Effects of soil-structure interaction on base-isolated structures

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Abstract. Structural integrity and seismic protection of the buildings against earthquake have been challenging among structural engineers. Many studies have been devoted to development of seismic isolators to improve the seismic behavior of civil structures. This study presents the analysis of building structures with SAP2000 considering soil structure interaction and base isolation effects under El Centro. Four different models are analyzed including fixed base structure, base isolated structure, frame supported by spring representing the soil and structure with combined base isolation and spring. The seismic results are investigated in terms of displacement, shear force, axial force, moment and drift of the columns and beams. It was observed that the soil structure interaction provides some flexibility to the structure by increasing the displacements of the structure and imposing internal forces variation to the system. Therefore, modeling base isolation together with consideration of soil structure interaction leads to better prediction of structural response.

1. Introduction

Geological faults cause earthquake rupture and as a consequence of that earthquakes have claimed hundreds of thousands of life in the past years and technology improvements have slightly decreased the death tolls. Property damage, loss of lives and many more casualties caused by an earthquake must be lowered and to do so engineers should come up with solutions [1-3]. Inclusion of soil-structure interaction (SSI) in seismic analysis has proved to enhance the seismic performance of civil structures. Soil structure interaction had not been seriously given enough attention to evaluate until the 1971. Significant number of journal papers like and design guides were published in 1970s and showed importance of soil SSI [4, 5]. SSI was investigated in 1980s and 1990s through numerical methods [6-9]. Furthermore, effects of such interaction analysis on special structures have been studied by many researchers including [10, 11]. Two methods were presented for soil structure interaction analysis during the seismic motion [12]. As the first method, the change of motions in the structure and surrounding soils was considered and in the second one the motion of surrounding soil was assumed to be same in all directions above the substructure depth and internal analysis of the soil was then considered.

Fixed base support system is valid only for structures on rock or high-stiffness soil. In general, soil and structural interaction reduces modification of energy dissipation in the structure. Analytical techniques and discussions of SSI effects on the seismic response of structures are presented [13].
Effects of SSI on a three span bridge with LRBs were studied, taking into account frequency independent expressions for the stiffness of the soil and damping parameters[14]. It was concluded that the seismic displacement increases due to SSI effect. Different cases of seismic SSI analysis are studied by different investigators [15, 16].

The role of non-linear dynamic soil-foundation interaction on the seismic response of structures was investigated [17]. Experimental results of seismically loaded structures supported by shallow foundations, theoretical improvement of macro-element modeling of the soil foundation system, examples of seismic design of bridge piers and numerical results of incremental non-linear dynamic analyses were presented to provide a concrete support to the concept of a controlled share of ductility demand between foundation and superstructure. It was shown that displacement-based seismic design can help engineers to achieve a controlled share ductility demand between the foundation and the superstructure.

During seismic disturbance, earthquake forces are applied to the structures at base level and unless flexibility is provided at the lower bottom of the building, Structures experience damages depending on magnitude of the seismic shaking. Base Isolation (BI) techniques are increasingly used in seismic areas for upgrading existing structures as well as effectively moderating the earthquake liability of new buildings. Base isolation techniques and respective applications have been studied throughout the world, e.g., in United State, Europe and Japan, [18-20]. Seismic code provisions such as IBC[21] and BS 1377 [22] assisted the development of base isolation applications for minimizing the seismic interfered demanded in seismic-prone countries.

Effectiveness of passive isolators and semi-active dampers on an existing cable-stayed bridge were numerically evaluated [23]. Given that the bridge towers were founded on a soft 35m thick soil layers, SSI was taken into account. Soil produces flexibility which moderates the dampers deformation and, in consequence, the amount of damping in the retrofitted bridge. The effects of earthquake shaking such as inter-story deformations and the floor accelerations by producing elements with high axial and low horizontal stiffness between the structure and the foundation was studied [24]. Rubberbearings base-isolation systems were implemented to limit structural damages undertaken by structures subjected to different seismic disturbance and assessed the presence of any changes related to the damage [25]. Analysis of base-isolated structures was conducted considering seismic reliability of the buildings [26]. Five-storey base-isolated building has been investigated and probabilistic ground motion model was created using 100 recorded earthquake motions. The first order reliability method and Monte Carlo simulation method are applied to predict the possibility of failure associated with the top floor acceleration response of the buildings. The probability of failure calculated using both methods was in close range.

Several investigations have been carried out to evaluate the effects of SSI phenomena on the earthquake response of base-isolated bridges. Four base isolated bridges were clarified using available information (theoretical modals and data) from recent earthquake [27]. It was reported that SSI effects depend on the horizontal pier stiffness, and that the important reduction in the soil shear modulus for moderate earthquakes should be definitely incorporated into SSI analysis. Analytical investigations of SSI effects were carried out on horizontal response of base isolated bridge piers concerning damping increment and the base shear degradation calculated by bridge design codes [28, 29]. Finally, it was figured out that SSI causes a significant decrease in the system Eigen frequencies and a rather insignificant increase in the damping of the system that is dominated by the isolated system damping ratio.

Combined effects of base isolation and soil structure interaction on the structures have attracted many researchers during last few years. Soil structure interaction has been considered for base isolated bridges and liquid storage tanks. The effects of SSI on the response of base isolated bridges have been investigated [3]. It was concluded that the soil structure interaction affects the modal properties of the system and it has small impact on the damping, especially for slender structures. Performance of base-isolated structures to protect buildings from natural disasters such as earthquake is affected by the soil structure interaction [24].
Distributed mass representation of the superstructure that has four possible dynamic response modes has been introduced [30]. Foundation and soil is treated as rigid block and equivalent spring-damper virtual mass system respectively. Good accuracy by the application of distributed mass structural model was found. Base isolation design has to consider soil structure interaction in order to have an adequate acceptance of performances based on the ground conditions. There is no enough detail on effect of base isolation in time history response of frame structures subjected to earthquake excitation. On the other hand, majority of seismic designs take into account linear base isolation design while in reality, performance of base isolation system should be assumed as nonlinear behavior.

Therefore, this paper presents seismic analysis of reinforced concrete (RC) frame with SAP2000 software accounting for SSI effects. Spring stiffness method has been employed to model the soil response under El Centro earthquake to evaluate soil structure interaction in frame structures equipped with base isolation system. Four different cases are considered with encompassing a same frame but different support condition including fixed-support frame, base-isolated frame, frame combined with springs as the underlying soil and frame with both springs and base isolation.

2. Methodology of Analysis

Soil flexibility under foundation of the structure is an important factor for design of the structure located in seismic prone zones. Soil effect has the ability to modify both amplitude and the resonant frequency of the structural response during earthquakes. This effect can be taken into account in the seismic analysis by using equivalent spring to represent the soil structure interaction effects.

Schematic view of a rectangular footing is shown in Figure 1. Lateral, vertical and rocking motions of the foundation are considered by introducing linear compliance springs. The soil is assumed to be linearly elastic, isotropic and semi-infinite half-space.

![Figure 1. Rectangular footing.](image)

The spring constant represents a linear relation between applied load and displacement of the foundation, which implies a linear stress-strain relationship for the soil. To simulate the soil structure interaction effects, the base of the structure is assumed to be supported by a system of frequency independent springs in horizontal, rocking and vertical degree of freedom.

Embedment significantly increases the stiffness of the foundation primarily because the contact area between the foundation and the soil is increased. A complete set of expressions as well as dimensionless charts for readily computing the dynamic stiffness and damping coefficients for foundations harmonically oscillating on or in a homogenous half-space was presented3. The effect of actual side wall-soil contact area on the stiffness parameters was considered as well as the effects due to separation (gapping) and slippage that is likely to occur near the ground surface where the initial confining pressure is small. The dynamic stiffness coefficients corresponding to the six-degrees of freedom for a soil-foundation system were also presented. These expressions are derived for arbitrary shapes. However in this study only the expressions for a rectangular foundation have been used.
Components of spring stiffness which represent the underlying soil are tabulated in Table 1.

**Table 1. Stiffness for a rigid plate on a semi infinite homogeneous elastic half space.**

| Stiffness parameters | Rigid Plate Stiffness at Surface |
|----------------------|----------------------------------|
| Vertical Translation | \( K_{0v} = \frac{GB}{1-v}(1.55\left(\frac{L}{B}\right)^{0.75} + 0.8) \) |
| Horizontal Translation (along X direction) | \( K_{0x} = \frac{GB}{2-v}(3.4(\frac{L}{B})^{1.65} + 1.2) \) |
| Horizontal Translation (along Z direction) | \( K_{0z} = \frac{GB}{2-v}(3.4(\frac{L}{B})^{1.65} + 0.4(\frac{L}{B}) + 0.8) \) |
| Rotation about Z axis | \( K_{0z} = \frac{GB}{1-v}(0.4(\frac{L}{B}) + 0.1) \) |
| Rotation about X axis | \( K_{0x} = \frac{GB}{1-v}(0.47(\frac{L}{B})^{1.1} + 0.034) \) |
| Torsion | \( K_{0T} = GB(0.53(\frac{L}{B})^{3.45} + 0.51) \) |

As shown in Table 1, \( G \) is shear modulus, \( B \) is width of footing, \( L \) stands for length of the footing and \( v \) is poisons ratio. \( K_{0HX}, K_{0VY} \) and \( K_{0HZ} \) are translations along \( X, Y \) and \( Z \) directions respectively. \( K_{0RX} \) represents for rotation about \( X \) axes, \( K_{0RZ} \) is rotation about \( Z \) axes and \( K_{0RY} \) is torsion. The shear modulus \( (G) \) can be obtained from the shear wave velocity \( (V_s) \) and the mass density of the soil \( (\rho) \) as:

\[
G = \rho (V_s^2) \tag{1}
\]

3. Analysis Steps

A moment resisting frame is modelled by running the steps presented in Figure 2. SAP2000 has been used for the last 20 years in the arts of design of structures. This sophisticated numerical analysis software is an analysis and design commercial package program. SAP2000 has been extended to latest version SAP2000 Version 15 which is used in this study.

4. Case Study

The current analysis encompasses numerical analysis of a 2-D six-storey frame with four different support conditions as shown in Table 2. Properties of the frame such as dimensions, reinforcements and the spring properties are same throughout this research. Storey height is equal to 3m and bay length is 6 m. Beam and column sections are presented in Figure 3.

**Table 2. Models considered during this research.**

| Model No. | Support condition |
|-----------|------------------|
| Model 1   | Fixed            |
| Model 2   | Base isolators  |
| Model 3   | Springs          |
| Model 4   | Base isolators and Springs |
For the first model, foundation is assigned to be fixed support, Figure 4(a). Rigid supports are assigned at the base of each column. The second model is associated with base isolation, Figure 4(b). This frame is isolated from the ground with base isolators installed below each column. A base isolated system is supported by a series of bearing pads which are installed between the foundation and building. When the ground shakes, the base isolation rolls. If the base isolators are properly chosen, the forces induced by ground motion are anticipated to be few times smaller compared to fixed-base frame. In the third model springs represent the soil, therefore, soil structure interaction is considered, Figure 4(c). In a combined Soil foundation system more flexibility is provided to the buildings. When loading is applied on the structure, due to soil movement, building displacement occurs depending on type of underlying soil. This movement causes higher energy dissipation in the performance of soil-structure system. The last case has spring and base isolation techniques combined together, Figure 4(d). In this model, when loads are transferred to the building, the structural members transfer the loads to the ground and the soil may settle allowing structure to experience some deformation. To reduce this effect, base isolation installation is introduced in the system to isolate the structural displacements from soil.
Table 3 shows geotechnical properties of three different soil layers such as soil type, shear wave velocity, elastic modulus, shear modulus, density of the soil and poisons ratio. These mechanical properties of soil are used to calculate the stiffness of the springs.

Table 3. Geotechnical characteristics of the soil [31].

| Soil type | Shear Wave Velocity $V_s$(m/s) | Elastic Module, $E$(Kg/cm$^2$) | Shear Module, $G_{max}$(Kg/cm$^2$) | $P$ (Kgs$/m^4$) | Poisson's Ratio |
|-----------|-------------------------------|-------------------------------|-------------------------------|----------------|----------------|
| I         | 600                           | 16400                         | 6480                          | 180            | 0.28           |
| II        | 320                           | 4945                          | 1808                          | 175            | 0.39           |
| III       | 150                           | 935                           | 335                           | 150            | 0.4            |

5. Results and Discussion
The selected 2D frame structure was subjected to El Centro earthquake. In order to conduct a parametric study, the joint located at top right corner, exterior left-side columns and middle-bay beams of the considered frame are selected (Figure 5). The aim is to evaluate the effects of supporting conditions to the corresponding displacements in horizontal direction (X), Rotations about Y axes, axial forces, shear forces and bending moments.
5.1. Displacement of the selected top right joint

Displacements of time history analysis for top corner node for all four models are plotted together in Figure 6 which shows that the fixed base system has the second smallest displacement among four models because the movement of the system is prevented due to rigidity of the system and fixity of the base of the structure but when base isolation is installed the displacement is decreased even further by 58% of the fixed base.

The same model without base isolation is analyzed by taking into account the soil interaction. This analysis showed that huge displacements in the system are caused by earthquake loading but base isolation is applied to prevent damages and absorb the earthquake energy. The building frame equipped with springs has 54.4 mm displacement. However, when the structure is equipped by base isolation, the maximum displacement in the top corner node is reduced to 39.9 mm.

Maximum and minimum displacements in X direction for all models are presented in Table 5. The soil structure interaction also affects the amplitude, as shown in Table 5 the peak amplitude of frame assigned with spring is the highest values 100.7 mm and after installation of base isolation the peak amplitude is reduced to 78.0 mm. Therefore, soil increases the amplitude as compared to fixed base structure which has the peak amplitude of 44.37 mm.
Table 4. Displacement in X direction.

| Model               | Max displ. (mm) | Variation (%) | Min displ. (mm) | Variation (%) | Amplitude (mm) | Variation (%) |
|---------------------|-----------------|---------------|-----------------|---------------|----------------|---------------|
| Frame with fixed Base | 22.8            | 0.0           | -21.5           | 0.0           | 44.3           | 0.0           |
| Frame with BI       | 9.5             | -57.9         | -9.0            | -8.0          | 18.6           | -58.0         |
| Frame with Spring   | 54.4            | 138.9         | -46.2           | 114.5         | 100.7          | 127.1         |
| Spring+BI           | 39.9            | 74.9          | -38.1           | 76.8          | 78.0           | 75.8          |

5.2. Rotation of Selected Joint in The Considered Models

Rotation of top right corner node is shown in Table 6. The resulting rotations are compared in Figure 7 and it is observed that the frame with spring and base isolation has got the minimum rotation of 0.000349 radian. The second smallest is the fixed base structure with magnitude of 0.000417 radian. The third smallest value is that of base isolated frame with 0.001128 radian.

5.3. Drift of The Frame Due to External Seismic Load

Drift of left side of the frame due to the external load is depicted in Figure 8. The base isolated structure has more drift than the rest because of the base isolation flexibility in horizontal direction. In base isolated system, first storey has the largest drift and it decreases toward the last storey as shown in Figure 8. The structure without base isolation shows that, the system is almost near to zero drift. Both systems, fixed base and spring equipped system, have less drift compared to base isolated structure in horizontal direction.

5.4. Rotational Drift in Y Direction For Four Models

Figure 9 presents rotational drift of four models. It shows that base isolated systems have lower rotation which is because the base isolation system separates the structure from rotations introduced by the earthquake. According to Figure 9, the first storey of frame with spring system has experienced more rotation than the other systems.

Table 5. Rotation of top node.

| Model               | Max. rotation (radian) | Variation (%) | Min. rotation (radian) | Variation (%) | Amplitude (radian) | Variation (%) |
|---------------------|------------------------|---------------|------------------------|---------------|-------------------|---------------|
| Fixed frame support | 0.0004                 | 0.0           | -0.0004                | 0.0           | 0.0009            | 0.0           |
| Frame with BI       | -0.0011                | -370.5        | 0.0010                 | -332.3        | -0.0001           | -110.0        |
| Frame with Spring   | 0.0016                 | 285.1         | -0.0013                | 201.1         | 0.0030            | 241.6         |
| Frame with Spring + BI | 0.0003              | -16.3         | -0.0004                | 0.0           | 0.0007            | -18.9         |
Figure 7. Rotation of top node in all considered models.

Figure 8. Drift of all models in X direction for all models.

Figure 9. Rotational drift around Y direction.
5.5. Vertical drift in z direction for four models
The vertical drift of the frame models are presented in Figure 10. The Figure shows that the structure supported by spring has largest vertical drift while the frame equipped with base isolation and spring takes the second position. Fixed base and base isolated systems have lower vertical drifts. Therefore, soil structure interaction clearly affects the vertical drift of the system since soil presence leads to soil settlement as some vertical movement is provided into the frame structure.

5.6. Axial forces of the left-side columns under el centro earthquake
In order to investigate the effect of support condition on the overall behavior of structure, member forces like axial, shear and moment associated with the left exterior columns of the frame are discussed. The axial forces of left side columns in all storey levels are shown in Table 9. This table shows that the axial force of fixed base structure is larger compared to other models except for the frame with spring that is because of soil flexibility. Axial forces in the exterior columns of base isolated system are degraded by 681% to 79.6% for first and sixth floor respectively. Also axial forces undertaken by frame with base isolation and soil are decreased from 71.2% at the first floor column to 85.3% at sixth floor. However, axial forces of the outer columns with soil structure interaction are overestimating other cases. Therefore, soil structure interaction has increased the axial forces in the exterior columns of system while base isolation reduces these forces. Figure 11 shows trend of axial force alteration against number of stories.

5.7. Shear forces of the left side exterior columns
Table 10 shows the shear forces of outer left columns. It is clear that fixed base frame model has suffered larger shear forces due the fixity of supports. On the other hand, inspection of the variation of shear forces indicates that the columns on base isolated frame and frame with combined spring and base isolation have considerably undertaken lower magnitudes of shear force. However, frame supported by springs has experienced larger forces than the fixed base system.

![Figure 10. Comparison of vertical drifts of all models.](image)

| No. of storeys | Drifts (mm) |
|----------------|-------------|
| 1              | 4.0         |
| 2              | 9.0         |
| 3              | 1.0         |
| 4              | -1.0        |
| 5              | 2.0         |
| 6              | -3.0        |

**Figure 10.** Comparison of vertical drifts of all models.

**Table 6.** Axial forces of left corner column.

| Floor No. | Fixed frame (kN) | base isolated frame (kN) | Variation (%) | Spring Frame (kN) | Variation (%) | BI+ Spring Frame (kN) | Variation (%) |
|-----------|------------------|--------------------------|---------------|-------------------|---------------|-----------------------|---------------|
| 1         | 570.51           | 181.94                   | -68.1         | 687.45            | 20.5          | 164.10                | -71.2         |
| 2         | 449.85           | 116.65                   | -74.0         | 521.50            | 15.9          | 101.68                | -77.4         |
| 3         | 309.29           | 72.79                    | -76.4         | 355.81            | 15.0          | 62.11                 | -79.9         |
| 4         | 184.62           | 41.18                    | -77.7         | 221.03            | 19.7          | 35.18                 | -80.9         |
| 5         | 91.80            | 19.52                    | -78.7         | 114.26            | 24.4          | 15.29                 | -83.3         |
| 6         | 32.55            | 6.63                     | -79.6         | 40.51             | 24.4          | 4.76                  | -85.3         |
Figure 11. Axial forces of left corner column.

Table 7. Shear forces of left exterior columns.

| Floor No | fixed base frame (kN) | base isolated frame (kN) | Variation (%) | spring frame (kN) | Variation (%) | BI+ Spring frame (kN) | Variation (%) |
|----------|------------------------|--------------------------|---------------|------------------|---------------|-----------------------|---------------|
| 6        | 230.72                 | 63.12                    | -72.6         | 322.43           | 39.7          | 75.81                 | -67.1         |
| 5        | 186.92                 | 58.74                    | -68.5         | 189.00           | 1.1           | 26.17                 | -86.0         |
| 4        | 157.76                 | 43.39                    | -72.5         | 175.78           | 11.4          | 23.05                 | -85.3         |
| 3        | 120.38                 | 38.37                    | -68.1         | 129.36           | 7.4           | 19.66                 | -81.3         |
| 2        | 80.90                  | 16.45                    | -79.6         | 85.88            | 6.1           | 19.66                 | -75.7         |
| 1        | 25.90                  | 9.17                     | -64.5         | 17.17            | -33.7         | 4.82                  | -81.3         |

Figure 12 shows the shear force graph plotted against number of storey. It is shown that the spring-equipped frame has been subjected to larger shear forces compared to fixed base frame, base isolated frame and frame with base isolation and spring.

5.8. Moments of the exterior left side columns

Table 11 indicates variation of moments of exterior columns at the left side of the frame. It is found that those columns at the two lower storey levels in frame with base isolation experience less force.
compared to other frames while for floors 3 to 6, columns of the frame model equipped by base isolation system and springs have experienced the least moments. The implemented El Centro earthquake has caused larger moments to the structures supported by springs. However, presence of base isolation system led to degradation of moment along the height of the frame building as depicted in Figure 13.

Table 8. Moment of the left corner columns.

| Floor No. | Fixed base frame (kN.mm) | Base isolated frame (kN.mm) | Variation (%) | Spring frame (kN.mm) | Variation (%) | BI+ Spring frame (kN.mm) | Variation (%) |
|-----------|--------------------------|-----------------------------|---------------|----------------------|---------------|--------------------------|---------------|
| 6         | 652.54                   | 158.53                      | -75.7         | 708.69               | 8.6           | 237.03                   | -63.6         |
| 5         | 329.31                   | 94.74                       | -71.2         | 263.18               | -20.0         | 115.85                   | -64.8         |
| 4         | 242.64                   | 118.55                      | -51.1         | 278.43               | 14.7          | 65.55                    | -72.9         |
| 3         | 240.90                   | 102.86                      | -57.3         | 243.12               | 18.8          | 52.32                    | -78.2         |
| 2         | 209.07                   | 64.10                       | -69.3         | 195.61               | -16.2         | 51.71                    | -75.2         |
| 1         | 107.97                   | 20.66                       | -80.8         | 75.64                | -29.9         | 21.35                    | -80.2         |

5.9. Axial forces of the middle bay beams

Table 12 shows alteration of axial forces induced in the middle bay beams of the considered frame for four different frame models. Axial forces in middle-bay beams of based isolated frame have all considerably reduced with respect to fixed base model while variation of axial force in the two remaining models has not followed a regular pattern as shown in Figure 14.

Table 9. Axial forces of the beams.

| Floor No. | Fixed base frame (kN) | Base isolated frame (kN) | Variation (%) | Spring frame (kN) | Variation (%) | BI+Spring frame (kN) | Variation (%) |
|-----------|-----------------------|--------------------------|---------------|-------------------|---------------|----------------------|---------------|
| 1         | 0.038                 | 0.009                    | -76.3         | 0.022             | -42.1         | 0.045                | 18.4          |
| 2         | 0.038                 | 0.023                    | -39.4         | 0.044             | 15.7          | 0.017                | -55.2         |
| 3         | 0.043                 | 0.030                    | -30.2         | 0.016             | -62.7         | 0.011                | -74.4         |
| 4         | 0.013                 | 0.012                    | -7.6          | 0.020             | 53.8          | 0.022                | 69.2          |
| 5         | 0.036                 | 0.035                    | -2.7          | 0.032             | -11.1         | 0.002                | -94.4         |
| 6         | 0.020                 | 0.014                    | -30.0         | 0.036             | 80.0          | 0.017                | -15.0         |
5.10. Shear forces of the middle bay beams

Shear force of the beams located in the middle bay are tabulated in Table 13. It is shown that the shear forces in the base isolated frame and base isolated with spring system are less than that of fixed base except the frame equipped with spring. This is due to the soil settlement and corresponding frame deformation. The base isolated frame has the lowest beam shear forces among considered models. Presence of base isolation system together with soil modeling showed to have subtractive effect on the shear forces. This trend is also illustrated in Figure 15.

| Floor No. | fixed base frame (kN) | base isolated frame (kN) | Variation (%) | spring frame (kN) | Variation (%) | BI+Spring Frame (kN) | Variation (%) |
|-----------|-----------------------|-------------------------|--------------|------------------|--------------|----------------------|--------------|
| 1         | 114.01                | 56.73                   | -50.2        | 187.5            | 64.4         | 63.5                 | -44.3        |
| 2         | 134.13                | 55.21                   | -58.8        | 194.7            | 45.2         | 47.0                 | -65.0        |
| 3         | 119.41                | 43.22                   | -63.8        | 167.6            | 40.3         | 32.9                 | -72.4        |
| 4         | 90.44                 | 27.57                   | -69.5        | 131.9            | 45.9         | 26.4                 | -70.9        |
| 5         | 58.09                 | 14.73                   | -74.6        | 93.9             | 61.6         | 18.2                 | -68.7        |
| 6         | 30.54                 | 6.97                    | -77.2        | 58.6             | 91.9         | 10.7                 | -65.0        |

Figure 14. Comparisons of axial forces of the beams.

Figure 15. Shear forces of the beams in the middle.
5.11. Moments of the middle bay beams

The induced moments in all considered models are compared in Table 14 and also illustrated in Figure 16. As can be seen in Table 14, the varying trends of moments associated with two models namely baseisolated frame and base isolated with springs have similarity in the way from lower floor beam to the highest one. In these earlier models all middle bay beams have experienced degradation of induced moments compared to fixed base model and that means presence of base isolation system has generally a positive effect on the beam moments. For instance, in the 6th floor the moment of fixed base is 91.6 (kN.mm) and that of base isolated frame has reduced by 77.2% to 20.9 (kN.mm). The higher is the floor level the larger is the beam moment degradation. However, the chart displays the negative impact of springs on the beam moments by considerably raising them. Comparison of the frame equipped with spring to fixed base one, shows that moment is increased by 64.4% to 91.9% from first floor to sixth floor respectively. Figure 16 represents the moment of considered models with different support assignments. Moment values associated with frame with spring is obviously overestimating other models by noticeable difference.

| Floor No. | fixed base frame (kN.mm) | base isolated frame (kN.mm) | Variation (%) | spring frame (kN.mm) | Variation (%) | BI +Spring Frame (kN.mm) | Variation (%) |
|-----------|--------------------------|----------------------------|---------------|----------------------|---------------|--------------------------|---------------|
| 1         | 342.1                    | 170.2                      | -50.2         | 562.4                | 64.4          | 190.5                    | -44.3         |
| 2         | 402.4                    | 165.6                      | -58.8         | 584.2                | 24.9          | 140.9                    | -65.0         |
| 3         | 358.2                    | 129.7                      | -63.8         | 502.8                | 63.1          | 98.8                     | -72.4         |
| 4         | 271.3                    | 82.7                       | -69.5         | 395.8                | 45.9          | 79.1                     | -70.9         |
| 5         | 174.3                    | 44.2                       | -74.6         | 281.6                | 61.6          | 54.6                     | -68.7         |
| 6         | 91.6                     | 20.9                       | -77.2         | 175.9                | 91.9          | 32.1                     | -65.0         |

Figure 16. Comparison of the moment of middle beams in the middle bay.

6. Conclusions

This paper focused on the effects of soil structure interaction, base isolation system and combined base isolation along with soil idealization on building structures subjected to seismic disturbance. The displacements as well as forces such as shear forces, axial forces, bending moments and also drift of the storey were studied and compared with fixed base support to investigate the impact of support
condition on the frame structures. These models were analysed and examined using El Centro earthquake and the following conclusions are obtained:

a) Frame structure supported by spring had larger displacements, rotations, shear forces, axial forces, bending moments and drifts compared to the other models.

b) The base isolated structure experienced lower earthquake effects compared to base isolated and spring equipped structures.

c) The soil structure interaction has lessened the performance of base isolators and made frame building vulnerable to earthquake impact as it increased some of the reactions of the system compared to base isolated building.

Therefore, it is generally concluded that base isolation together with soil affect the very response of the building subjected to seismic loading. Soil structure interaction reduces the performance of the structure by providing more flexibility to the system and consequently larger deformation of the structure.

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References

[1] Hejazi F, Noorzaei J, Jaafar MS, Thanoon WA, Abdullah A, Ali A. Optimization of active variable stiffness system for controlling structural response of a building under earthquake excitation. J Struct Eng.;36(4):235-242.(2009)

[2] Abdi H, Hejazi F, Saifulnaz R, Karim IA, Jaafar MS. Response modification factor for steel structure equipped with viscous damper device. Int J Steel Struct.;15(3):605-622. doi:10.1007/s13296-015-9008-4. (2015)

[3] Hejazi F, Shoaei MD, Tousi A, Jaafar MS. Analytical Model for Viscous Wall Dampers. Comput Civ Infrastruct Eng.;31(5):381-399. doi:10.1111/mice.12161.(2016)

[4] Idriss I. Analyses for Soil-structure Interaction Effects for Nuclear Power Plants. American Society of Civil Engineers. ASCE: New York, 1979.

[5] Wong H, Luco J. Dynamic response of rigid foundations of arbitrary shape. Earthquake engineering & structural dynamics.;4(6):579-587.(1976)

[6] Gazetas G. Foundation vibrations. Springer; 1991.

[7] Spyrakos C, Beskos D. Dynamic response of flexible strip-foundations by boundary and finite elements. Soil Dynamics and Earthquake Engineering.;5(2):84-96.(1986)

[8] Wolf JP. Foundation vibration analysis using simple physical models. Pearson Education; 1994.

[9] Wolf JP. Dynamic soil-structure interaction. Prentice-Hall Englewood Cliffs, NJ; 1985.

[10] Goyal A, Chopra AK. Earthquake analysis of intake-outlet towers including tower-water-foundation-soil interaction. Earthquake engineering & structural dynamics.;18(3):325-344.(1989)

[11] Xu C, Spyrakos C. Seismic analysis of towers including foundation uplift. Engineering Structures.;18(4):271-278.(1996)

[12] Rahgozar MA. Seismic soil-structure interaction analysis of structural base shear amplification. Ottawa, Ontario, Canada: Carleton University; 1993.

[13] Johnson J. Earthquake Engineering Handbook. Florida, USA: CRC Press; 2003.

[14] Tongaonkar N, Jangid R. Seismic response of isolated bridges with soil–structure interaction. Soil Dynamics and Earthquake Engineering.;23(4):287-302.(2003)

[15] Gazetas G. Seismic design of foundations and soil-structure interaction. First European conference on earthquake engineering and seismology. 2006.

[16] Kolekova Y, Schmid G, Stojanovski K. Soil-structure interaction under seismic excitation. Slovak Journal of Civil Engineering.;18-21.(2007)
[17] Pecker A, Paolucci R, Chatzigogos C, Correia AA, Figini R. The role of non-linear dynamic soil-foundation interaction on the seismic response of structures. Bulletin of Earthquake Engineering.;1:20.(2013)
[18] Kelly JM, Naeim F. Design of seismic isolated structures: From theory to practice. Nueva York, John Wiley & Sons. 1999.
[19] Komodromos P, Stiemer S. Seismic isolation for earthquake resistant structures. Applied Mechanics Reviews.;54:112.(2001)
[20] Skinner RJ, Robinson WH, McVerry GH. An introduction to seismic isolation. USA, New York: Wiley; 1993.
[21] International Building Code. Dearborn Trade Publishing; 2000.
[22] Eurocode 8: Design of structures for earthquake resistance. 1990.
[23] Iemura H, Pradono MH. Passive and semi-active seismic response control of a cable-stayed bridge. Journal of Structural Control.;9(3):189-204.(2002)
[24] Spyrakos C, Maniatakis CA, Koutromanos I. Soil–structure interaction effects on base-isolated buildings founded on soil stratum. Engineering Structures.;31(3):729-737.(2009)
[25] Gueguen P. Experimental analysis of the seismic response of one base-isolation building according to different levels of shaking: example of the Martinique earthquake (2007/11/29) Mw 7.3. Bulletin of Earthquake Engineering.;10(4):1285-1298.(2012)
[26] Jacob M, Dodagoudar G, Matsagar V. Seismic Reliability Analysis of Base-Isolated Buildings. Proceedings of the International Symposium on Engineering under Uncertainty: Safety Assessment and Management (ISEUSAM-2012). Springer: India.; 1251-1265.(2013)
[27] Chaudhary M, Abe M, Fujino Y. Identification of soil–structure interaction effect in base-isolated bridges from earthquake records. Soil Dynamics and Earthquake Engineering.;21(8):713-725.(2001)
[28] Spyrakos C, Vlassis A. Effect of soil-structure interaction on seismically isolated bridges. Journal of earthquake engineering.;6(03):391-429.(2002)
[29] Vlassis A, Spyrakos C. Seismically isolated bridge piers on shallow soil stratum with soil–structure interaction. Computers & structures.;79(32):2847-2861.(2001)
[30] Manolis GD, Markou A. A distributed mass structural system for soil-structure-interaction and base isolation studies. Archive of Applied Mechanics.;82(10-11):1513-1529.(2012)
[31] Tabatabaieefar HR, Massumi A. A simplified method to determine seismic responses of reinforced concrete moment resisting building frames under influence of soil–structure interaction. Soil Dynamics and Earthquake Engineering.;30(11):1259-1267.