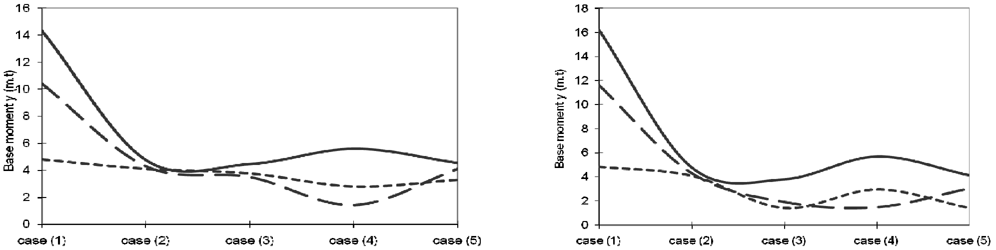


vii) Base moment col.(7)

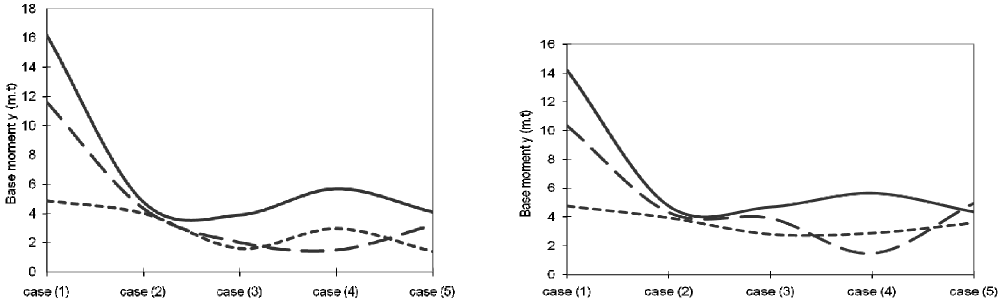
viii) Base moment col.(8)

…… three stories – – – six stories —— twelve stories

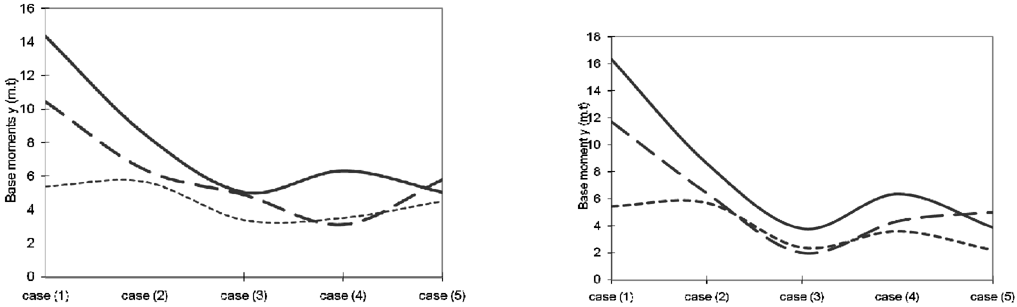
Figure (19): base moment in X-direction for different elements in three, six and twelve stories building



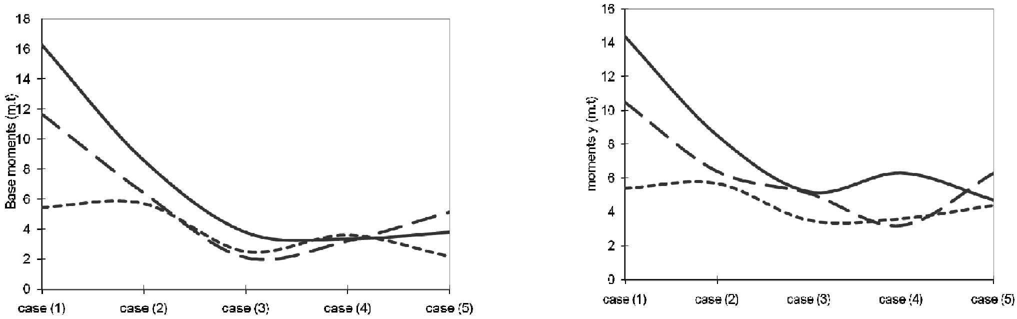
i) Base moment col. (1) ii) Base moment col.(2)



iii) Base moment col.(3) iv) Base moment col.(4)



v) Base moment col. (5) vi) Base moment col. (6)

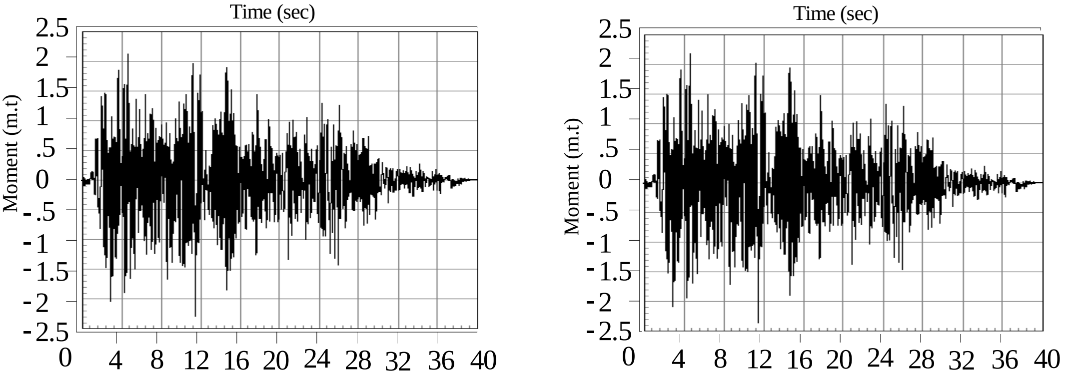


vii) Base moment col. (7) viii) Base moment col. (8)

······· three stories – – – six stories ―― twelve stories

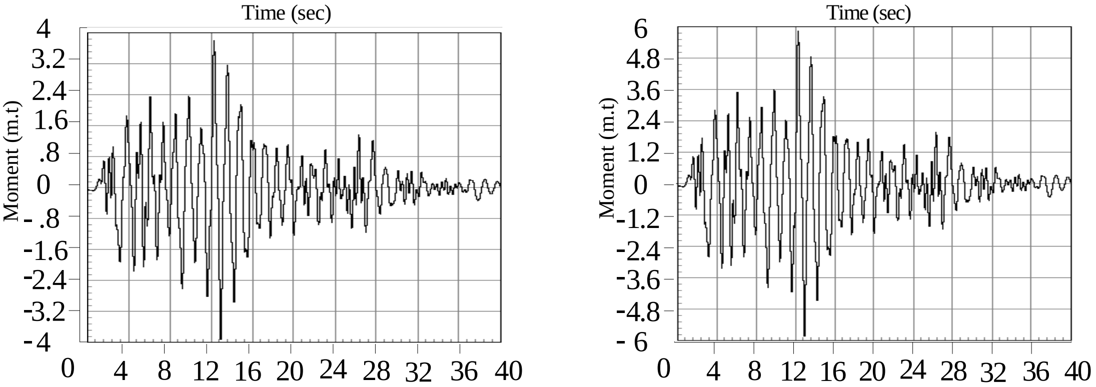
Figure (20): base moment in Y-direction for different elements in three, six and twelve stories building

The soil structure interaction effect on the generated base column moments can be understood from the time histories schemes as shown in fig. (21-22). the current results prove again of the effectiveness of the soil – structure interaction on the column base moment dynamic response. It is seen that the reduction generated in base column moment of high building has tendency to be larger as the building height increases compared with the fixed base buildings.



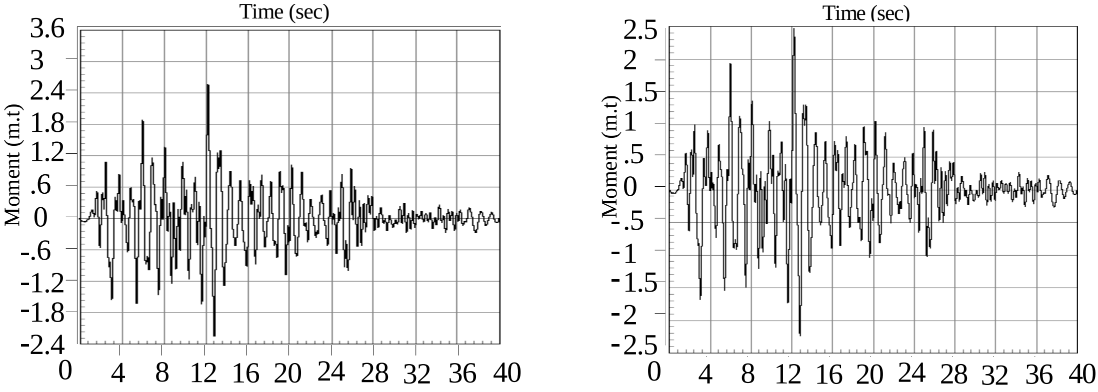
Col (1) Col (6)

Fixed base



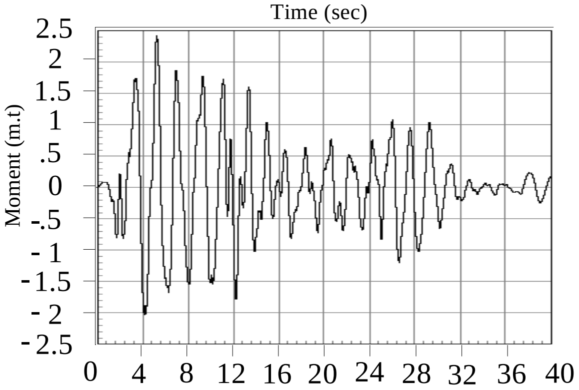
Col (1) Col (6)

Isolated tie foundation at level-2.5

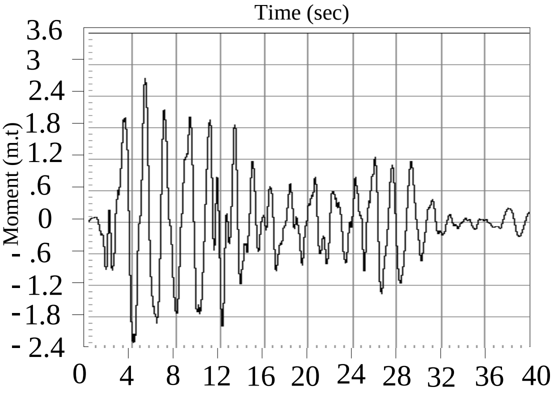


Col (1) Col (6)

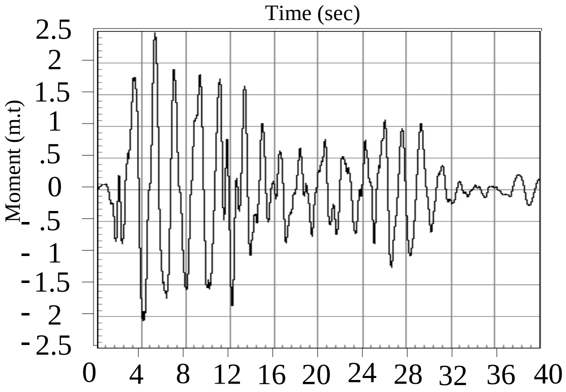
Isolated tie foundation at level -4 (retaining wall model)



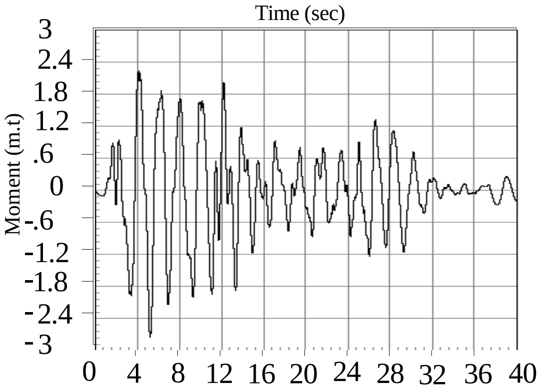
Col (1)



Col(2)

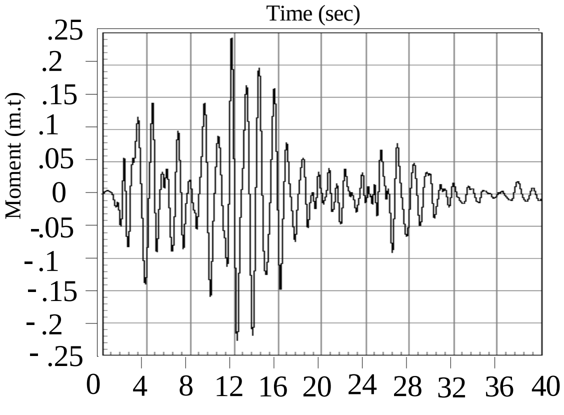


Col (5)

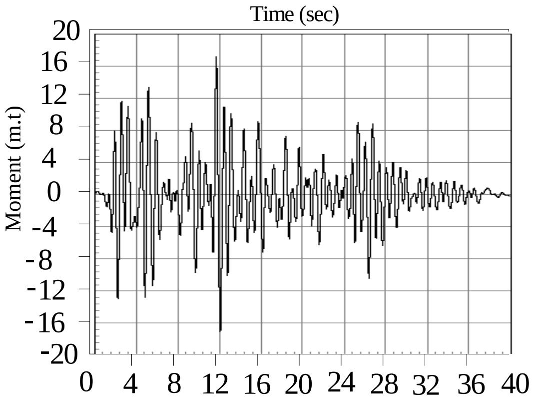


Col(6)

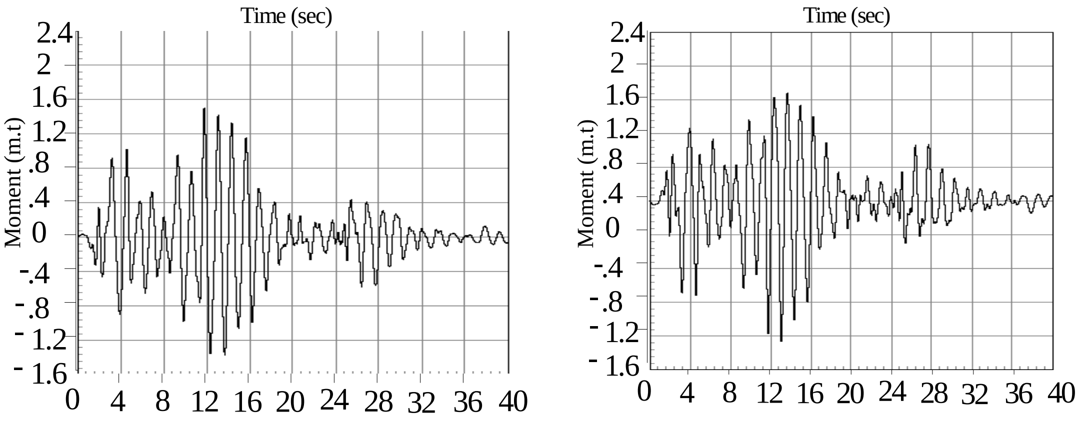
Raft foundation at level-2.5



Col (1)



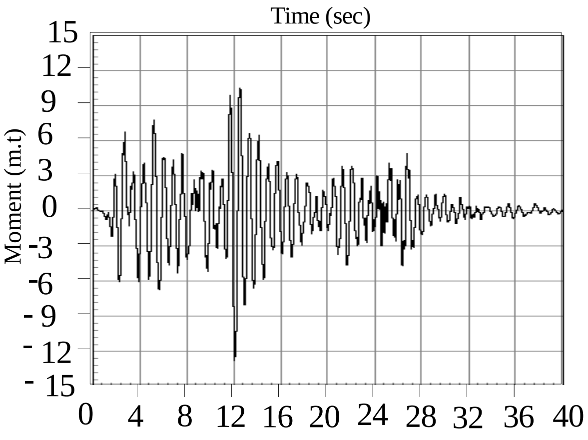
Col (2)



Col (5) Col (6)

Raft foundation at level-4

Figure (21): Time History of Base moment X-direction -3 stories



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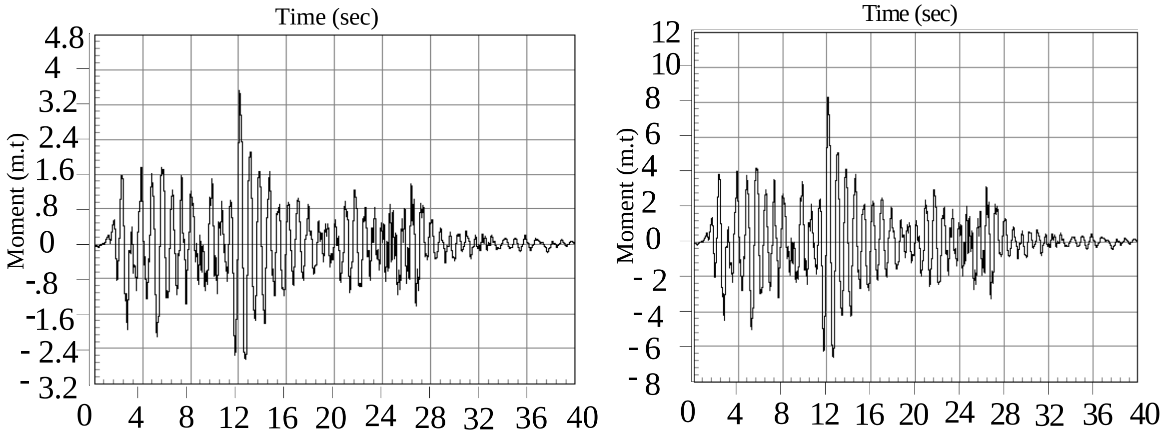
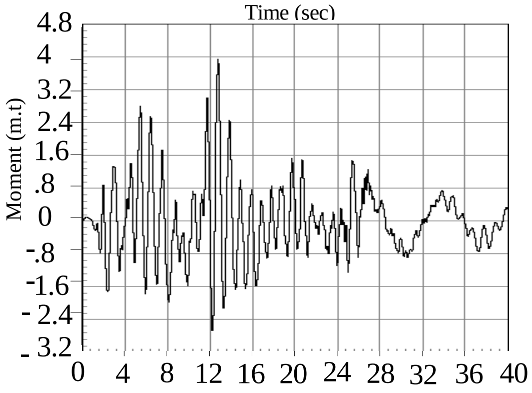


Col (5) Col (6)

Fixed base



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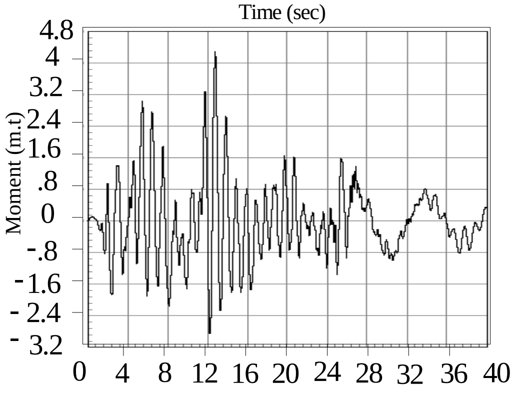

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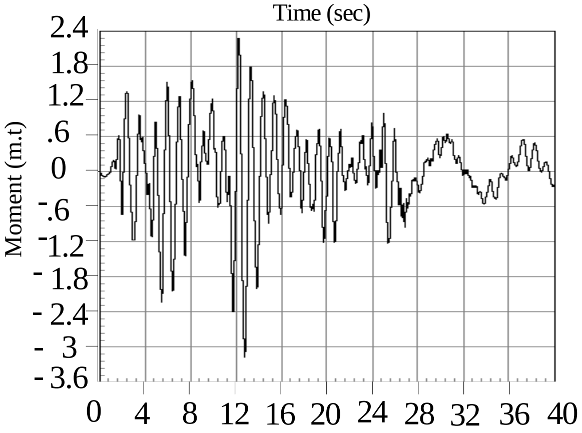

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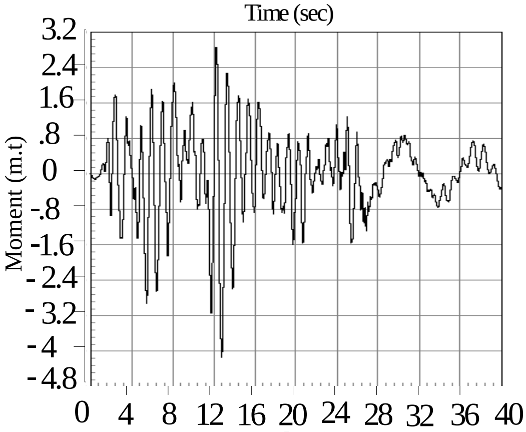
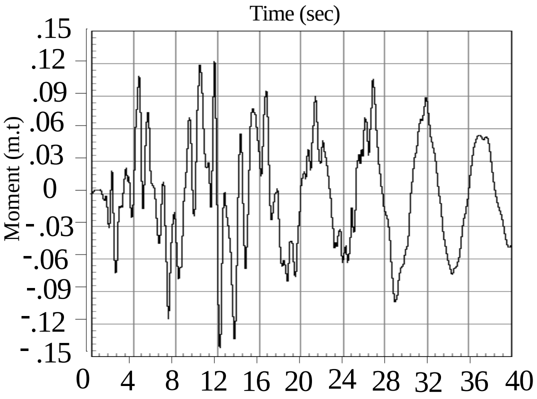
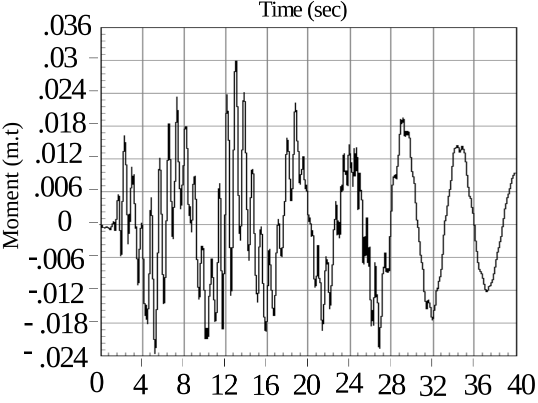


Col (6)

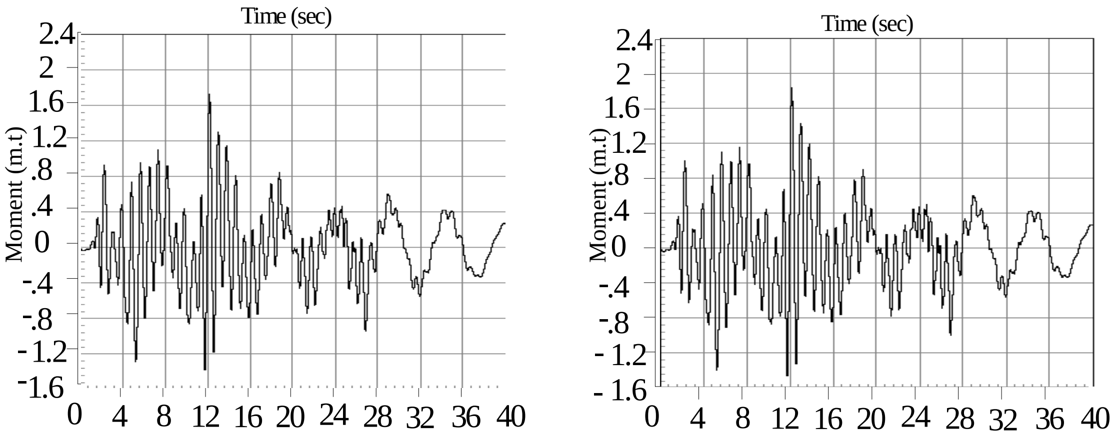
Raft foundation at level-2.5



Col (1)



Col (2)



Col (5) Col (6)

Raft foundation at level-4

Figure (22): Time History of Base moment X-direction -12 stories

7. CONCLUSIONS

An incremental iterative finite element technique for dynamic analysis of nonlinear soil – foundation super structure subjected to three dimensional ground motions is performed to study the effects of soil structure interaction on the seismic response of different building models. The connection between the soil and foundations were taken as a multi-linear Winkler springs and dashpots in three directions and around the perimeter of retaining wall to the ground level. As a result, a great deal of insight has been obtained on the dynamic response of building and the following conclusions could be drawn out:

- Incorporating soil structure interaction in the nonlinear earthquake analysis displays significantly unfavorable effect on the building top displacement response and performance. Thus effect is characterized by overestimation the top displacement of building and has highly dependence on the buildings height. The short buildings have the largest top displacement response that is associated with short duration of high frequency relative to that of fixed base.
- The fixed base buildings exhibit a high frequency feature. However the fundamental frequency modes for multi story buildings is characterized by decreasing as the soil becomes softer.
- The ground motions effect on the seismic response of buildings depends totally on the damping radiation of soil which is pronouncedly affected by the mass of entire building and the surface area of foundation. It is appeared that high damping in high rise building structures (raft foundation) leads to lower frequency modes compared with that of light buildings founded on the isolated foundation.
- The soil structure interaction generated by the soil against the sides of the executed retaining wall around the building demonstrated its capability and effectiveness in reducing and controlling building maximum top displacement and improving the building seismic performance.

- The soil structure interaction could lead to effective reduction in the deduced column base shear and this reduction reaches 70% and 30% for high and short building respectively relative to that of the original fixed base column.
- In the light buildings (three and six stories), the soil structure interaction has reasonably effect in decreasing the generated axial force with a negligible amount compared with that of the fixed base column while, that soil structure interaction can be activated in reducing the generated axial forces in the column of the heaviness buildings (12 stories) subjected to large earthquake excitations. The axial force decreases up to 20% of that fixed base column. On the other hand, the corner columns are suffered high response of axial force which reaches about 12 times of fixed base columns.
- The results prove again the effective role of the soil structure interaction on the column base moment responses. The reduction in the column base moment reaches 70% compared to that of the fixed base. This reduction becomes more pronounced as the building height increases.
- Comparison of different building model response with and without the soil interaction confirmed and detected that the soil structure interaction should be recommended for conservative nonlinear seismic response of high buildings since it mitigates of earthquake hazards.

8. REFERENCES

(1) Nasreddin el Mezaini *“Effects of Soil-Structure Interaction on the Analysis of Cylindrical Tanks”*, Pract. Periodical on Struct. Des. And Constr. Volume 11, Issue 1, pp. 50-57 (February 2006)

(2) R. Livaoğlu and A. Doğangün “*Simplified seismic analysis procedures for elevated tanks considering fluid–structure–soil interaction*” journal of Fluids and Structures, Volume 22, Issue 3, April 2006, Pages 421-439

(3) A. M. Chandler, and G. L. Hutchinson *“Parametric earthquake response of torsionally coupled buildings with foundation interaction”, Soil Dynamics and Earthquake Engineering, Volume 6, Issue 3, July 1987, Pages 138-148*.

(4) H. Sikaroudi, and A. M. Chandler *“Structure-foundation interaction in the earthquake response of torsionally asymmetric buildings”Soil Dynamics and Earthquake Engineering, Volume 11, Issue 1, 1992, Pages 1-16*.

(5) R. Clough, and J. Penzien, *Dynamics of Structures*, Second Edition, McGraw-Hill, Inc., ISBN 0-07-011394-7, 1993.

(6) Broms, B. B.(1964b). “Lateral resistance of piles in cohesionless soils.” J. Soil Mech and Found. Div., ASCE, 90(3), 136-156.

(7) Byrne, P.M., Anderson, D.L., and Janzen, W. (1984). “Response of piles and casings to Horizontal free-field soil displacements.” Can. Geotech. J., Ottawa, Canada, 21:4, 720-725.

(8) Chi-Chang Lin, M.EERI; Jer-Fu Wang, and Cheng-Hsing Tsai “*Dynamic Parameter Identification for Irregular Buildings Considering Soil-Structure Interaction Effects*”, Earthquake Spectra Volume 24, Issue 3, pp. 641-666 (August 2008).

(9) Stewart, D.P., Jewell, R. J., and Randolph, M. F. (1994). “Design of piled bridge Abutments on soft clay for loading from lateral soil movements.” Geotechnique, London, England, 44:2, 277-296.

(10) BARNALI GHOSH & S.P.G. MADABHUSHI *“EFFECTS OF LOCALISED SOIL INHOMOGENITY IN MODYFYING SEISMIC SOIL STRUCTURE INTERACTION” Paper for ASCE 16th Engineering Mechanics Conference in Seattle 16-18th July 2000.*

(11) Damage Synthesis Project DS-3 “*Advance Simulation Tools Soil-Structure Interaction*” Mid-America Earthquake Center.

(12) Martin, G., R., and Lam, I. P. (2000), *Earthquake Resistant Design of Foundations: Retrofit of Existing Foundations Proceedings,* GeoEng 2000 Conference, Melbourne.

(13) Housner, G., (1963). *The Behavior of Inverted Pendulum Structures During Earthquakes*. Bulletin of the Seismological Society of America. 53(2), 404-417.

(14) El Ganainy HM., ElNaggar M.H. “*Efficient 3D non linear Winkler model for shallow foundations*”, Soil Dynamics and Earthquake Engineering 29 (2009) 1236–1248 .

(15) D. K. Baidya Associate Professor *Department of Civil engineering I. I. T., Kharagpur* NPCBEERM, MHA (DM)*“EARTHQUAKE RESISTANT DESIGN OF SHALLOW FOUNDATION”.*

(16) Stewart, J. P., Seed, R. B., and Fenves, G. L. (1999). “*Seismic soil-structure interaction in buildings. II: Emprical findings*.” Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 125(1), 38-48.

(17) Ohba, S. (1992). “*Influences of the foundation types and the ground conditions on the natural period of actual buildings*.” Transaction of AIJ, 23-31.

(18) Seed, H. B., Lysmer, J., and Hwang, R. (1975). “*Soil-structure interaction analysis for seismic response*.” Journal of the Geotechnical Engineering Division, ASCE, 101, 439-459.

(19) Duke, C. M., Luco, J. E., Carriveau, A. R., Hardilek, P. J., Lastrico, R., and Ostrom, D., "Strong Earthquake Motions and Site Conditions: Hollywood," Bull. Seism. Soc. Amer., Vol. 60, No. 4, 1970, pp. 1271-1289.

(20) Kano, K., "Relation Between the Earthquake Damage of Non-wooden Buildings and the Nature of the Ground," Bull. Earth. Res. Inst. Tokyo, Vol. 27, 1949, pp. 97-100.

(21) Suyehior, K., "*Engineering \seismology, Notes on American Lectures,*" Proceedings ASCE, Vol. 58, No.4, Part2, May 1972, 110 pp.

(22) Ishizaki, H. and Hatakeyama, N., "*Experimental and Numerical Studies on Vibrations of Buildings,*" Proc. 2nd World Conf. on Earthquake Engng., Japan, 1960, Vol. 2, pp. 1263-1284.

(23) Newmark, N. M., and Rosenblueth, E. (1971). *Fundamentals of earthquake engineering*. Prentice Hall, Englewood Cliffs, NJ, 93-100.

(24) D’ONOFRIO, A. and F. SILVESTRI (2001): *Influence of microstructure on small strain stiffness and damping of fine graded soils and effects on local site response*, in Fourth International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, March 2001, San Diego, California.

اسهام الفعل المتبادل بين المنشأ و التربة فى اللإستجابة الزلزالية للمبانى

ما زال التحليل الانشائى للمبانى المعرضة للهزات الارضية يعتمد على كون الاساسات كتلة جاسئه مفترضا الارتكاز على التربة الصخرية و مهملا تغير الخواص التركيبية والجيوتقنية لمكونات التربة الرخوية اثناء انتقال الهزات الارضية من التربة الى المبنى و رجوعها الى اعماق التربة مرة ثانية و هذا التداخل بين المبنى و تربة الارتكاز اصبح يجذب اهتمام العديد من الباحثين فى النصف الاخير من القرن الماضى.

لذلك يطمح هذا البحث فى توضيح و تفسير مدى اسهام الفعل المتبادل و المتداخل بين اساسات المبنى والتربة الرخوية فى استجابة هذه المبانى المعرضة للحركات الارضية القوية لاتخاذ الاجراءات الوقائية للضرر الناجم و تعزيز مستوى الامان لتك المبانى. لذلك تم اجراء التحليل الديناميكى لثلاثة نماذج من المبانى مختلفة الارتفاع و المشيدة على اساسات منفصلة و مسطحة على اعماق تاسيس مختلفة باستخدام طريقة العناصر المحددة مع الاخذ فى الاعتبار التغير اللاخطى التكرارى التدريجى للفعل المتبادل بين التربة الرخوية الاساسات اثناء انتقال الهزات الارضية من التربة الى المبنى و الرجوع مرة ثانية مستخدما طريقة السجل الزمنى ولعجلات زلزالية قصوى 0.25 من قيمة عجلة الجاذبية الارضية و المقدم من الكود المصرى لحساب الاحمال و القوى فى الاعمال الانشائية و المبانى (اصدار 2008).

وقد تم تمثيل لاخطية التربة بنموذج زنبركات وينكلر فى الاتجاهات الثلاثة وصدامات لقياس معاملات الاخماد اللازمة للحسابات التكرارية لمعاملات رد فعل التبادل و الناجمة عن تشكلات التربة الجديدة و المتخلفة اثناء الحركات الارضية.

وقد اقترح نموذج نيومارك وروزنبلوث (23) لتمثيل لاخطية التربة (علاقة تبعية الانفعال) المعتمدة على جساءة و اخماد التربة وفى حساب معاملات التربة متوسطة الرخوّه.

وقد اظهرت نتائج البحث كم هائل من الادراك بتاثير رد الفعل المتبادل بين التربة الرخوية و المبانى على اداء و استجابة تلك المبانى المعرضة للهزات الارضية كالتالى:

- التحليل الديناميكى للمبانى ذات الاساس الثابت الراسخ (تربة صخرية) يظهر قسمات لنبضات ازاحات الذروة (العلوية) و القوى الدلخلية عالية التكرار و السعة فى فترة زمنية وجيزة بينما تتميز هذه القسمات بنبضات تكرارية منخفضة وسعة اكبر فى ازاحات الذروة وتلطيف و تسكين لنبضات القوى الداخلية عندما تصبح التربة اكثر رخوة خاصة فى المبانى العالية. يعزى ذلك الى الاخماد الاشعاعى الكبير للتربة المتأثر الواضح بالوزن الثقيل و المساحة السطحية الكبيرة للاساس فى المنشات العالية على النقيض فى المبانى المنخفضة المقامة على اساسات منفصلة.

- ادماج رد الفعل المتبادل فى التحليل الديناميكى للمبانى يؤدى الى الزيادة المفرطة فى ازاحات الذروة (العلوية) للمبانى مقارنة بنظيراتها فى المبانى ذات الاساس الثابت و تعتمد قيمة هذه الازاحات بدرجة عالية على ارتفاع المبنى وعمق التاسيس فى المبانى العالية.
- تنفيذ الحائط الساند على محيط المبانى عمل هام وضرورى لان ادماج رد الفعل المتبادل بين التربة و الحائط له تاثير فعال و جوهرى فى تقليل ازاحات الذروة و تحسين الاداء الزلزالى للمبانى العالية.
- تضّمن التحليل الديناميكى للمبانى رد الفعل المتبادل يؤدى الى نقص مؤثر فى قوى القص المتولدة عند القاعدة يصل الى 70% و 30% من قوى القص المتولدة فى حالة المبانى العالية و القصيرة ذات القواعد الثابتة على الترتيب.
- فى المبانى الخفيفة المنخفضة رد الفعل المتبادل يؤدى الى نقص القوى الرأسية فى الاعمدة عند القاعدة بتاثير جدير بالاهمال بينما فى المبانى الثقيلة العالية يساهم ويحرض بهمة فى نقص القوى الراسية لتصل الى 20% نظيراتها حالة القواعد الثابتة الراسخة و من ناحية اخرى يتسبب فى حدوث زيادة كبيرة للقوى الرأسية لاعمدة الاركان تصل الى 12 مرة نظيراتها فى حالة القواعد الثابتة.
- أثبت النتائج الدور المؤثر لاحتواء التغير الديناميكى لخصائص بنيان التربة فى التحليل الديناميكى فى تقليل عزوم الانحناءات المتولدة عند قاعدة الاعمدة وهذا النقص يصبح اكثر وضوحا كلما زاد ارتفاع المبنى.
- مقارنة مردود (إستجابة) نماذج المبانى المختلفة الموضوعة تحت تأثير هزات ارضية قوية و المقامة على قواعد ثابتة وقواعد مرنة اكدت وكشفت ضرورية احتواء التحليل الديناميكى للمنشات العالية على الخصائص الديناميكية لبنيان التربة المتغيرة اثناء الزلازل العنيفة للتخفيف والحد من مخاطرها.