




Case Study

Comparison between fixed base and isolated base in seismic response of high-rise buildings: a case study

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ABSTRACT

In this study, the influence of soil condition under the isolated and fixed bases is studied by using ETABS 16 software for a high-rise regular building. A regular building with 10 floors is modeled and the results are obtained for story displacements, story shear forces and spectral acceleration according to the Uniform Building Code 97 (UBC-97) code. The time history analysis has been performed by using 1999 Izmit earthquake record. 3 types of soil which have different stiffnesses are considered in this study. The results show that the value of the base shear increases when the soil stiffness decreases. It also noticed that the spectral acceleration is larger in soft soil condition than that of other soil conditions; and this confirms that the structural response spectrum depends on the soil condition. In addition, when using base isolated building the drift of lower floors will be larger than that of using base isolated, but in the upper floors the drifts of fixed base building will be larger than that of the isolated base building. Finally, the time history method in the seismic design will produce base shear less than that from equivalent static method, so calibration factor for design purpose shall be used.

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1. Introduction

Loads are transferred from vertical structural elements to the soil by foundations. The foundations represent the upper layer of the earth. The condition of soil under foundations may be assumed as an important factor in the seismic analysis and design of structures. The engineering codes such as the Uniform Building Code 97 (UBC-97, 1997) and the International Building Code (IBC) have been classified soil according to its stiffness. In UBC-97, the soil is classified into 6 categories: 1) hard rock (SA), 2) rock (SB), 3) very dense soil and soft rock (SC), 4) stiff soil profile (SD), 5) soft soil profile (SE), 6) very soft soil which requiring site-specific analysis (SF). (UBC-97, 1997). During the earthquake, the deformation and vibration of the soil under the footings of the building cause the structure to vibrate and floors to move which produce base shear, base moment, and lateral displacement of slabs (Sayani and Ryan, 2009; Hatami, 2015).

Researchers (Sayani and Ryan, 2009; Hatami, 2015; Hassan et al., 2018) have tried to study the effect of soil-structure interaction on the seismic response of structures. They found that the interaction between soil and structure play major role especially in the results of natural frequency of building and in the energy dissipation. Conflicting assumptions in design process are found between structural engineers who assume flexible structures on rigid foundations and geotechnical engineers who assume flexible foundations supporting rigid structures (Touqan, 2008). Researchers found that the damages which occur during the earthquake are not in the same pattern for buildings which locate in the same region, and same earthquake magnitude (Jayalekshmi et al., 2016).

It means that there are some factors which affect the shape of damage of structures like: soil condition under foundations, structural system of plans, building mass and stiffness and vertical irregularities of buildings (Gjorgjiev, 2012; Magade et al., 2008).

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Nomenclature	
C_a	acceleration seismic coefficient
C_v	velocity seismic coefficient
V	total base shear
R	overstrength factor
I	importance factor of the building
W	total weight of the building
T	fundamental period of the building
F_y	yielding strength of steel
f'_c	concrete compressive strength
h	height of the building
C_t	coefficient of period depending on the lateral resisting system
f_i	lateral force at level i of the floor
δ_i	elastic deflection due to lateral force at level i of the floor
g	gravity acceleration
w_i	weight at level i of the floor

It is thus of prime importance to quantify the effect of soil condition beneath the foundation on the dynamic performance of the building. To conduct this study the popular commercial finite element program, ETABS16

software, has been used by running nonlinear time history analysis (CSI, 2017). Then, the seismic response of the building which is provided by fixed base and isolated base of the structure at 3 different soil type conditions according to UBC-97 will be discussed. The soil profiles are: hard rock (S_A), very dense soil and soft rock (S_c) and soft soil profile (S_E).

When using UBC-97 code, the seismic coefficient C_a and C_v shall be found from code tables for a specific seismic zone (Z). In this paper and for seismic zone $Z=0.30$, the C_a and C_v are found and summarized in Table 1. The reasons for using the same seismic zone are to compare the results of the three different soil types at that same zone. Moreover, to study the effect of the stiffness of soil on the seismic response of the high buildings in both fixed bases and isolated bases conditions.

Fig. 1 shows the UBC-97 response spectrum curve for the previous types of soil.

Table 1. Seismic coefficient.

Z=0.30		
Soil type	C_a	C_v
S_A	0.24	0.24
S_c	0.33	0.45
S_E	0.36	0.84

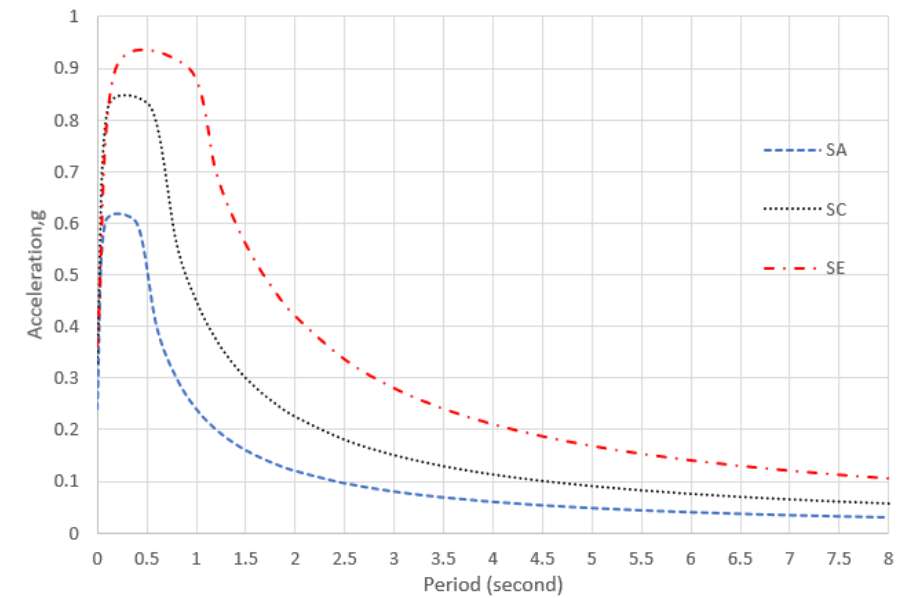


Fig. 1. UBC-97 response spectrum curve.

2. Modeling of the Building

In this study, ETABS 16 has been used as a commercial Finite Element software. The nonlinear time history analysis is conducted. The slabs are modeled as 2D shell-thin members. The beams and columns are modeled as 1D line members. The results from the program will show the performance levels and the behavior of the buildings.

10 floors are simulated and Uniform Building Code 1997 (UBC-97) is taken into consideration. All input data for materials properties, reinforced concrete sections, and type of loads as given in Table 2.

Isolator characteristics are as described and calculated at the book of Kelly and Naeim (Kelly J. and Naeim F., Design of seismic isolated structures, 1999) and Table 3 summarizes the final results. The isolator which used in the model will be the same for all columns and depending on the maximum axial load in the building. This

assumption is used to simplify the modeling process and to make the analysis as fast as possible. The structural system is chosen to be special moment resisting frames.

Fig. 2 shows the modeled columns layout, while Fig. 3 shows the 3D view of the building as modeled in ETABS 16. The building is assumed to be regular in the both main directions, because this type of building behaves more safely during the earthquake. Moreover, using this assumption leads to simplifying the modeling process and it reduces the time which is required to analyze the model using nonlinear time history analysis.

Figs. 4, 5 and 6 show the matched response spectrum-time history functions for Izmit 1999 earthquake for hard rock (S_A), very dense soil and soft rock (S_c) and soft soil (S_E) respectively. The direction of the time history is south to north (S-N).

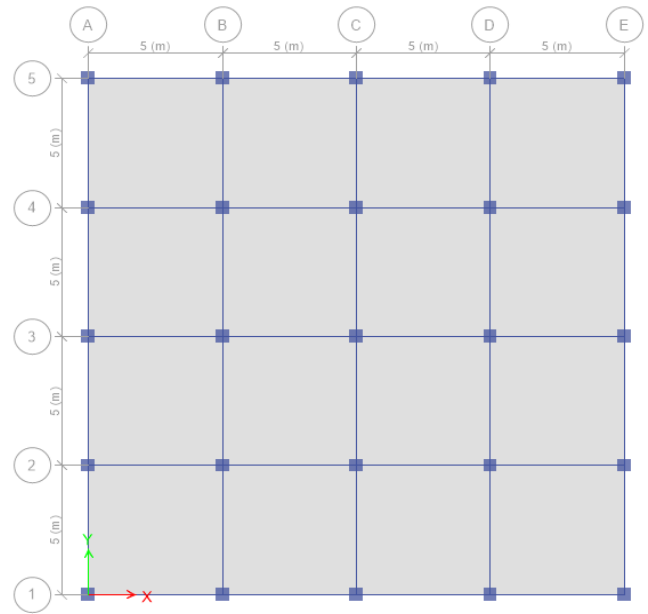


Fig. 2. Columns layout.

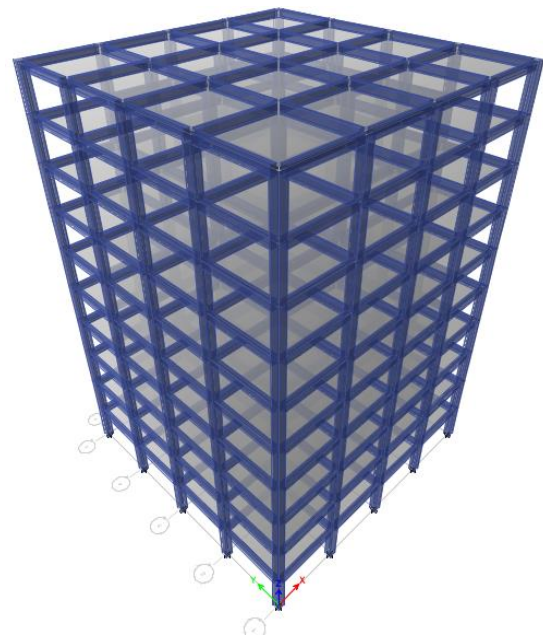


Fig. 3. 3D model of building.

Table 2. ETABS input data.

Concrete f_c	24 MPa
Steel f_y	420 MPa
Floor height	3.00 m
Superimposed load	4.00 kN/m ²
Live load	2.5 kN/m ²
Masonry wall load	15 kN/m
Columns	50x50 cm
Beams	30/50 cm
Two-way solid slab thickness	20 cm
Overstrength factor, R	8.5
Eccentricity ratio	0.05

Table 3. Isolator characteristics.

Maximum vertical column load	4296 kN
U_1 effective stiffness	2668580.68 kN/m
U_2 and U_3 effective stiffness	2668.60 kN/m
Yield displacement	0.00321 m
U_2 and U_3 stiffness	24591 kN/m
Damping ratio	0.05

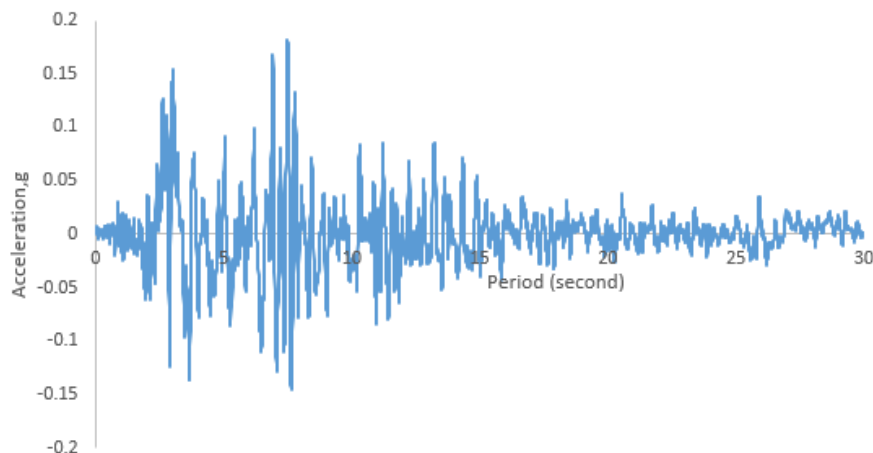


Fig. 4. Matched response spectrum- time history function for Izmit 1999 earthquake for hard rock (S_A).

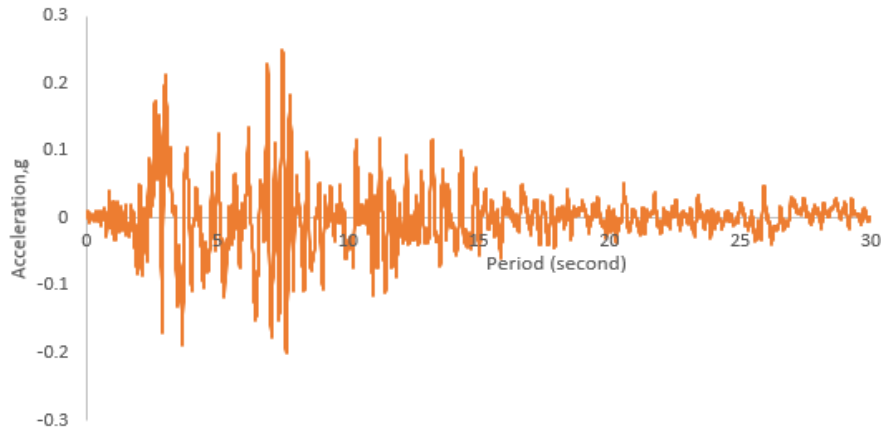


Fig. 5. Matched response spectrum- time history function for Izmit 1999 earthquake for very dense soil and soft rock (S_c).

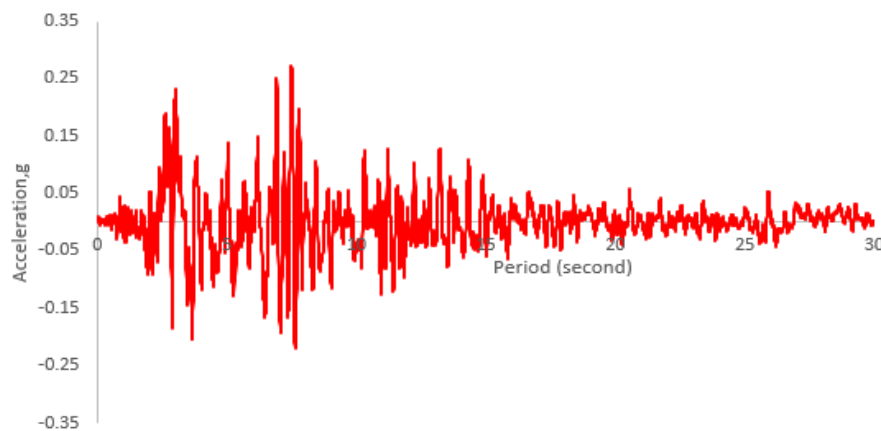


Fig. 6. Matched response spectrum- time history function for Izmit 1999 earthquake for soft soil (S_E).

3. Verification of the Analysis

When using any finite element program, it is much important to verify the analysis results which will obtain. The verifications can be found as a percentage of difference between hand calculation and program results (Al-najajra et al., 2017). This difference shall not be greater than a certain value which described in the ETABS manual. The results of the static analysis are proved according to CSI (2017):

1. The condition of compatibility: Where all members in the model should be connected and move together with no gaps. Fig. 7 shows the satisfaction of this condition from the dead load deflected shape.
2. The condition of equilibrium: Where the applied loads shall be equal to the reaction loads from the analysis; If it is not, then a difference between program results and manual results should be less than or equal to 5% to be accepted. This condition is satisfied as shown in Table 4.
3. The stress strain relationship: Where the internal forces such as bending moment, shear and axial forces from program results should be equal to the manual results; If it is not, then an acceptable difference between program results and manual results should be less than or equal to 10%. This condition is satisfied by finding axial load in a specific column as shown in Fig. 8 and Table 5.

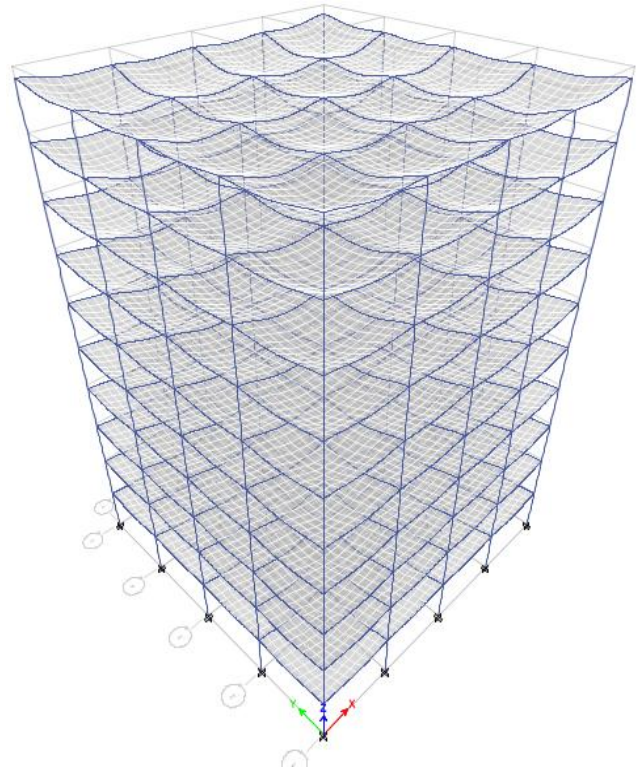
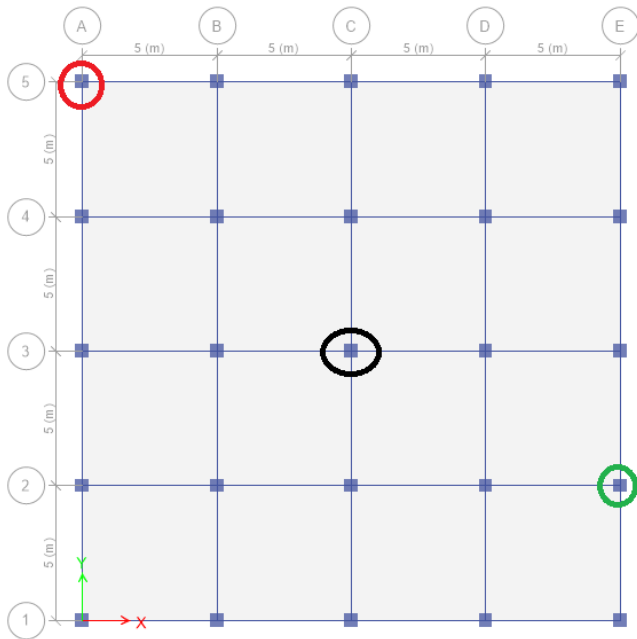


Fig. 7. 3D deflection shape from dead load.

Table 4. Check for the balance of forces.

Item	ETABS results	Manual results	Difference (%)
Weight of the structure (kN)	28737.50	29187.50	1.54
Superimposed dead load (kN)	28000	28000	0.00
Live load (kN)	10000	10000	0.00

**Fig. 8.** Location of the checked columns.

4. Results of the Building Analysis

After analyzing the models, the results are obtained and curves are drawn.

4.1. Story displacement

Fig. 9 shows the floors top displacement results for both conditions of isolated base (IB) and fixed base (FB) for soil S_A for Time History Analysis in X direction. Due to the symmetry of the building the THA results are the same for both X direction and Y direction. Fig. 10 shows the same but for medium soil S_C and for soft soil S_E Fig. 11.

Tables 6, 7 and 8 show the difference between floors top displacements according to fixed base and isolated base for soil S_A , S_C and S_A respectively. The differences are calculated with respect to fixed base condition.

As shown in the following figures and tables, the soil stiffness is playing a major role in the lateral displacement of each floor in the building. When the soil stiffness is very strong as in S_A case, then the lateral displacement value of floors will be small comparing to the other cases such as S_C and S_E soils. This result can make advice to engineers to construct buildings on a hard soil such as rock, and to avoid build structures on a weak soil.

Also, when using base isolated buildings, the first floor lateral displacement value shall be more than that of the fixed base building and if you move away from the footing, the lateral displacement of floors of fixed base will be larger than the base isolated buildings, and this trend is the same for all type of soil cases.

In general, it can be illustrated that base isolated gives lateral displacement more than that of fixed base, and this will produce flexible structures.

Table 5. Check for the axial load internal force.

Columns position	Item	ETABS results	Manual results	Difference (%)
Internal	Dead load (kN)	1646.50	1662.50	0.97
Internal	Superimposed load (kN)	994.87	1000	0.51
Internal	Live load (kN)	628	625	0.47
Edge	Dead load (kN)	965.22	981.25	1.66
Edge	Superimposed load (kN)	1223.93	1250	2.13
Edge	Live load (kN)	312.86	312.50	0.11
Corner	Dead load (kN)	586.09	612.50	4.50
Corner	Superimposed load (kN)	968.26	1000	3.27
Corner	Live load (kN)	147.69	156.25	5.79

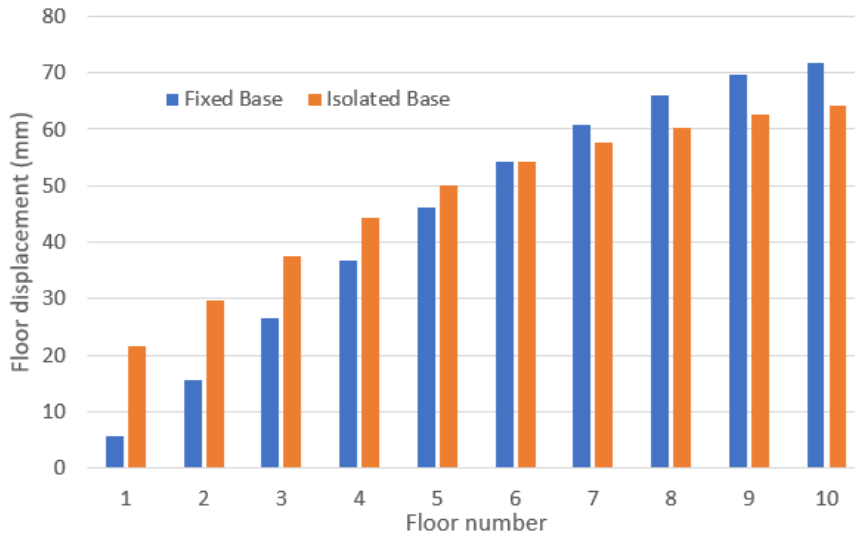


Fig. 9. Floor displacements for hard rock (SA).

Table 6. Variation of floor displacement for hard rock (SA).

Floor number	Floor displacement for FB (mm)	Floor displacement for IB (mm)	Difference (%)
1	5.59	21.70	288.02
2	15.70	29.81	89.91
3	26.51	37.46	41.32
4	36.82	44.41	20.62
5	46.13	50.05	8.50
6	54.20	54.30	0.19
7	60.86	57.57	-5.41
8	66.02	60.31	-8.64
9	69.64	62.63	-10.07
10	71.85	64.27	-10.54

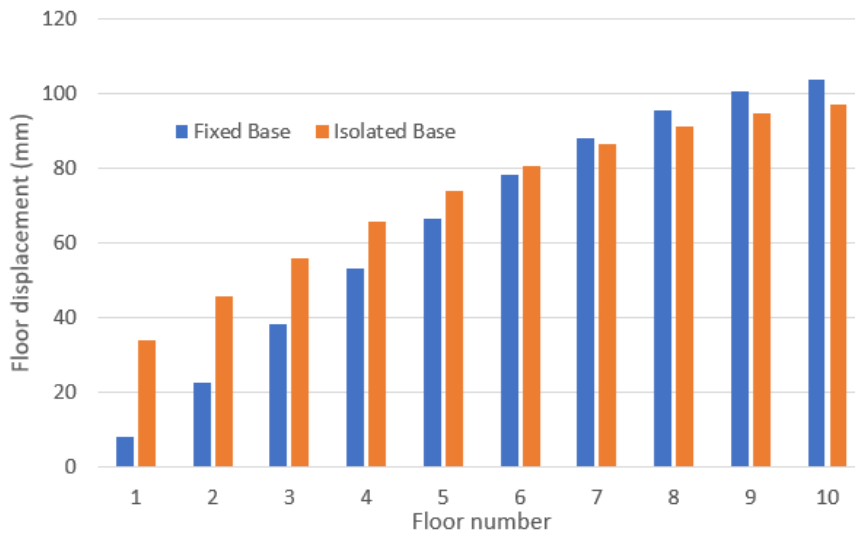


Fig. 10. Floor displacements for medium soil (Sc).

Table 7. Variation of floor displacement for medium soil (S_C).

Floor number	Floor displacement for FB (mm)	Floor displacement for IB (mm)	Difference (%)
1	8.08	33.90	319.62
2	22.67	45.57	100.96
3	38.29	56.09	46.48
4	53.18	65.69	23.52
5	66.63	73.9	10.97
6	78.29	80.75	3.15
7	87.91	86.40	-1.72
8	95.36	91.09	-4.48
9	100.59	94.72	-5.84
10	103.78	97.12	-6.41

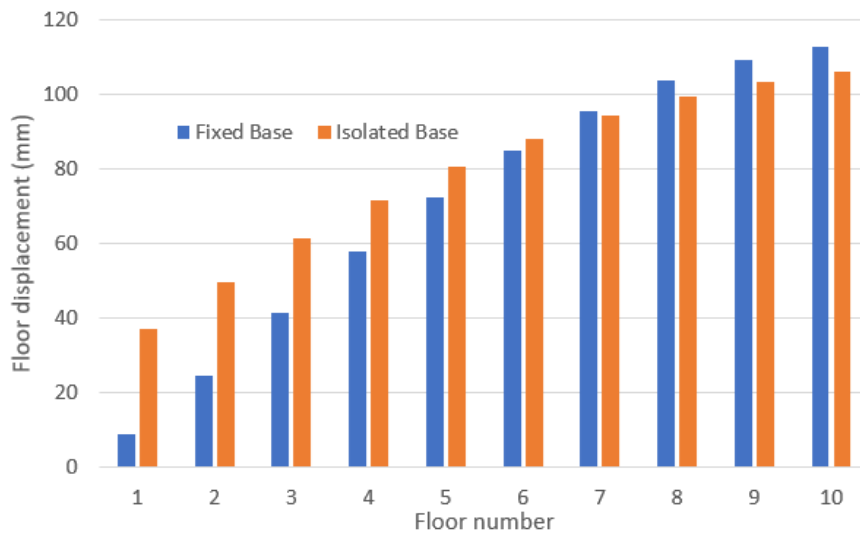


Fig. 11. Floor displacements for soft soil (S_E).

Table 8. Variation of floor displacement for soft soil (S_E).

Floor number	Floor displacement for FB (mm)	Floor displacement for IB (mm)	Difference (%)
1	8.77	37.15	323.48
2	24.62	49.83	102.38
3	41.58	61.23	47.25
4	57.75	71.66	24.08
5	72.36	80.69	11.51
6	85.02	88.21	3.75
7	95.47	94.45	-1.07
8	103.56	99.58	-3.84
9	109.24	103.50	-5.26
10	103.78	97.12	-6.41

4.2. Story shear

Fig. 12 shows the maximum story shear results for both conditions of isolated base (IB) and fixed base (FB) for soil SA for time history analysis in X direction, and due to the symmetry of the building the THA results is the same for both X direction and Y direction. Fig. 13 shows the same but for medium soil Sc and Fig. 14 for soft soil SE.

According to UBC-97, the total base shear by using manual equivalent static method shall be calculated as Eq. (1). It shall not be less than Eq. (2) and greater than the result of Eq. (3).

$$V = \frac{C_v I}{R T} W \tag{1}$$

$$V = 0.11 C_a I W \tag{2}$$

$$V = \frac{2.5 C_a I}{R} W \tag{3}$$

UBC-97 provides two methods to calculate the period of building, either by using the simple quick equation Eq. (4), which only requires to know the building height and lateral force resisting system, or by using a more detailed equation Eq. (5), which needs stiffness of building and it depends on the rational analysis such as the Rayleigh's method.

$$T_a = c_t (h^{0.75}) \tag{4}$$

$$T_b = 2\pi \sqrt{(\sum_{i=1}^n w_i \delta_i^2) \div (g \sum_{i=1}^n f_i \delta_i)} \tag{5}$$

Table 9 shows the final results from applying Eqs. (1-4) for each soil type.

Table 9. Hand calculation of the total base shear.

W (dead + superimposed dead load)	56737.50 kN
C_t	0.0731
h	30 m
T_a	0.93 second
V manual, hard soil SA	1722.58 kN
V manual, medium soil Sc	3229.90 kN
V manual, soft soil SE	6007.50 kN

From Table 9, it can be noticed that using hand calculation equivalent static method to find the total base shear will produce larger values than that from using time history analysis for all types of soils, and this value will appear obviously in the soft soil type. Thus, when using time history method in the design against earthquake calibration factor should be used to make the final base shear which calculated from time history method is equal to that from equivalent static method, to be conservative by using high value of force in the design process.

Also, it can be seen in Figs. 12, 13 and 14 that increase the soil stiffness will decrease the floor shear due to earthquake, and that's produce another confirmation for the previous advice to construct structures on a strong soil to reduce the cost of building. Moreover, the largest story shear is in the top of the building. Thus, putting plastic water tanks on the roofs shall be avoided.

The isolated base building story shears are smaller than those obtained from fixed base building as shown in the figures.

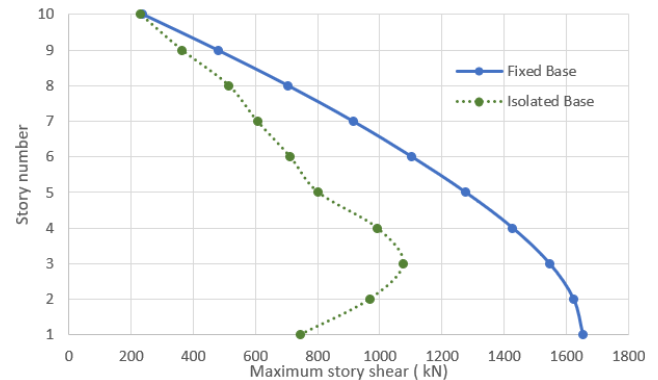


Fig. 12. Maximum story shear for strong soil (SA).

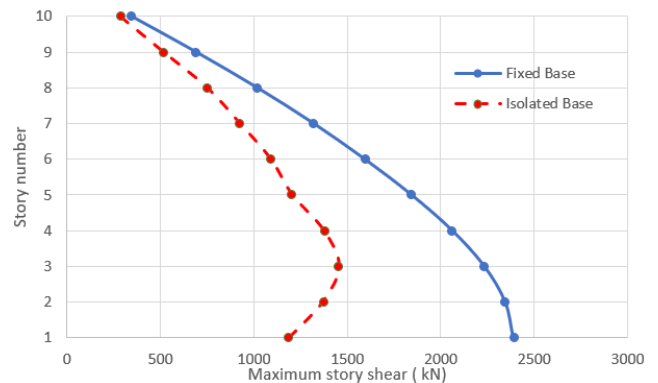


Fig. 13. Maximum story shear for medium soil (Sc).

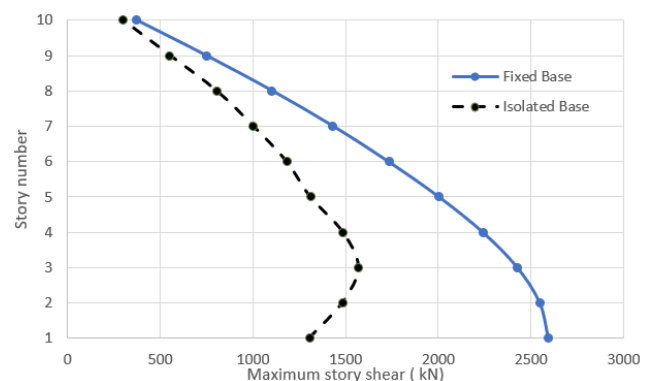


Fig. 14. Maximum story shear for weak soil (SE).

4.3. Spectral acceleration

The maximum ground acceleration that occurred during ground motion at a site is called the peak ground acceleration (PGA) (Hassan et al., 2018).

During the earthquake the largest absolute acceleration amplitude recorded on an accelerogram at a studied location equals the PGA. Earthquakes usually occur in all three directions (Hatami, 2015). So, PGA can be components in horizontal and vertical. In general, the horizontal PGAs direction are larger than the vertical direction. Therefore, in engineering applications, the peak horizontal acceleration (PHA) is the most frequently used.

Fig. 15 shows isolated base building spectral acceleration for the three cases of soil: hard, medium, and soft for 0.05 damping ratio. It can be noticed that the maximum spectral acceleration values can be produced by

soft soil and this will give maximum shear force in building. The maximum values of spectral acceleration are 1545.29 mm/second², 2155.10 mm/second² and 2304.52 mm/second² for hard soil, medium soil, and soft soil respectively.

As it is seen in Fig. 16, it is found that the increasing percentage of spectral acceleration values obtained by considering the hard soil condition is 39.46% when comparing to the medium soil condition, and 49.13% when comparing to the soft soil condition. So, as it is found, the soft soil condition produces higher acceleration as compared to other type of soils.

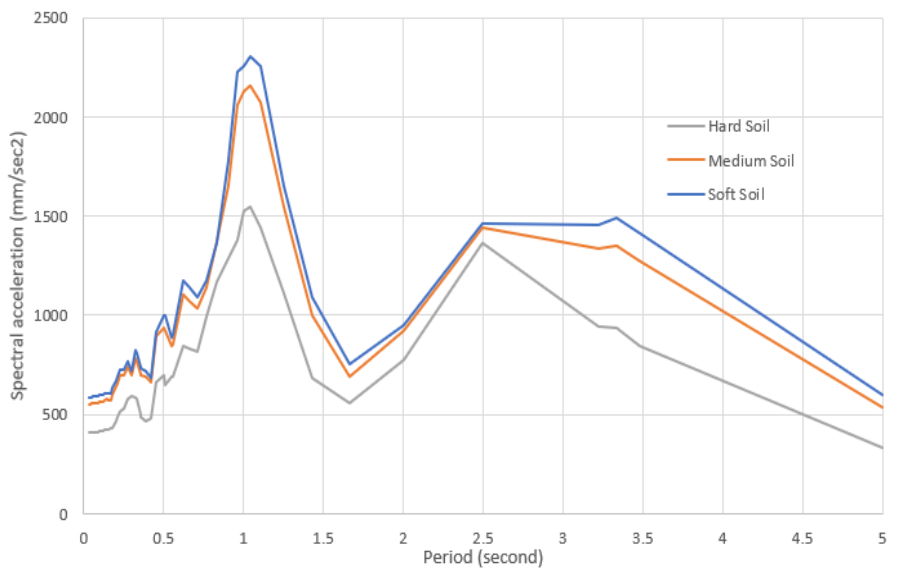


Fig. 15. Spectral acceleration.

Figs. 16, 17 and 18 show comparison between isolated and fixed base building in term of maximum values of spectral acceleration for three cases of soil. In these figures the maximum values of spectral acceleration for isolated and fixed base respectively are; 1545.29 mm/s², 3150.91 mm/s² in case of hard soil, and 2155.10 mm/s², 4511.32 mm/s² in case of medium soil. The increasing in

spectral acceleration will be in the case of soft soil, the values are 2304.52 mm/s² for isolate base condition and 4942.61 mm/s² for fixed base condition. As it is noticed in the three cases of soil, the fixed base model's spectral acceleration values are greater than that in isolated base models. Thus, the design base shear of fixed base building will be larger than isolated base building.

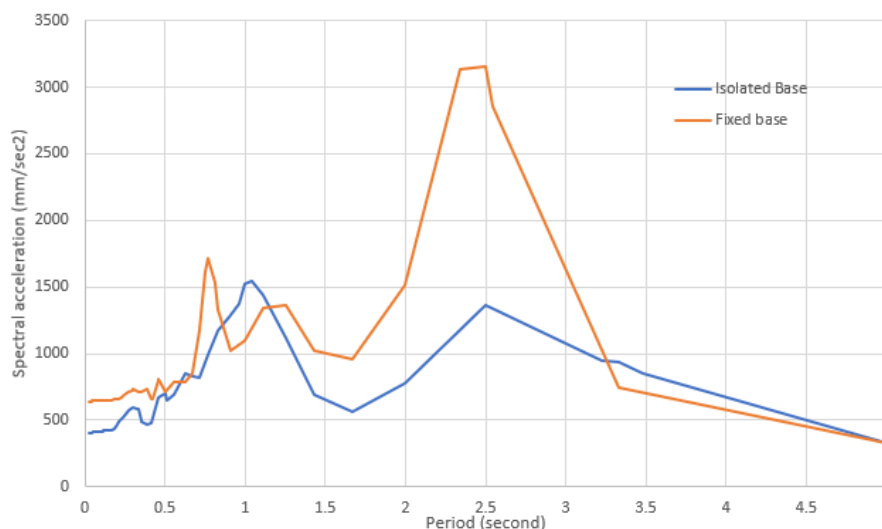


Fig. 16. Spectral acceleration for hard soil.

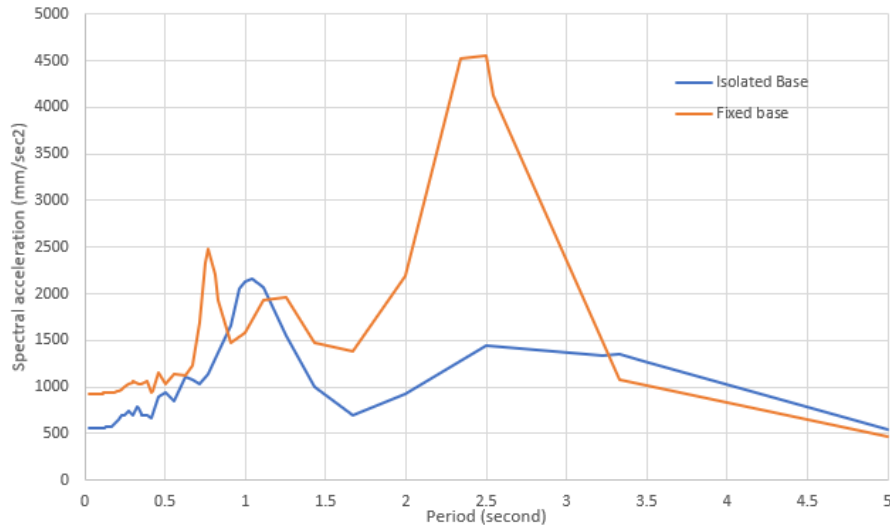


Fig. 17. Spectral acceleration for medium soil.

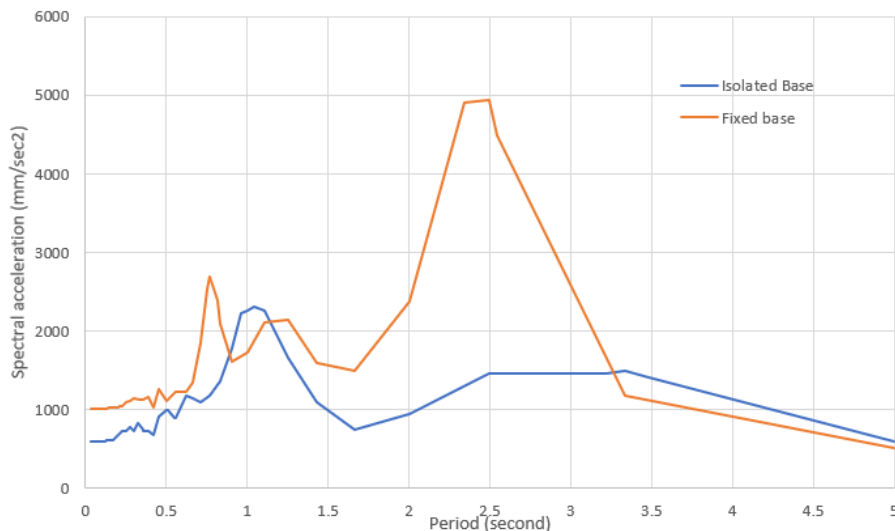


Fig. 18. Spectral acceleration for soft soil.

5. Conclusions

This study is an investigation in the seismic performance of an isolated and fixed base regular buildings under different soil conditions according to UBC-97. 10-floors high-rise building with an isolated base and fixed base has been studied for three types of soil: hard, medium and soft soil conditions according to UBC-97 code. Nonlinear time history analysis has been carried out using ETABS16 software and Izmit 1999 earthquake. Story displacements, story shear force and roof spectral acceleration have been studied. The main results and conclusions in this study as follows:

- Story shear force value increases when the soil stiffness decreases. It is found that the value of shear force will be the highest for soft soil and the lowest for hard soil type.
- Using equivalent static method will produce a total base shear larger than that by using time history analysis, and this appears clearly when reducing the stiffness of the soil.
- When using time history method in the seismic design, calibration factor shall be used to make the final base shear value from time history method equaled to that from equivalent static method.
- The roof level spectral acceleration of an isolated base model increases in medium soil condition by 39.46% and 49.13% in soft soil condition when compared with hard soil.
- Soft soil conditions produced the largest displacement compared with hard soil and medium soil.
- The first-floor lateral displacement value will be more than that of the fixed base building when using base isolated buildings. But if you move away from the foundations, the lateral displacement of floors of fixed base will be larger than that of the base isolated buildings, and this trend is the same for all types of soil cases.
- When using base isolated building, the drift of lower floors will be larger than that of the case of base isolated; but in the upper floors the drifts of fixed base building will be larger than that of the isolated base building.

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