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EFFECT OF NON-LINEAR SOIL STRUCTURE INTERACTION IN SEISMIC RESPONSE OF ASYMMETRIC STRUCTURES

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Abstract

Post-earthquake damage survey of asymmetric structures has revealed the significant vulnerability of failure as compared to symmetric structures. The asymmetric structures with asymmetric strength and stiffness induce a coupled torsional translational motion leads to additional ductility and displacement demands. The sensitivity analysis of the effect of the torsional component in the seismic response of structures requires an accurate analysis incorporating the effect of non-linear soil-structure interaction. The present study investigates the effect of asymmetry in seismic structural response particularly, the base shear, top drift, and inter-story drift of a structure incorporating a non-linear soil-foundation interface. A 3-story asymmetric and symmetric reinforced concrete structure is considered for the study. The structure is representative of existing buildings in the United Arab Emirates resting in loose sandy deposits. The structural elements are modeled as nonlinear beam-column elements that allow the spread of plasticity. The foundation-soil interface is modeled as fixed and Beams on Non-linear Winkler Foundation (BNWF) models in Opensees. The BNWF model has been calibrated to provide good predictive behavior to capture the base rotation, settlement, and sliding. The study shows that by introducing flexibility in asymmetric structures, the displacement demand increases by 24% and force demand decreases by 30% with respect to the symmetric structure with a fixed base. The study also shows that asymmetry in the structure causes a reduction in displacement due to increased structural stiffness.

Keywords: Asymmetric structures, Non-linear Soil Structure interaction, BNWF model.

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1 INTRODUCTION

Dynamic behavior of asymmetric structures for earthquake actions is significantly more complex due to their torsional response to earthquake excitations [1]. It is also been very well established that the dynamic behavior of a structure may significantly be influenced by the flexibility of its foundations, particularly when the structure is built on a soft soil bed. An accurate analysis of the seismic response of structures requires sensitivity analysis incorporating both the effect of the torsional component as well as the non-linear soil-structure interaction.

The various modes of foundation deformations, such as sliding, settlement, and rotation, can introduce additional flexibility to the system of structure and foundation, thereby changing the modal properties, such as natural period and mode shape [2]. Moreover, earthquake-induced large deformations of the foundations can activate the foundation capacity, leading to energy dissipation at the soil-foundation interface. This can enhance the overall damping capacity of the system of structure and foundation. These phenomena, referred to as inertial soil-structure interactions, significantly affect the seismic demands of structures with shallow foundations on soft to medium-stiff soil. Additionally, foundation deformations can modify the free-field ground motions, which can influence the structural responses due to kinematic soil-structure interaction. To comprehend the key aspects of the soil-structure-interaction mechanism, comprehensive performance-based studies are necessary considering both structural and foundation deformations. In the last few decades, numerous research endeavors have been carried out to comprehend and characterize the impact of SSI on structural responses [3-6].

During an earthquake, buildings with an uneven distribution of stiffness and strength in plan, experience coupled lateral and torsional motions. The torsional effect increases with a larger eccentricity between the center of stiffness and the center of mass of the structure. The equilibrium between the inertial force and the resistance force relies on the eccentricity (e), which is the distance between the center of mass and the center of resistance [7]. The torsional vibrations induced by the earthquake can result in additional force and ductility demands in the lateral direction. Research has also shown that in asymmetric building structures, the lateral torsional coupling resulting from the eccentricity between the center of mass (CM) and the center of resistance (CR) can create torsional vibration even in the absence of rotational ground shaking.

Significant research has been done to evaluate the effect of elastic and inelastic torsional rigidity of structure with rigid base under dynamic loading [8-11]. The response of a single-story, asymmetric, and inelastic RC buildings on a rigid base under seismic loading was compared with the behavior of simplified shear-beam models, evaluating overall damage indices and ductility demands. [8]. Dynamic analysis was conducted to investigate the effect of accidental eccentricity on the inelastic behavior of single and multi-story R/C buildings [9]. The macroscopic response parameters of an asymmetric in-plan buildings on a rigid base were examined by a seismic analysis and concluded that the seismic structural response is heavily influenced by torsional stiffness and resistance [10]. The nonlinear dynamic analysis conducted on complex, multistory, in-plan R/C buildings, with a focus on inelastic chord rotations, revealed that the fundamental periods of these buildings were situated in the velocity-sensitive portion of the spectrum [11]. The analysis of a multi-storey RC buildings under earthquake excitation, with a focus on the influence of soil-structure interaction (SSI) showed that incorporating SSI led to a decrease in the base shear and inter-story drift ratio [12]. The time-history analysis conducted on an RC structure established that the structure with SSI case results in a redistribution of internal elastoplastic torque of R/C elements, compared to the rigid soil base structure [13]. Despite several investigations into the torsional effect of asymmetric and irregular buildings, there remains an open area of research in earthquake-resistant design for structures.

The objective of this study is to investigate the effect of asymmetry on the seismic response of a structure that includes a non-linear soil-foundation interface. To achieve this objective, a comparative analysis is conducted between a symmetric and asymmetric 3-story reinforced concrete structure with two different base fixities: fixed and flexible. The asymmetry is introduced by adding shear beams, resulting in an eccentricity between the center of mass and center of resistance. These structures are representative of many low to medium rise buildings in the United Arab Emirates that are located on loose sandy deposits. The finite element framework of Opensees is used to model the structure-foundation soil system. The study emphasizes the SSI effects on various engineering demand parameters, such as total drift, inter-story drift, base shear, and base moment.

2 DESCRIPTION OF THE STRUCTURE

Three-dimensional model of a 3-storey 2-bay reinforced concrete framed structure is considered for the study. The structure is designed in accordance with the ACI 318-2008 for high ductile class structures. The structure has a plan dimension of 12 m x 6 m with an inter-storey height of 3 m. As shown in Figure 1 (a), the structure is symmetric with respect to X direction and Z direction. The materials used for the RC structure is M30 grade concrete and Fe415 grade steel. The symmetric structure has columns of size 600 mm x 600 mm and beams of size 300 mm x 300 mm. The structure has a rigid solid slab of 150 mm thick for all floors. In the design of the structure, the density of concrete is equal to 24 kN/m^3, with a live load of 4 kN/m^2 for each floor and 2 kN/m^2 for the roof. The site class is designated as D, the building importance factor is set to 1, and an assumed peak ground acceleration of 0.36g is considered. As shown in Figure 1(b), the asymmetry is introduced to the structure by a shear beam of size 0.3 m x 6 m. The inertial force applied through external loadings in the Z direction creates a tortional moment about Y direction. A representative loose sandy soil which covers a large part of United Arab Emirates is chosen as the soil bed. Table 1 provides the property of the soil used in this study. To provide flexiblity to the base of the structure, isolated foundations of size 2 m x 2 m are designed.

Property	Value
Specific gravity, G_s	2.67
Uniformity coefficient, C_u	2.06
Coefficient of curvature, C_c	1.01
Effective size, D_{10}	0.15
Maximum unit weight	17.5 kN/m^3
Minimum unit weight	11.5 kN/m^3
Maximum void ratio, e_{max}	0.97
Minimum void ratio, e_{min}	0.68
Relative density, R_d	36%
Effective friction angle	32.5^o
Shear modulus,G_{soil}	7.89 MPa

Table 1: Property of soil

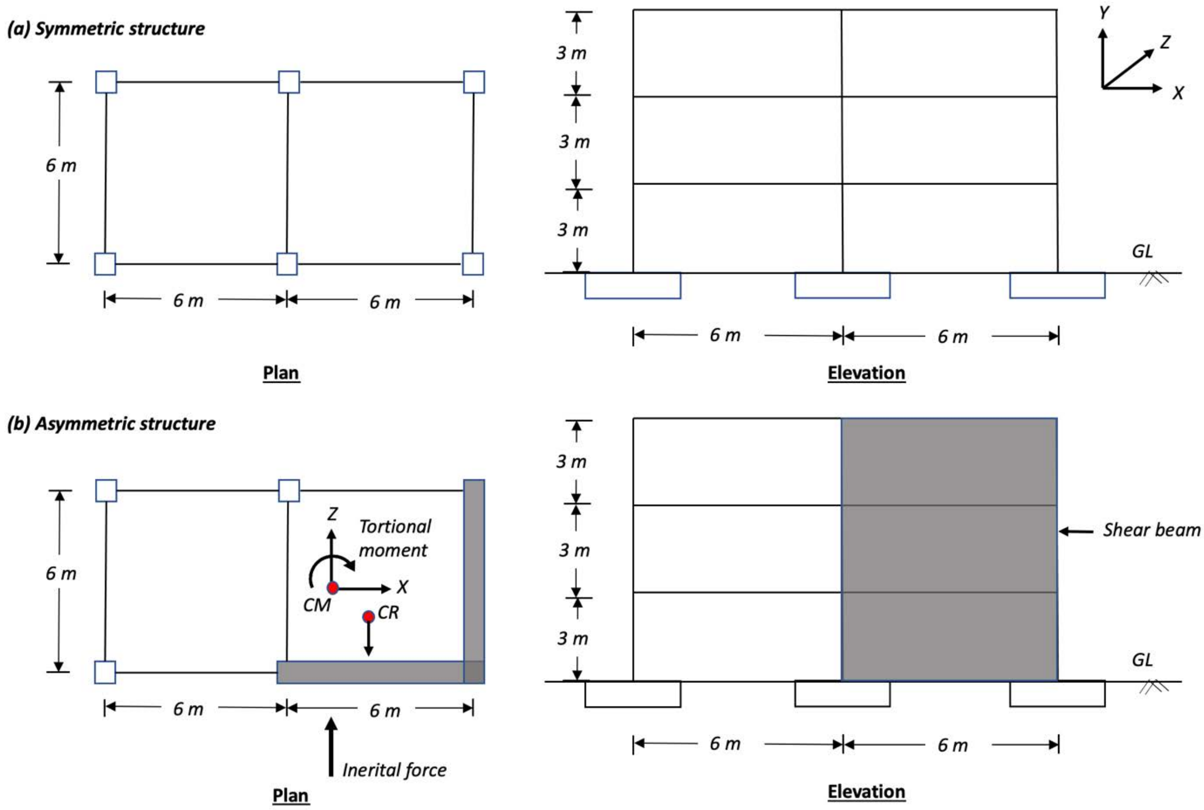

Figure 1. Plan and elevation of (a) Symmetric structure and (b) Asymmetric structure.

3 NUMERICAL MODEL

The soil-foundation interface behavior is simulated using the well-accepted beams-on-Winker-foundation (BNWF) model. The numerical model of the structure-foundation-soil system is modelled in the finite element framework of Opensees [14]. The reinforced concrete structural members such as the beams, columns are modeled by a displacement based FiberBeamColumn element with the cross-sectional area of the element is divided into multiple fibers, and the behavior of each fiber is modeled using an appropriate constitutive material models such as Concrete04 and Steel01. The FiberBeamColumn element also accurately incorporates the bond-slip behavior using Modified Ibarra-Medina-Krawinkler model. The isolated footing is further modelled by an ElasticBeamColumn element assuming an elastic stress-strain behavior during the dynamic loads. The ElasticBeamColumn element is also used to model the shear beam of the asymmetric structure, accounting both the bending and shear deformation characteristics. The structure-foundation-soil system is analyzed for fixed base along with the non-linear base condition to better understand the extend of influence of soil-interface non-linearity on the structural response. Figure 2 illustrates two types of foundation fixities available for both the symmetric and asymmetric structures: Rigid base and Flexible base (Isolated footing).

The soil-foundation interface behavior is simulated using the well-accepted beams-on-Winker-foundation (BNWF) model. The BNWF model utilizes a system of closely-spaced non-linear mechanistic springs to simulate the soil-foundation interface behavior, consisting of independent vertical and lateral elements comprising of non-linear springs, dashpots, and gap elements. The BNWF model uses an array of zerolength spring elements such as the q-z springs, p-x and t-x springs as shown in Figure 2. The vertical q-z springs that are distributed along the base of the footing captures the vertical and rotational resistances of the footing. The differential movement of the q-z springs in the model implicitly accounts for the vertical and rocking

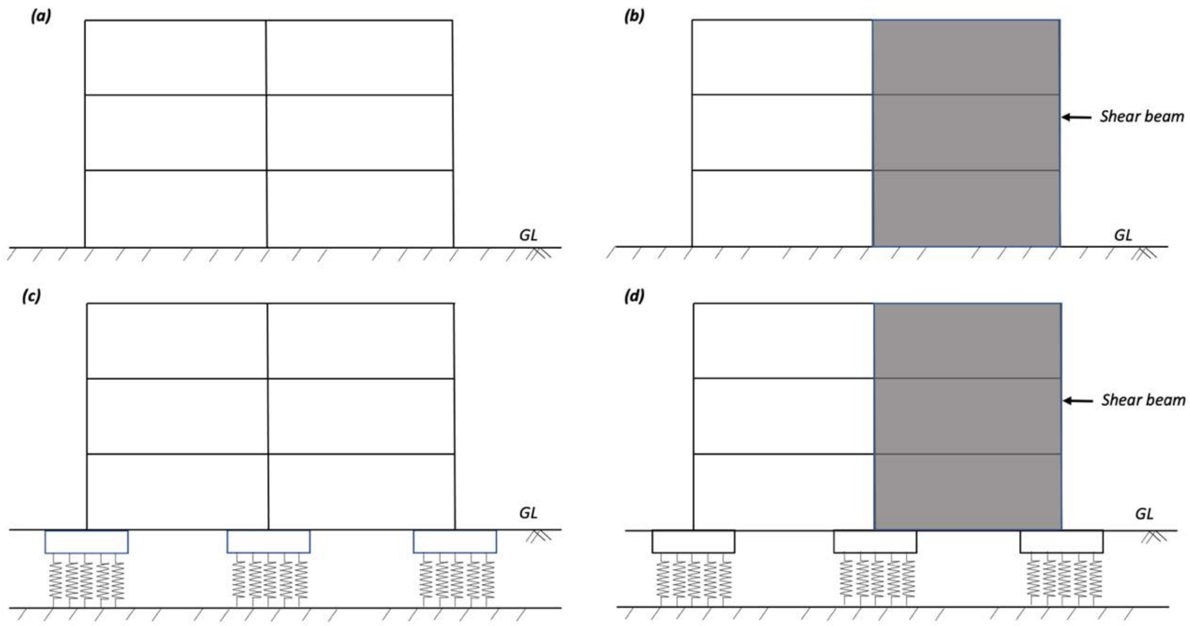

Figure 2. Case scenarios (a) Symmetric structure with rigid base (b) Asymmetric structure with rigid base (c) Symmetric structure with flexible base (d) Asymmetric structure with flexible base.

impedances of the foundation. Additionally, the model accounts for the passive soil resistance and the frictional sliding resistance of the footing through the horizontal p-x and t-x springs.

The backbone curves of these elements have a linear elastic region, followed by an increasingly growing nonlinear region [15]. The backbone curve of the q-z material accounts for the ultimate load on the compression side and the reduced strength in the tension side to develop an asymmetric hysteretic response. The t-x material captures the frictional resistance along the base of the shallow foundation and the backbone curve is characterized by large initial stiffness and broad hysteresis loop. The p-x material captures the passive resistance of the soil and is characterized by a pinched hysteretic behavior to account for gapping during rocking on the other side of the foundation. The BNWF model thereby is capable to adequately capture the material nonlinearity, geometric nonlinearity, hysteretic damping and radiation damping characteristics. The material models are named as QzSimple2, PxSimple1 and TxSimple1 within OpenSees. The material models consist of two key components: a viscoelastic component that describes the behavior of the material under far-field conditions, and a plastic, drag, and closure component that characterizes the displacement under near-field conditions.

The q-z material is designed to have an asymmetric hysteretic response with a backbone curve defined by an ultimate load on the compression side and reduced strength in tension to In order to achieve a desired foundation rocking stiffness, each spring in the foundation is assigned a stiffness based on its tributary length and with the global foundation stiffness distributed over the entire length of the footing. Specifically, the vertical springs have been spaced at a rate of 1% of the footing length at the end region and 2% of the footing length at the mid region. The end region has a higher stiffness than the mid region, extending 10% of the footing length at each end, while the mid region has a comparatively lower stiffness [15].

Transient analysis is performed using uniform excitations, and a Rayleigh damping of 5% is assumed for the first two modes. Newmark's solution parameters of 0.25 and 0.5 (linear acceleration method) are used in the transient analysis. The nonlinear equilibrium equations are solved using the Krylov-Newton algorithm, and the convergence rate is increased through the utilization of a Krylov subspace accelerator. The convergence criteria for the equilibrium equation are determined by the NormDispIncr test, with a maximum of 50 iterations and a tolerance limit of 1 x e-5.

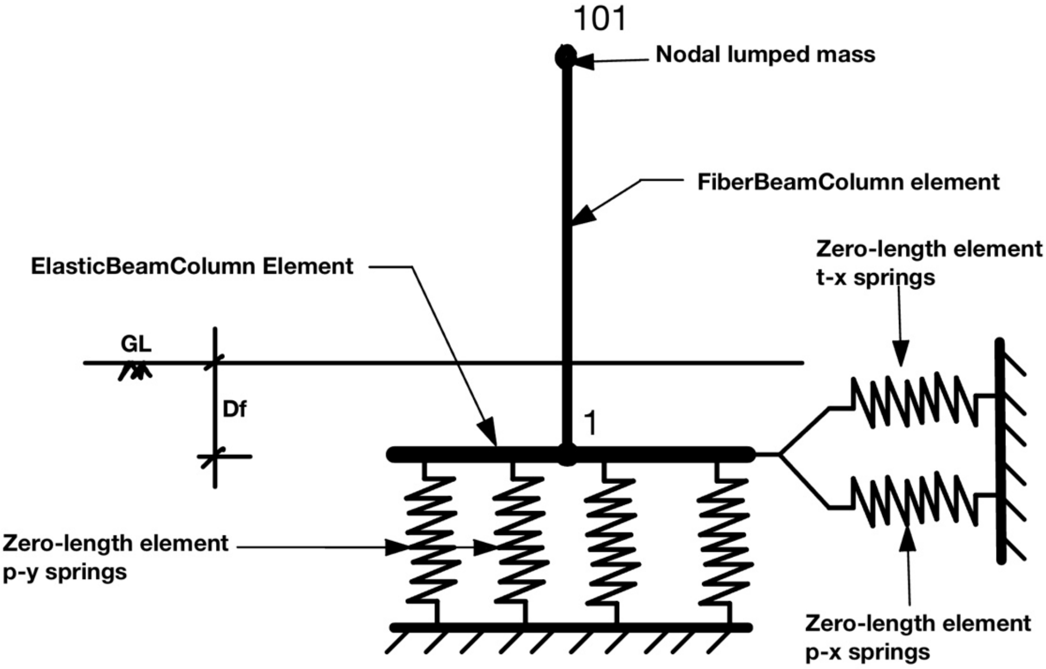

Figure 3. Beams-on-Winker-foundation (BNWF) model

4 RESULTS AND DISCUSSION

Static pushover analysis in accordance with the Building Seismic Safety Council's (2005) guidelines evaluates the capacity of symmetric and asymmetric structures under fixed and non-linear base conditions. Displacement increments of 0.1% of the structure height were applied till a target displacement of 15% of the structure height is achieved. Figure 4 depicts the push-over curves obtained from the study, which illustrate the relationship between base shear and roof displacement. It has been observed that the incorporation of nonlinear SSI in both symmetric and asymmetric structure results in increased displacement demand and reduced force demand. For the symmetric structure, the base shear decreases by 32% when non-linearity is introduced while asymmetric structure yields a base shear decrement of 30%. It was also noted that the displacement demand increased by 28% for symmetric structure and 24% for asymmetric structures with the introduction of flexibility to the foundation base.

Dynamic analysis with a harmonic input ground motion (Amplitude = 0.01m and time period = 0.35 s) in both symmetric and asymmetric structure demonstrated that although the total roof displacement is observed to increase with increasing base flexibility, the flexural deformation is observed to decrease with increasing flexibility of the base. Asymmetric structure causes a reduction in storey displacement due to increased structural stiffness as compared to the symmetric structures. The Figure 5 shows the inter-storey drift ratio that relates closely to the structural collapse. It has been deduced that the inter-story drift ratio is highest on the 1st floor for both symmetric and asymmetric structures.

The dynamic response of both symmetric and unsymmetric structures was characterized through time history analysis using an input ground motion with a PGA of 0.35g, a duration of 28 seconds, and an Mw of 6.5. It is observed that the displacement and force distribution are highly sensitive to the frequency content of the input ground motion. The changes in the first and second mode shapes are consistent when the base fixity is altered. Furthermore, the higher modes of vibration significantly contribute to the overall dynamic response. Figure 6 illustrates that the frequency content of the input earthquake is amplified when it matches the fundamental frequencies of the structure-soil-foundation system. The resonant frequency of the symmetric and asymmetric structures with fixed base is amplified at 0.85 Hz, whereas for the flexible base structure, it is amplified at 0.25 Hz. The fundamental frequency for the flexible base is lower than the fixed base structure which indicates the energy dissipation mechanism due to the Soil-Structure Interaction (SSI) effect.

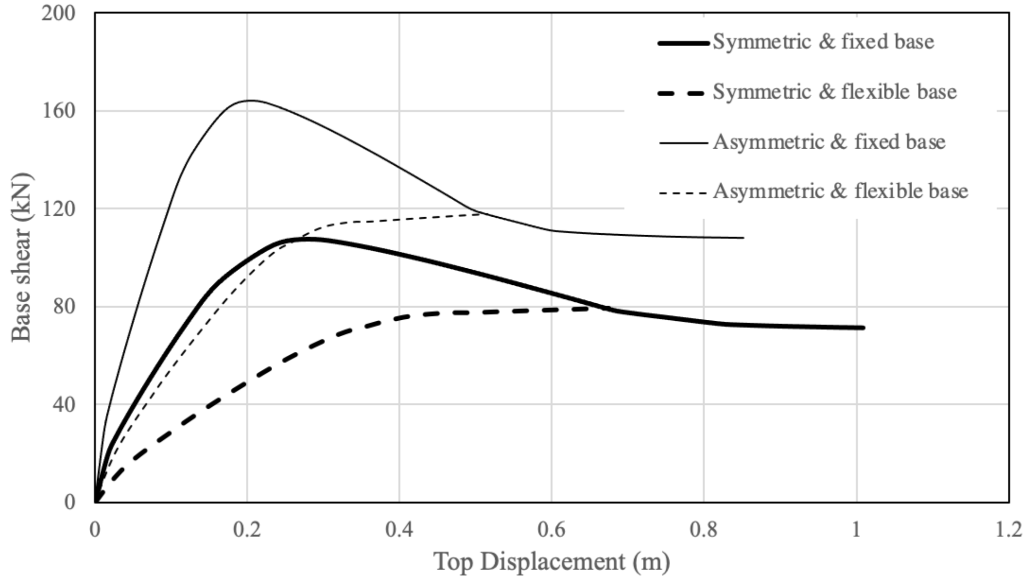

Figure 4. Pushover analysis for various case scenarios considered for the study

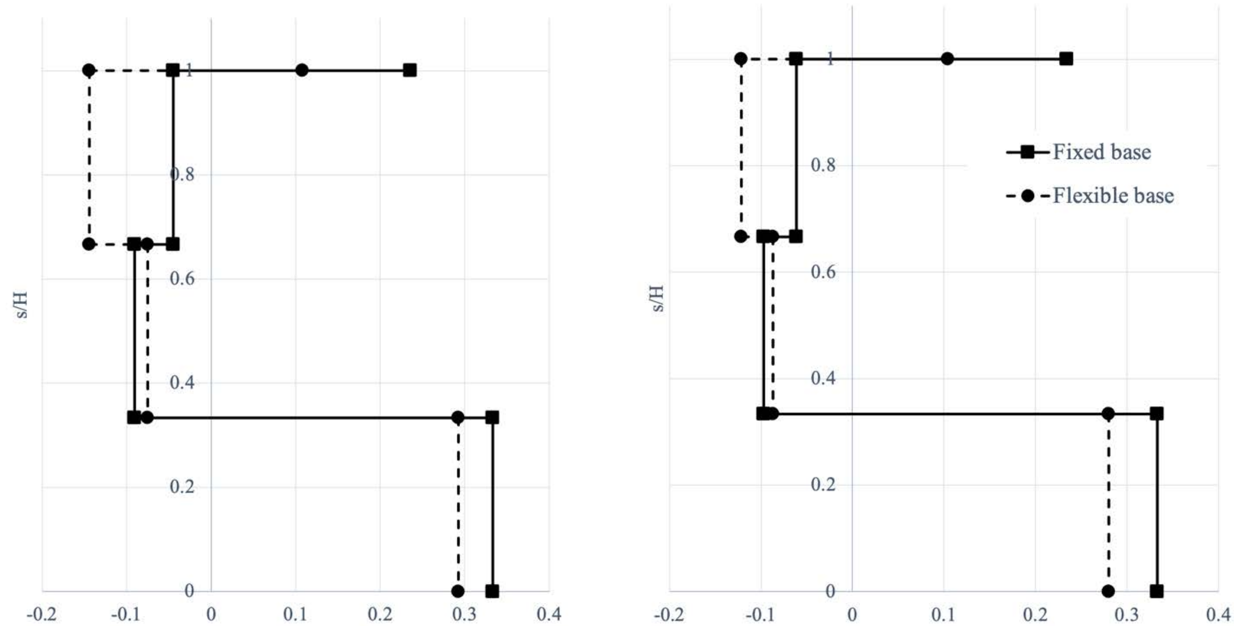

Figure 5. Effect of base excitation amplitude to the inter-storey drift ratio for (a) symmetric structure and (b) Asymmetric structure.

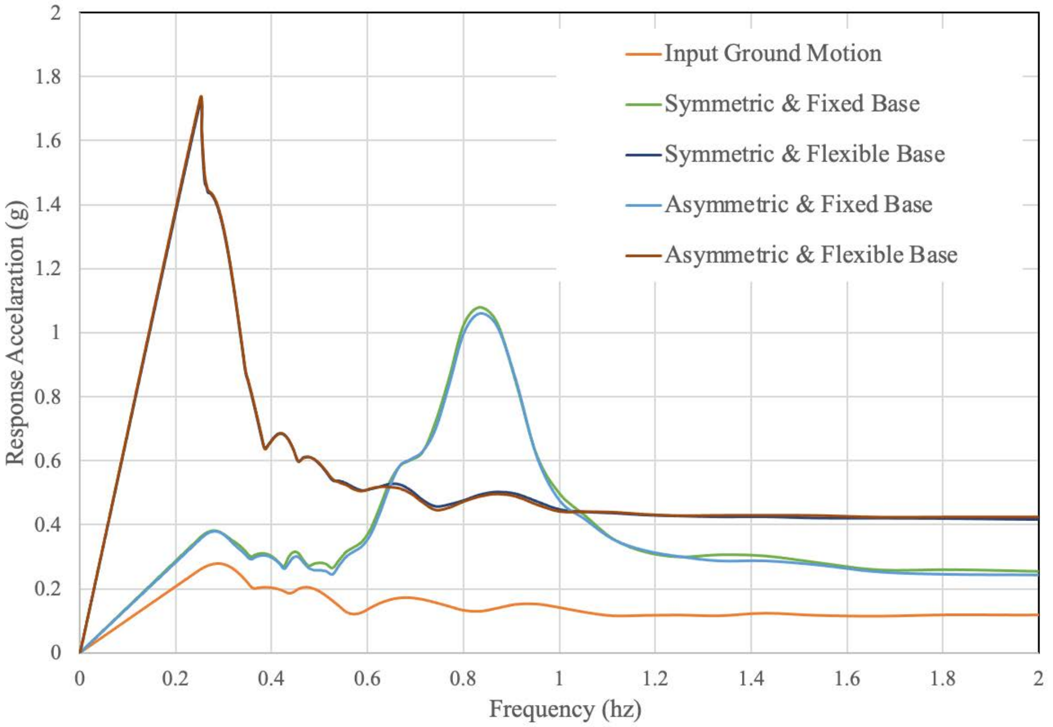

Figure 6. Spectral acceleration response of a symmetric and asymmetric structure with fixed and flexible base subjected to the an input earthquake ground motion.

CONCLUSION

This study focuses on the effect of soil structure interaction in the dynamic response of a symmetric and asymmetric structure. A 3 storey 2 bay low-to-medium rise buildings resting on loose sands are mainly focused upon. The following key conclusions can be made:

- Introducing nonlinear SSI in both symmetric and asymmetric structure results both beneficial and detrimental effects. The force demand decreases, but the displacement demand increases. For the symmetric structure, introducing non-linearity results in a 32% decrease in base shear, while for the asymmetric structure, there is a beneficial 30% decrement in base shear. However, introducing flexibility to the foundation base leads to a 28% increase in displacement demand for the symmetric structure and a 24% increase for the asymmetric structure, which is detrimental.
- Asymmetric structure causes a reduction in storey displacement due to increased structural stiffness as compared to the symmetric structures. The inter-story drift ratio is highest on the 1st floor for both symmetric and asymmetric structures which is in consistent with other literatures.
- The displacement and force distribution in both symmetric and asymmetric structures are highly sensitive to the frequency content of the input ground motion The fundamental frequency for the flexible base of structures is lower than the fixed base structures which indicates effective energy dissipation mechanism due to SSI.

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