Effects of Soil Medium on Response of Base Isolated Multistory Frame Structures

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SUMMARY:

In conventional modeling of frame structures, soil-structure interaction is usually not taken into account. This leads to differences in the response of the structure. Base isolation is aimed at uncoupling the upper structure from the foundation, reducing thus the structural internal forces. For the last three decades, there have been done a lot of investigations to prove the effectiveness of base-isolation. The procedure for design and analysis of base isolated structures is usually based on the fixed base assumption where soil-structure interaction (SSI) effects are not considered. The presented investigations were aimed at analyzing the effects of SSI on base isolated frame structures. The influence of SSI on the structural response was shown by analysis of the results obtained for two models: the first model represented a base isolated frame structure, while the second model included the influence of the soil medium. In the presented investigations, three types of soil were taken into consideration, namely hard, medium and soft soils, as stated in Eurocode 8. The sub-soil conditions are represented by 30m thick soil deposits with four layers which rest on the bedrock. The side boundaries of the finite element model were composed of newly programmed infinite elements to eliminate the reflection of the seismic waves back to the model. The base isolated frame structure was supported by four high damping rubber bearings (HDRB). The lateral behavior of HDRB was considered as bilinear. The results from the performed 2D nonlinear dynamic analysis show that, in addition to the soil medium considered in the analysis, the structural properties and soil characteristics play a considerable role in seismic response of base isolated structures. Attention should be paid in case of base isolated structures founded in soft soil local conditions, because the flexibility of the soil can significantly increase the internal structural forces.

Keywords: Soil structure interaction, infinite element, base isolation, bilinear model

1. INTRODUCTION

One of the most effective techniques for design of earthquake resistant structures is the seismic isolation. The first implementation of rubber bearings to protect a structure from an earthquake was in 1969 for an elementary school in Skopje. This building was isolated by rubber bearings, whose behavior was linear elastic. Nowadays, modern rubber bearings are produced of high damping rubber, whose behavior is approximated by a bilinear model. Implementation of base isolation reduces the seismic loading on the building by interposing a flexible layer (with a very low lateral stiffness) between the foundation and the building. Flexibility in the horizontal direction increases the fundamental period of the building, which usually dominate in the earthquake input. The concept of seismic isolation has practically become a reality for the last 30 years with the development of the multi-layered elastomeric bearings. The investigations done by (Kelly J. M., 1986) (Kelly J. M., 1987), (Naeim & Kelly, 1999) and (Skinner, Robinson, & McVerry, 1993) et al. have given a huge contribution to acquiring knowledge on the behavior of base isolated structures and different types of bearings. The popularity of modern rubber bearings for base isolation of structures has been increased particularly after the Kobe (1995) earthquake (Fujita, 1998).

The seismic design of isolated structures is often based on the rigid base assumption and soil structure interaction (SSI) is ignored. Ignoring the SSI effects may lead to inaccurate structural response assessment. The aim of this paper is to evaluate the influence of the base isolation system together with SSI effects on the structural response of a multi-story frame during ground motion. In this work, soil is taken into consideration as dense, medium dense and loose soil, as stated in Eurocode 8, part 1. In order to examine the SSI effects on structural behaviour, an RC three story base isolated frame was modeled and a nonlinear dynamic analysis has been performed. The model has been excited by the time history of the El Centro NS record (1940-May-18 El Centro earthquake). The dynamic analysis was done by using the general finite element program ANSYS providing the possibility of modeling of both soil and structure, taking the soil-structure interaction into consideration. The variations in structural response to acceleration are presented in a graphic and tabular form and comparisons are made accordingly.

2. SOIL MODELLING

The soil medium is presented as a two dimensional model composed of four layers resting on bedrock. The bottom boundary of the soil model is fixed while the side boundaries are simulated using infinite elements in order to prevent the reflection of the waves.

The formulation of infinite elements is the same as for the finite elements in addition to the mapping of the domain. Zienkiewicz et al. (2000) was the first to develop infinite elements and since then, these have been developed in both frequency and time domain. Absorbent infinite elements have been proposed by Häggblad et al. (1987) and can be used in time domain. The infinite element is obtained from a six noded finite element as shown in Figure 1.

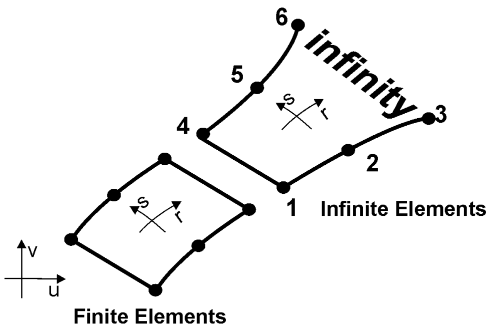


Figure 1. Finite and infinite element coupling

The element displacement in u and v direction is interpolated with the usual shape functions *N1*, *N2*, *N4* and *N5* :

$$u = [N_1 \quad N_2 \quad 0 \quad N_4 \quad N_5 \quad 0]\mathbf{u} \qquad\qquad v = [N_1 \quad N_2 \quad 0 \quad N_4 \quad N_5 \quad 0]\mathbf{v} \qquad (1)$$

Vectors **u** and **v** of expression (1) are nodal point displacements in global coordinates. For coordinate interpolation in the *r-s* coordinate system, a one-dimensional mapping is applied.

$$r = [M_1 \quad M_2 \quad 0 \quad M_4 \quad M_5 \quad 0]\mathbf{r}$$

$$s = [M_1 \quad M_2 \quad 0 \quad M_4 \quad M_5 \quad 0]\mathbf{s} \tag{2}$$

where

$$\begin{aligned} M_1 &= -\frac{(1-s)r}{1-r} \\ M_2 &= -\frac{1}{2}\frac{(1-s)(1+r)}{1-r} \\ M_4 &= -\frac{(1+s)r}{1-r} \\ M_5 &= -\frac{1}{2}\frac{(1+s)(1+r)}{1-r} \end{aligned} \tag{3}$$

In expression (3), **r** and **s** are vectors of nodal point displacements in local coordinates where it is to be mentioned that, on the side of infinity (*r=1*), no mappings have been assigned to the nodes as it is taken that no displacement is possible at infinity. The new coordinate interpolation functions are taken into consideration in the Jacobian matrix (Bettess (1992)). The approximation for the element integrals is done by Gauss qaudrature formulas. For the absorbing layer of the infinite element, the Lysmer-Kuhlmeyer approach (1969) is used. In all cases, a plane strain two dimensional case is studied. In Table 1, the soil layers properties are tabulated in a way that the bottom layers are characterized with better soil characteristics.

Table 1. Soil properties

Soil medium	Layer number	Thickness (m)	Unit weight (kN/m3)	Shear velocity (m/s)
Loose	1	3	16	100
	2	7	17	110
	3	6	17.5	130
	4	14	18	170
Medium Dense	1	3	16	170
	2	7	17	220
	3	6	17.5	260
	4	14	18	350
Dense	1	3	16	340
	2	7	17	430
	3	6	17.5	520
	4	14	18	700

The soil is assumed to be linear-elastic material and is discretized using four nodded plane strain elements PLANE42. The proportional viscous damping matrix is taken to be proportional to the mass and stiffness matrix (Rayleigh damping). The Rayleigh damping factors alpha and beta are calculated such that the critical damping is 5% for the first two modes. As stated in Anicic (1990), the natural period of the soil medium for the first mode can be analytically found using the following relation

$$T = \frac{4H}{Vs}$$

In order to verify the natural period of the soil medium, modal analysis is performed using the software ANSYS where the numerical results show good fitting with the analytical ones, as shown in Table 2.

Table 2. Comparison of analytical and numerical results of the natural period of the soil profile

Soil medium	Closed form result T (s)	FEM result T (s)
Loose	0.96	0.95
Medium Dense	0.48	0.49
Dense	0.24	0.24

3. COMPUTATION OF STIFFNESS CHARACTERISTICS OF THE RUBBER BEARING

The first step in these analyses was definition of the stiffness characteristics of the rubber bearings. The natural rubber planned to be used for production of the bearings had to be a high damping rubber with an average effective damping of βeff=0.10.

The effective stiffness of an isolator unit, Keff, is calculated for each cycle of loading by using the following formula:

$$K_{eff} = \frac{F^{+} - F^{-}}{\Delta^{+} - \Delta^{-}}$$

where F+ and F- are the positive and negative forces at Δ+ and Δ-, respectively.

The total effective stiffness of the bearings was computed on the basis of the assumed fundamental period of the structure.

$$K_{eff} = M\left(\frac{2\pi}{T_1}\right)^2$$

where, m is weight of the upper structure, T1 is the fundamental period of the base isolated structure. The behavior of the bearings was modeled by using a bilinear model (Figure 2). The bilinear diagram was defined by three parameters: initial elastic stiffness K1, post-elastic stiffness K2 and yield force FY (Table 3).

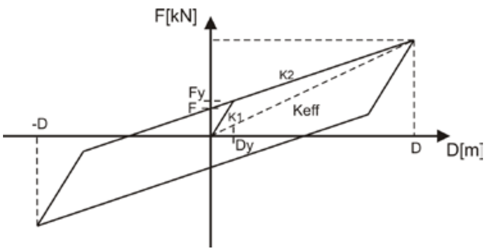


Figure 2. Bilinear model of the rubber bearing

The parameters of the bilinear model are given in table 3.

Table 3. Review of the parameters of the bilinear model

	Keff [kN/m]	K1 [kN/m]	K2 [kN/m]	FY [kN]
bilinear model	300.0	600.0	150.0	4.0

4. RESULTS FROM PERFORMED ANALYSIS

In order to show the influence of the soil on the structure, first, only a base-isolated structure and then a coupled soil-structure system were analyzed. The frame structure elements were idealized as two dimensional elastic beam elements BEAM3 having three degrees of freedom at each node, translations in the nodal x and y directions and rotation about the nodal z axis. The behaviour of the frame structure was supposed to be elastic and was modeled by use of two parameters, the elasticity modulus E=3.15E+7 kPa and the Poisson's ratio of 0.2. The bay length of the frame was taken to be 4.0 m and the storey height was considered to be 3.0 m. The beam cross-section was 40 x 50 cm while the column cross-section was 50 x 50cm. A mass of 11 tons was assigned to each node to simulate the real structural behaviour. The frame was base isolated by high damping rubber bearings. Finite element modeling of the frame and the coupled soil-structure systems was performed by use of the ANSYS software, as shown in Figure 3. The mathematical model has been excided by the acceleration time history of the El Centro earthquake with a peak ground acceleration of 0.3g (Fig 4).

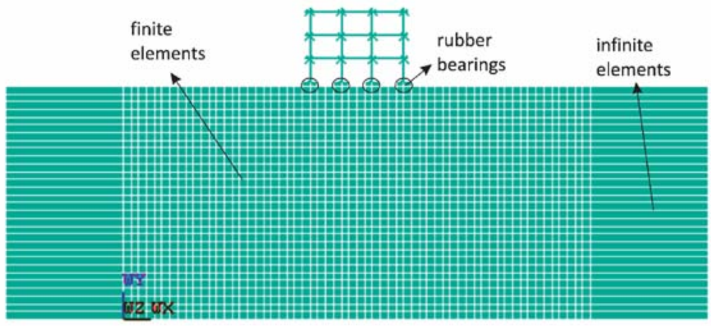


Figure 3. Coupled soil-structure system of a three storey base isolated frame

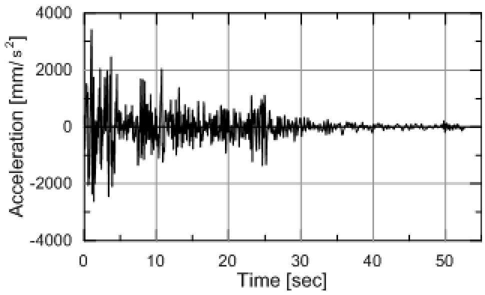
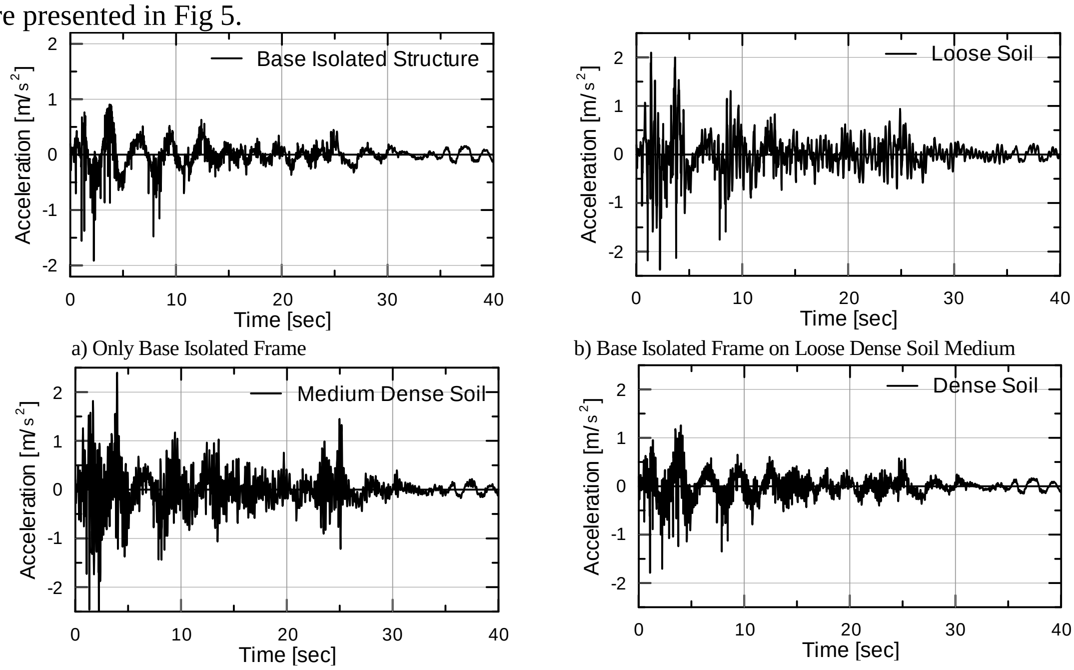


Figure 4. Acceleration time history of Imperial Valley EQ, El Centro record, 1940-May-18

The results from the performed dynamic analysis are presented for only two selected nodes: isolated level and the top of the frame. The time histories of horizontal acceleration at the top of four models are presented in Fig 5.



a) Only Base Isolated Frame

b) Base Isolated Frame on Loose Dense Soil Medium

c) Base Isolated Frame on Medium Dense Soil Medium

d) Base Isolated Frame on Dense Soil Medium

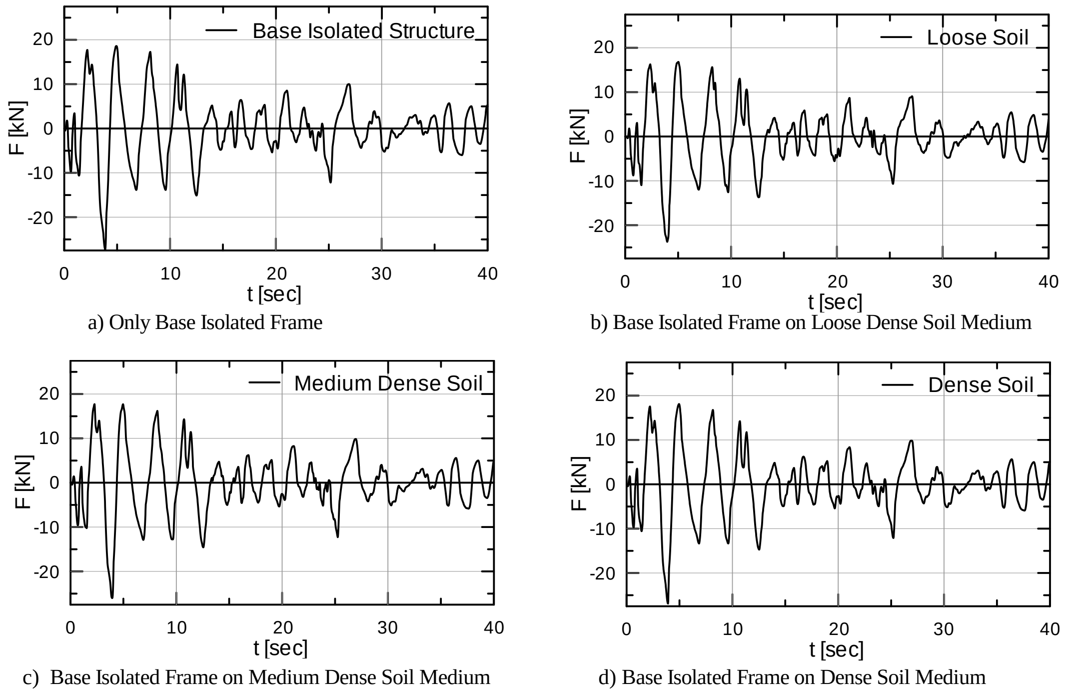
Figure 5. Time history of acceleration at the top of the frames

The pick horizontal acceleration at the isolation level and at the top of the frames of the four models is given in Table 4. The presented results show the importance of taking the SSI into consideration. In the case of a soft soil deposit, the acceleration at the top of the structure could be several times larger than the input acceleration. Including the soil medium (SSI), the acceleration at the top of the frame is significantly increased. The reason for such a behavior of the base isolated structure is the flexibility of the half-space which produces a resonance effect, since the fundamental period of the base isolated structures is larger than that of the conventional fixed-base structures. In all cases, deamplification of the input acceleration was observed. The SSI should always be included in the analysis of base isolated structures placed on soft soil medium.

Table 4. Peak accelerations at specified nodes and bearing shear force

Model	Input	Isolation Level	Top of the Structure	Bearing Shear Force
	[m/s^2]	[m/s^2]	[m/s^2]	[kN]
Base Isolated Frame	3.41	1.70	1.90	27.3
Loose soil	3.41	3.50	2.37	23.8
Medium dense soil	3.41	3.65	2.50	26.0
Dense soil	3.41	2.10	1.80	26.9

The time histories of internal bearing shear forces for all four models are shown in Fig.6. The values of these curves are analytically calculated from the nonlinear dynamic analysis of a base isolated frame subjected to the El Centro earthquake. The peak values are given in Table 4. These results show that the including of the soil medium in the analytical model does not significantly affect the base shear forces. The peak shear forces for the four models ranges between 24 and 27 kN.



a) Only Base Isolated Frame

b) Base Isolated Frame on Loose Dense Soil Medium

c) Base Isolated Frame on Medium Dense Soil Medium

d) Base Isolated Frame on Dense Soil Medium

Figure 6. Shear force in isolators

5. CONCLUSION

One of the benefits of using base isolation is the reduction of the structural response during ground motion. The displacements are concentrated in the isolators, allowing elastic behavior of the upper structure. The performed analytical investigations have shown that modeling of the soil media is important for base isolated structures. Using the SSI effect, the structural response is increased. It is presented by the acceleration at the top of the structure. The model with low and medium dense soil half-space was characterized by the highest acceleration at the top of the frame, but the isolation system managed to deamplify the input acceleration. Therefore, the effects of soil-structure interaction should be taken into consideration especially in the case of a soft soil medium. The peak horizontal deformation for all four models was around 0.16m. In order to use the dynamic analysis for seismic response calculation of soil-structure interaction problems, the soil medium should also be numerically verified by use of other software and experimental results.

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