Short Review on Soil-Structure Implementation in Base Isolated Structures

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Abstract. Structural control is a subject that has been gaining interest for almost the last forty years. However, soil-structure interaction (SSI) implementation in control studies is relatively new, but it has attracted many researchers’ attention for both theoretical and experimental research. Besides structural control SSI is an important topic which should be studied more. SSI was not considered during the design stages of different structures, which led in the unexpected results after the earthquakes. In this paper the studies considering SSI in base isolated structures are reviewed. From the structural and earthquake engineering point of view, many studies considered near or far fault earthquakes and used scaled mathematical models for numerical examples. Most of the research is based on existing results of the earthquakes and real building damages. On the other hand, there are some researchers who designed scaled structures to perform experimental works under artificial earthquake excitation in order to investigate the seismic performance of the structures. This study aims to demonstrate the conclusion and numerical examples obtained from base isolation studies considering SSI. With regards to the short review, it can be mentioned that SSI affects the structure and the behaviour of the base isolation. Considering SSI in base isolation research might increase the authenticity of the corresponding study and might result in more realistic results than fixed base structural analysis.

1. Introduction

The main purpose of the Base Isolation (BI) or known as seismic base isolation presented by Chopra [1] is the creation of an interface between the superstructure and foundation. In this interface the vertical stiffness is high while the horizontal one presents itself low. These characteristics allow the decoupling of the building during an earthquake and reducing the probability of damage by presenting lower base shear forces and inter-story drifts. BI increases the natural period of the superstructure which leads to smaller accelerations on the superstructure.

There are 3 main categories of BI as; 1) Passive base isolation techniques 2) Hybrid isolation with semi-active devices 3) Hybrid base isolation with passive energy dissipaters. As it is discussed by Dutta [2] and Jangid and Datta [3] The first passive base isolation was the idea of Lloyd Wright who created the seismic isolation of Imperial Hotel in Tokyo, which survived in an earthquake on 1923.

Soil Structure interaction (SSI), is the design notion of considering the responses of structure, foundation and soil medium. In FEMA 356 [4], SSI is classified as a rare case that can modify the spectral response of the structures, especially when it rests in soft soil.
SSI implementation in control studies (base isolated structures) is relatively new. Not considering SSI during the design stages of different structures led in the unexpected results after the earthquakes. Many researchers wanted to understand if behaviour of the BI is affected by the soil where the structure is founded. In this paper the studies considering SSI in base isolated structures are reviewed.

2. Studies Considering SSI in BI research

Giarlelis et al. [5] presents us some real life example where SSI reveals itself as an adverse factor. “Stavros Niarchios Cultural Center” and the National Library of Greece area construction, was mainly poor silty sands. A choice for the seismic isolator should be made by considering all the disadvantages that the soil type introduces. Choosing and designing the appropriate base isolation was done by three following stages. Firstly, it was analysed as a single degree of freedom system (SDOF). Dynamic response spectrum analyses were carried out using Finite Element Method for a design with more details. Their last method of design was non-linear time history analyses by using two sets of selected earthquake records. These records were semi-artificial and real earthquakes in the multiple seismic studies. The spectrum analysis based in the US Seismic codes showed that, the referenced peak ground acceleration was $a = 0.267 \, \text{g}$ compared to the value of $0.16 \, \text{g}$ which is the normal acceleration for the seismic zone. This great difference came as a result of the SSI. The only way to surpass the inconvenience of the damaging SSI factor and to reach the high seismic performance request was to place the appropriate BI. Choosing the friction pendulum isolators as a type of base isolation in the above mentioned conditions made the design well-known and admired in the design and construction industry [5]. Manolis and Markous [6] also used the Finite Element Method and performed the analysis with multiple degree of freedom (MDOF) system to present a combination of BI and SSI. They considered a cantilever beam, representing a system of distributed mass. Evaluating the mechanical properties of the SSI and BI together, and filtering the change in the ground movement encountered by the structure base, they conclude that the base isolation function depends on the type of soil the structure rests.

Finite Element Method was also used by Zhenxia and Haiping [7] to investigate SSI effects on base isolated structures. It was determined in their study that the behaviour of seismic isolators is related with soil conditions. Another study that should be mentioned was carried out by Alavi and Alidoost [8]. The aim of their study was to estimate the behaviour of SSI in seismic isolated structures qualitatively and quantitatively. It was performed by considering 4 different shear frames of 2, 4, 7 and 10 stories with BI. Firstly, they neglected SSI in their simulations. Fundamental periods ($T_0$) of seismically isolated structures were varying between 1.6, 2, 2.5 seconds. In the study 3 different soil types were taken into consideration. The model representation for the super-structure and the base isolators was done by the aid of dampers and the spring stiffness characteristics. In Figure 1 a 4-story building is illustrated by reproducing Figure 1 & 2 of [8]. The usage of the half-space cone model theory introduces the soil’s parameters below the structure. It also simulates the soil behaviour in seismic-isolated buildings to obtain seismic responses. Right side of Figure 2 displays the mathematical model that was chosen for the analysing of the seismically-isolated structure and soil system. Where parameters $C_s$, $K_s$, $m_s$, and $h_{eq}$ are damping, stiffness, lumped mass and equivalent height of structure. The height of each storey was given as 3.3 m, 3 bays in each direction with a span of 5 m and the effective weight of each storey is 2000 KN respectively.
The parameters of the soil were given with Equations 2.2, 2.3, 2.4 and 2.5 in their study. Please see [8] for more information. They defined an important parameter which was \( a_0 \). This parameter presents the ratio between the relative stiffness of the base isolated structure and soil. This ratio was 0 for fixed base structure with BI. In order to see the variation of it in different soil types and structures, Table 2.2 in [8] was compose. They concluded that bigger \( a_0 \) means more influence of SSI on the response. Bigger structure and softer soil displays larger value of \( a_0 \). The dynamic response spectrum analysis method was used to observe the changes in the fundamental period, base shear and total relative displacements of the buildings, considering different soils and base isolated structure. Please see Figures 4 and 5 in [8] for more information on the aforementioned details. The elements that should be considered for the SSI effect in the seismic response in a base isolated structure are the soil profiles, stiffness, mass, foundation type and aspect ratio of the structure. From the results of the seismic response spectra analysis in base isolated structures resting especially in soft soil, an increase in the fundamental periods was observed. It was concluded that these effects of SSI don’t manifest themselves in stiff and very stiff soil [8].

The behaviour of (SSI) on the response of base-isolated buildings was a matter of interest for Karabörk et al. [9] as well. For this purpose, multi-story structures with high damping rubber bearing (HDRB) seismically isolated, resting on soft soil was considered in the study. Superstructure and soil were modelled linearly, while the BI was modelled non-linearly. The ground motion data coming from Erzincan, Marmara and Düzce earthquakes were used by dynamic models in SAP2000 software. The properties of HDRB is given with Table 1 [9]. Table 1 is composed by considering the Table 1 of [9].

**Table 1. Properties of Rubber Bearing (Inspired by [9])**

| Soil type      | Density (Kg/m³) | Elastic Modulus (Pa) | Damping ratio \( \alpha \) | Damping ratio \( \beta \) | Poisson’s ratio \( \nu \) | \( \xi \) |
|----------------|-----------------|----------------------|-----------------------------|-----------------------------|-----------------------------|---------|
| Dense sand     | 1840            | 1.0E8                | 0.566351                    | 0.014813                    | 0.3                          | 0.05    |
| Loose sand     | 1470            | 2.5E7                | 0.268412                    | 0.00312554                  | 0.3                          | 0.05    |
| Concrete (5storey) | 2400           | 2.5E10               | 0.38832                     | 0.00424                     | 0.2                          | 0.05    |
| Concrete (20storey) | 2400             | 2.5E10               | 0.11817                     | 0.01335                     | 0.2                          | 0.05    |

**Figure 1. Redrawn Building and Mathematical Model [8]**
Time history analysis was considered and a comparison between isolated and fixed-base structures with and without SSI was carried out. Base shear forces, top story accelerations, base level accelerations, periods and maximum internal forces were observed. The Figures 12, 13, 14 from their study [9] show the variation of displacements with structure height for Düzce, Marmara and Erzincan Earthquake. For more details on these important figures please read [9]. From all the results gathered they reached the conclusion that SSI is a principal element (in terms of earthquakes) for the selection of an appropriate isolator for base-isolated structures on soft soils.

Another study done by Karabörk et al. [10] came up with the same conclusion with the study of Li et al., [11] introducing that the effect of SSI is more pronounced on a stiffer isolation system.

To reach a conclusion as it concerns the effect of soft soil in a base isolated structure during an earthquake, Kelly [12] used 2 models in the shaking tables. One of these models was with natural frequency taken by a nuclear powerplant and the second model had a lower frequency, quarter of the nuclear plant model. Second model had also high damping rubber seismically isolated. The study led to the result that increasing the period of the isolation system in soft soil is helpful, this augmentation should be reached from the elastomeric elements, and the large size of isolators is a beneficial in such terrains [12]. Another study performed on a seismically isolated power plant was carried out by Ashiquzzaman and Hong [13]. They pointed out that SSI effects can be inconsequential in tall buildings but not in stiffer ones. Moreover, they added that it can modify the modal attributes of structures.

A detailed study related to an isolated structure considering SSI with an unbounded section was conducted by Tsai et al. [14]. They underlined that the performance of the base isolation in decreasing the earthquake energy impact to the structure is dependent on the flexibility of the resting soil and the radiation damping. Controversially, another study done by Tsai et al. [15] for the same subject concluded that only the first mode of structure is affected by the seismic isolator, while higher modes by soil characteristics.

The study conducted by Spyarakos et al. [16] intended to determine the effect of SSI on the response of seismic-isolated multi-story buildings resting on an elastic soil stratum over a bedrock. This system given in Figure 2 was exposed to harmonic ground motion. Figure 2 is re-illustrated by considering Figures 1, 2 & 3 of [16]. Equations independent from frequency were used to point out damping and stiffness for rigid surface of foundation on the soil layer under which bedrock rests at shallow depth. Performing some series of parametric studies and assuming the mass of foundation to be negligible it was possible to transform the four-degree of freedom system into a two-degree of freedom fixed base.

Figure 2. Example System from the Study [16] (Redrawn)

Figure 2 given in [16] and other curves in the corresponding paper show the relations of the soil structure parameters. With respect to these figures and analysis, they concluded that SSI becomes meaningful for squat structures having a small mass resting on loose soil, with a significant large thickness. Spyarakos et al. [17] continued their path in analyzing the effect of SSI on the response of base-isolated building. They use the same expressions, parameters and models used in the study presented before Spyarakos et al. [16]. An important curve from [17] that defines how ω1 /ωs ratio (site angular frequency/structure angular frequency) varies with respect the dimensionless parameters ηs.
(stiffness ratio) expressing the relative stiffness between structure and soil is given in Figure 3 of [17]. Please see reference no [17] for the corresponding figure. The structural ratio damping is taken as $\zeta_s=2\%$ while for the base isolation it is $\zeta_b=25\%$. The soil viscous damping ratio is $\zeta_g=5\%$, which defines small-to-moderate soil deformation.

From the results obtained in their study it was concluded that SSI modifies the structure-base-isolation-foundation system frequency properties [17]. They also found that increasing the stiffness ratio leads to more significant effect of SSI in damping characteristics. In addition, as it was also mentioned in the previous study conclusions [16] the SSI affecting traces are more pronounced in squat, stiff structures resting in soft soils.

Du et al. [18] introduced a simplified technique to investigate the modal characteristics of base isolated high-rise structures considering the SSI. Formulas for natural periods, modes and modal damping ratios were derived by a 2DOF base isolated structure model. Their technique was also compared with the complex eigenvalue method defined by Costantinou and Kneifati [19], to verify their results [18]. Figure 3 shows the analytical model that they used in the study [18]. Figure 3 is illustrated considering [18]. They concluded that SSI might increase the contribution on higher modes in high-rise structures. Therefore, they mentioned that slender and tall building having stiff isolators are more affected by SSI than flexible structures. The usage of shear wall, sliding base isolation or pendulum ones was also suggested for these structures.

![Figure 3. Analytical Model Used by Du et al. [18] (Redrawn)](image)

During the study of a 3D nonlinear model of base isolation, Deb [20] investigated SSI and he obtained the results by using near fault earthquakes. As it concern the SSI issue Deb [20] relates it with the flexibility of isolation type. He also obtained that if the isolators have a greater flexibility compared to the soil, then the SSI has a negligible effect. His review was also based in the work of Novak and Henderson [21]. Novak and Henderson were also intrigued by the SSI issue. For this reason, in their study they derived the equation of motion for the structure by evaluating the SSI effect, especially in mat foundations consisting of joint or spread footings. They analyzed the SSI on buildings by taking into account the modal characteristics [21].
Another interesting subject was related with the behaviour of base isolators in bridges considering SSI. Two studies on this matter are presented in this paragraph. The first was carried out by Tongaonkar and Jangid [22]. They pointed out that SSI effects in isolated bridges can be favourable and may also cause a cut of the cost in design. They also mentioned that SSI effects are observed more in stiff bridges and especially when having stiff isolation systems [22]. While Dicleli et al. [23] performed their study in two types of bridges, one was heavy superstructure and the other was light. In their study it was emphasized that, SSI effect should be considered in soft soil type, not depending on the bridge type.

In order to observe the effect of SSI on base isolated structures Aden et al. [24] used SAP2000 software in their research. 4 different base conditions were considered to compare. These conditions were fixed base structure, structure with BI, structure supported by springs to describe the soil and the structure with base isolated and springs. The analysis was completed under the data of El Centro Earthquake. The seismic results analyzed were in terms of displacement, shear force, axial force, moment and drift of the columns and beams. Figure 4 shows the steps followed in their study [24]. Figure 5 shows the 2D 6 story frame structures analyzed in [24]. Figure 5 is illustrated using Figure 4 of [24]. For more information on the soil properties and drift results of their research, please check Table 3 and Figure 8 of [24]. Thanks to their numerical results obtained for moments, shear force, axial force and drifts, they reached to these important findings: i) when the frame structure is supported by springs, larger values of displacements, rotations, shear forces, axial forces, bending moments and drifts are obtained. ii) lower earthquake effects are observed in the base-isolated model in comparison with the BI and SSI combined model, iii) SSI effect has decreased the performance of seismic isolators, making the structure more and making the frame building more sensitive to earthquake impact by increasing some of the reactions of the system.

In the following section the conclusion obtained from this short review paper is given.

![Figure 4. Analysis Steps Considered in [24] (Redrawn)](image-url)
3. Conclusions
With respect to the outcomes from existing publications that use different methods and different models for their dynamic analysis, it might be stated that SSI affects the structure and the behaviour of the BI. Another result which is also supported by many studies is that, different types of soils display different effects on structures. Some of the works reviewed in this study focus on very soft soil and soft soil. Even though not all the research meet at the same point or focus in the same results, it might be concluded that BI needs to be studied together with SSI. Lastly it should be mentioned that this study is a short preliminary review on the subject. For futures studies, more detailed reviews considering more extensive literature on the usage of BI considering SSI might be useful for design engineers and researchers.

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