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Time history analysis of multi- storey building with basement story accounting for soil–structure interaction

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Abstract: Soil-Structure Interaction (SSI) is the effects of the soil (underlying and surrounding the structure) on the response of the structure. This study is a contribution in the soil structure interaction (SSI) field, as this interaction affects the seismic behavior of structures. Two series of Time History data were used in the analysis of reinforced concrete moment resisting frame building consisting of 9 stories with embedded basement storey building. The two approaches of SSI modeling that are substructure approach and direct approaches were compared with each other. Generally, and within the limits of this study, it was found that the responses of Substructure approach were identical with that of the direct approach in the two cases for all stories except for the Ground storey. It seems that SSI affects the higher stories rather than the lower stoerys. The dynamic analysis results comparison between the two approaches of modeling soil structure interaction, favored the substructure approach on the direct approach as the direct approach is time consuming. Also, the study found out that modeling the structure with only vertical spring led to doubtable results, which reflect present that is choosing this method represents the worst option. On the other hand, and according to the analysis results, study suggested that keeping use the fixed approach in design buildings (with embedded portion) does not represent the better choice. It is concluded that, the responses of Substructure approach is identical with that of the Direct approach in all cases for all stories except for the Ground storey. It seems that SSI affects the higher stories rather than the lower storey.

Keywords: *Basement storey, Direct modeling approach, Reinforced concrete Moment resistance frame, Soil structure interaction, Time history analysis.*

1. Introduction

Soil-Structure Interaction (SSI) is the effects of the soil (surrounding the structure) on the response of the structure. It is realized that SSI effects play an important role in determining the behavior of building structures under seismic load. It is true that taking the soil into account when calculating the seismic response of the structure does complicate the analysis considerably. It also makes it necessary to estimate additional key parameters, which are difficult to determine, such as the dynamic properties of the soil. Modern studies states have neglected the effects of SSI due to the detrimental effect to the seismic response of structure, presented in tendency of design to be un-conservative [1]. Additionally, the conventional design procedure already neglects the flexibility of foundation (upon an assumption of fixity at the base), the compressibility of soil mass and consequently the effect of foundation settlement on further redistribution of bending moment and shear force demands.

The interaction between the structure foundation and the surrounding soil is modeled by two common approaches, depending on the damping and flexibility of the soil. The *substructure approach and* the *direct analysis approach*:

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a) *Substructure approach* for a soil that modeled using vertical spring that commonly is the prevailing contributor of SSI effects. In this case the foundation is assumed as fixed translation in horizontal direction. A horizontal spring is suitable element used to restrict the horizontal displacement ability of the foundation.

b) The *direct analysis approach*, using finite elements method for modeling both soil and the structure. The soil is modeled sufficiently around the building which reflects realistic site properties, the effect of seismic waves that imparted its action on the soil boundary [2].

Venture recommended using fixed model and the flexible model by providing springs, for moment frame superstructure building to account SSI effects, as this represents reasonable and practical alternatives in case of basement existence. However, and for typical foundation situations, there is no consensus among structural engineers on the best modeling approaches to use [3].

Hence, this paper attempts to study the SSI effects on a multi-story building has a basement with raft foundation. Time History analysis (TH) has been performed on the 9-storey moment resisting frame building with one underground storey to compare results of dynamic analysis between the two approaches of modeling the SSI effects. A parametric study on both of modeling using different acceleration time histories records has been carried out throughout the analysis process as a trial to state the appropriate modeling for this type of buildings. The results will be obtained and discussed in terms total base shear, lateral story displacements, and storey shear force.

2. Site Soil Properties

The soil properties detail are listed in Table1 according to borehole soil test that were taken from nonspecific field investigation report which lies in Baghdad The bearing capacity from the report equal to 100 kN/m². As seen in Table1 indicates that the soil is a very stiff cohesive soil. It was noted that there is lack of information about some dynamic parametric properties that is needed through the analysis. (Mohammed & Shafiqu) [4] & [5] prepared geotechnical and geophysics properties as a database for different soils in different zones in Iraq including Baghdad. This database was useful in predicting the needed parameters by comparing the current type of soil among the ten sites database of Baghdad and take the most identical one as recorded in Table 1. So, the missing dynamic properties of the soil assumed to be equal to the values listed in this Table 2.

Table 1.
Test results of the soil.

Sample		Type	Depth of Sample		Index Property				Particle Size Distribution & Hydrometer Analysis				S.P.T. "N" Val.	Symbol	Description of Soil	Chemical Tests						
Field No.	Lab No.		From (m)	To (m)	M.C. %	L.L. %	P.I. %	L.Sh. %	Clay %	Silt %	Sand %	Gravel %				SO_3 %	Gyp %	$CaCO_3$ %	TSS %	Org %	pH	Cl %
B.H.No.1																						
1	8227	D	0.0	1.0					33	64	3	0	—	CL	Brown slightly gypseous lean clay							
2	8228	SS	1.0	1.5		36	16	7					19	CL	Ditto (very stiff)	2.87	6.17				8.84	0.201
3	8229	U	2.0	2.5									—	CL	Ditto							
4	8230	SS	2.5	3.0									23	CL	Ditto (moderately gypseous)	4.52	9.68				9.04	
5	8231	U	4.0	4.5									—	CL	Ditto							
6	8232	SS	4.5	5.0		33	15	8	26	71	3	0	26	CL	Ditto	11.80	25.60					
7	8233	SS	6.0	6.5									23	CL	Ditto							
8	8234	SS	7.5	8.0									19	CL	Ditto							
9	8235	SS	9.5	10.0					26	71	3	0	18	CL SM	Top: Ditto Bott: Medium grey silty sand with gravel	0.37	0.79				8.97	0.153
W. T. was not observed																						

Table 2.
Comparison of current soil type for (Shafiqu et al., 2018) of baghdad sample soil properties.

Baghdad sample soil properties (Shafiqu et al., 2018)													
No	**Site**	**Depth**	**Soil type**	**WT**	**γwet**	**γdry**	**C**	**ϕ**	**Vp**	**Vs**	**Ed**	**Gd**	**ν**
17	M1	0-10	Stiff to very stiff brown to green slightly, gypseousmarly lean to fat clay and silt clay (CL,CH,CL-ML)	2.1	18.7	14.8	76	12	544	186	187100	64840	0.446
Current baghdad sample soil properties													
-	-	0-10	Very stiff brown slightly to moderately gypseous lean clay (CL)	-	-	-	-	-	-	-	-	-	-

3. Case Study

A reinforced concrete fictitious moment resisting frame building of 9 stories with one basement storey was selected to be the case study of this subject. It is a regular building consists of 5 bays in each direction, and was designed by STAAD PRO V8 for seismic loading leading to the member sections listed in Table 3.

Table 3.
Section properties of the structural members of the frame resisting building.

Structural member	Element	Member section
Beam	Beam	0.5*0.3 M
Column	Beam	0.55*0.55m
Slab	Plate	0.15 m Thick.
Basement wall	Plate	0.3m Thick
Raft foundation	Plate	1 m Thick
Soil surrounding building	Solid	(1*1*1) m and 1*1*1.25m

According to Eliwi & Attiyah [6] the mapped acceleration parameters Ss and S_1 for Baghdad equal to 0.3 and 0.1respectivly. Since the soil is very stiff, then the site is classifying as C class, Fa equal 1.56 and Fv is 2.4. as a result S_{MS} , S_{M1} ,S_{DS} and S_{D1} 0.468 and 0.24, 0.312 and 0.16 respectively. With value 1 for important factor (for residential buildings), the seismic design category from S_{DS} is *B* and from S_{D1} is *C* which is the more severe Seismic design category. So, the design category is C and the moment resistance frame system is permitted for this category by ASCE, 2013 [7].

4. Modeling SSI Effects

The three methods that will be utilized to model the case study are: a) fixed modeling represents the case without considering SSI effect named *Fixed*, b) substructure approach modeling denoted by *Flexible* accounts for SSI with vertical, horizontal and rotational springs (see Figure. 1), and elastic continuum approach (direct approach) for SSI effects used to idealize the soil respectively and called *Continuum* as explained in Figure. 1.

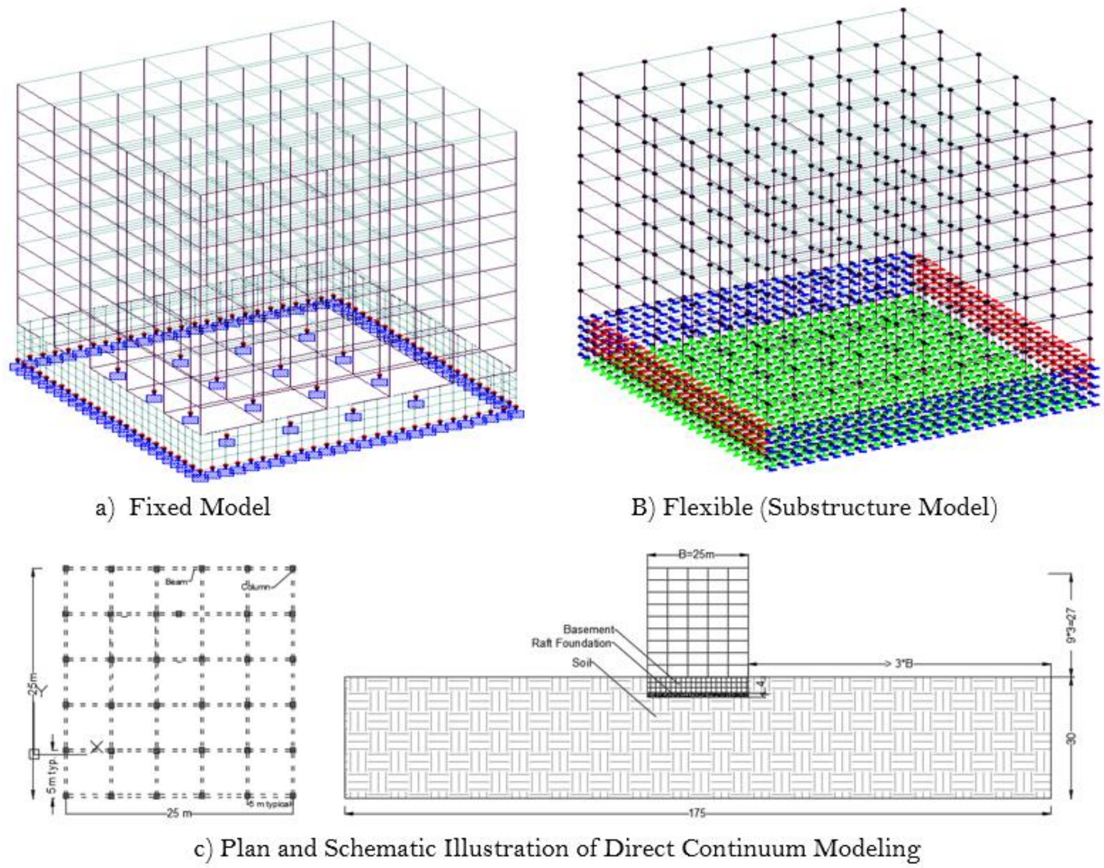

Figure 1.
Fixed and Flexible and continuum Modeling of the Building by STAAD PRO.

With the direct approach the soil modeled by soil element, with a whole dimension that was shown in Figure.1. The top 30 m of surface soil stratum is considered key influence on the structure and its respectively ground motions Kiku [8].

Springs stiffness for surface and embedded locations are calculated as recorded in Table 4, according to the formulae of Gazetas [9] then applied on footing and retaining walls throughout the analysis.

5. Time History Analysis

The results of the time history depend mainly on the characteristic of the used acceleration time-history records and the shapes of their corresponding elastic response spectra. Iraq is a region of moderate seismicity, however, infrequent earthquakes that can be considered severe have occurred recently. Owing to the lack of natural earthquake records data, it was gone towards taking the required data from Haddadi [10] web site. This site archives numerous recorded information about the main earthquake events from stations in many regions all over the world. Iraq is not included in this archive, so it is decided to depend upon West Iran region data. The choice of this region was due to the direct impact of Iraq from these events specially in recent years. Series of Time History data was considered in this study, but only two of these that made significant effects, will be presented (see Figure. 2).

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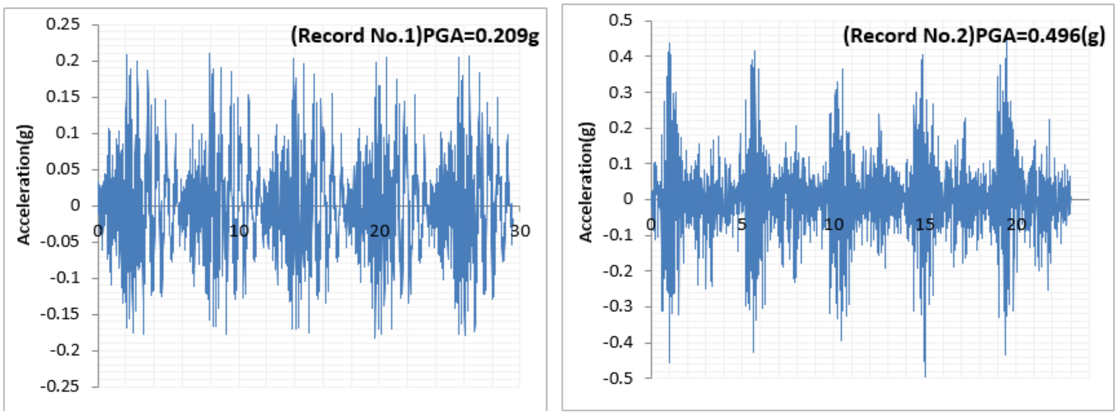

Figure 2.
Two Seismic Records Used in the Study [Strong Motion].

6. Results and Discussion

Running the dynamic analysis by STAAD.PRO Advanced CONNECT resulted the following fundamental periods (among other results) that are listed in Table 4. It is clear that there is lengthening in period with respect to the Fixed model. The fact that consideration of modeling soil flexibility by utilizing springs in lateral analysis, leads to lengthening the fundamental periods, behind these period results. The inertial interaction can affect results through increasing period time of the building depending the degree of the inertial flexibility of the foundation this property reflect the dynamic soil structure interaction which includes**:**

(1) Increasing in the building time period because of the flexibility of its foundation.

(2) A damping value change in radial shape that caused through the propagation of the seismic waves that lie in far distance of the foundation due to dynamic acts on displacements against the field displacements.

(3) The soil damping behavior has hysteretic shape that similar to viscous damping for the super-structure, beside that it is clear there is no relation with the flexible-base period of the structure according FEM analysis [11].

Table 4.
Fundamental periods for each model.

Fundamental period	**Fixed**	**Flexible**	**Continuum**
	1.347 s	1.354 s	1.399 s
Difference ratio	-	0.52%	3.86%

Different responses were obtained from the results of the two-seismic records analysis which will be shown separately in terms of a lateral displacement and storey shear. A comparison discussion will be presented after the results review, to show the effects of modeling type on the structural response of the case study building.

6.1. Seismic Record No. 1

This time history with modest peak ground acceleration (0.209g) , affected the building response with the manner shown in Figs.7 to 9. The lateral displacement of the Continuum is greater than the Fixed model, but somewhat agree with the Flexible. Whereas the storey shear almost exhibits very close values for the three models. The corresponding inter storey drift does not reach 0.15%.

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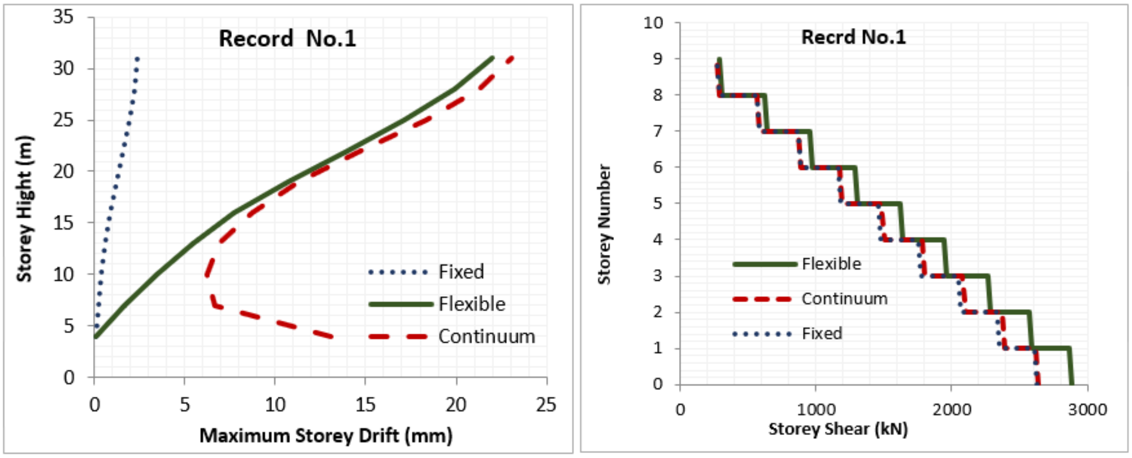
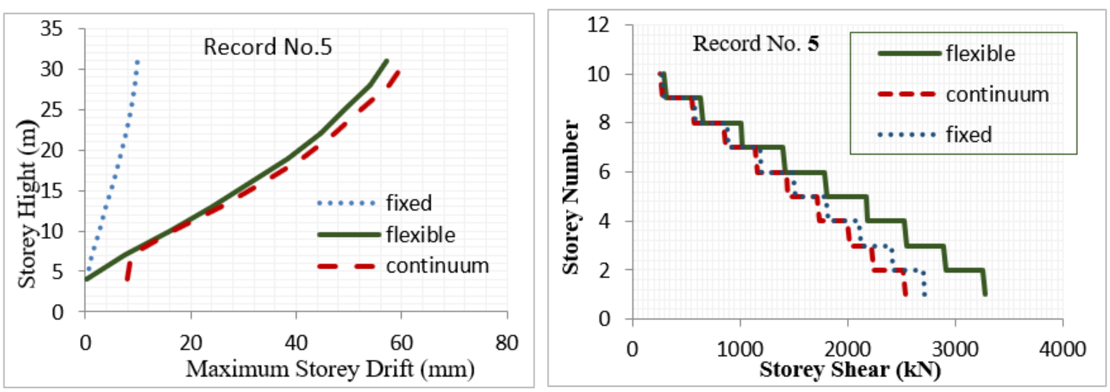


a): Lateral displacement of Record No.1   b): Storey Shear of Record No.1

Figure 3.
Fixed and Flexible and continuum Modeling of the Building by STAAD PRO.

6.2. Seismic Record No.2

The last record with the maximum PGA value of 0.496 g leads to the following responses shown in Figs 19 to 21. Again, there is good convergence of results for both modeling types of SSI for all curves of results. Divergence of Fixed model with both SSI models is clear concerns displacement issue.



a): Lateral displacement of Record No.19   b): Storey Shear of Record No.20

Figure 4.
Fixed and Flexible and continuum Modeling of the Building by STAAD PRO.

After the overall review of the results, now it is the time to compare the results with each other to find out the significant effects and reasons led to these responses.

1)When dealing with the results of *lateral storey drift*, the differences pop up between the three models, noting that neither of the two models matches the Fixed model. The mismatch is due to the SSI influences, of course. The degree of agreement between the two approaches of SSI seems to be depends on the intensity of earth shakes related to the PGA magnitude. That is because in an earthquake, damage to buildings and infrastructure is related more closely to ground motion, of which PGA is a measure, rather than the magnitude of the earthquake itself. For moderate earthquakes, PGA is a reasonably good determinant of damage. All the time Fixed model recorded the least value of displacement, and the Continuum appeared the largest values, that response as a result of the shift to longer fundamental period that necessitates increasing the displacement response. Period lengthening lead to increase spectral displacement that is related with storey drifts increments Margus [2] .

It should be mentioned that (ASCE, 2013) specified a maximum allowable story drift which depends on the type of building and on the Risk Category. This limit is 0.02 h_{sx} , where h_{sx} is the story height below level x, that mean it equal to 60mm in this case study. The largest two cases of drift are tabulated in Table 6 to show that even the worst two cases were within this limit.

2) *Story Shear*: As a comprehensive overview of the topic, turns out that the Fixed storey shear results is very close to Continuum results, however the Continuum values of storey shear have the lowest bound among the three models. This behavior was expected due to the inertia of SSI which reduces the adopted seismic force in the design. The effect of inertial interaction was evaluated according to variations of fixed- and flexible base parameters (lengthening of first-mode period) due to the foundation translation, rocking and the damping attribution to foundation-soil interaction. Inertial interaction actions increase with the amplitude of ground motion due to strain softening for foundation soils. While the shear modulus is decreased, the effect on the hysteretic damping is shown through value increases. The magnitude of inertial interaction effects increased with the severity of ground shaking Stewart [13].

In general, the responses of Flexible Model were identical with that of the Continuum model in all record cases for all stories except for the Ground storey. It seems that SSI affects the higher stories rather than the lower storey. However, Abdel Raheem [12] found out that Lower and upper stories are more affected with SSI than middle stories, and Lower stories are more affected with SSI than the rest stories. Lower stories displacements are more affected than the rest stories when using the SSI method.
Finally, it is worthy to mention that the modeling the building by vertical springs which is one of suggested choices of the substructure approach resulted unreasonable values of displacements during the analysis foe the same building and loading cases.

7. Conclusions

Within the limit of this study, the main concluded remarks that can be gained from this limited study on a moderate rise building that has one embedded storey (basement) for different acceleration time histories records are:

1. The substructure approach can simulate SSI effects very well, if the soil simulates by horizontal, vertical and torsional springs, as this simulation results were in a good agreement with results obtained from the direct approach which is considered the most reliable method. Noting that the direct method depends on finite element method and it is time and effort consuming. So, the simulating SSI effects by this model will gain both time and efforts.
2. The springs of the modelling should be representing the dynamic soil properties very well in order to ensure the real simulation and get a trustworthy result of analysis.
3. The study suggests to start thinking about giving up the idea of modeling the structures (with embedded portion) by Fixed model since the analysis results recorded drift and period values that do not correspond to reality, in addition to its high cost came from conservative deign principles.
4. Utilizing the substructure approach in modeling by only vertical springs led to obtain unreasonable values of displacements,
5. Generally, it was found that, the responses of Substructure approach were identical with that of the Direct approach in all cases for all stories except for the Ground storey. It seems that SSI affects the higher stories rather than the lower storey.

Symbols:
Fa, Fv: short period & long period site coefficient respectively.
S1: mapped 5% damped spectral response acceleration parameter at a period of 1 s.
SD1, SDS: design 5% damped, spectral response acceleration parameter at a period of 1s & short period respectively.

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SM1, SMS: 5% damped, spectral response acceleration parameter at a period of 1s & short period adjusted for site class effects respectively.
SS: mapped 5% damped spectral response acceleration parameter at short periods.

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