Evaluation of Sensitivity of soil structure interaction Effects, to frequency content of base excitation

S.A.Mirfattah
PhD Student of European School for Advanced Studies in Reduction of Seismic Risk
ROSE Programme, UME School, IUSS Pavia, Italy

SUMMARY:
In substructure method used in soil-structure interaction (SSI) analysis, interaction between soil and foundation is modelled via spring and dashpot elements. Mechanical properties of these elements depend on soil characteristics, foundation properties and also frequency of motion. Therefore the response of the whole system is also frequency dependant. In this study a number of structures are considered as simplified lumped mass SDOF systems and equivalent spring and dashpot properties are calculated according to foundation impedance by program DYNA. Circular foundations on soft soil (ground type D) are considered. Then sensitivity of SSI effects on the response, to excitation frequencies in form of harmonic motions and real ground motions are studied. Results show when the excitation frequency is below a certain threshold, dramatic increase in maximum drift in short period systems and considerable even in long period ones is observed this threshold is fundamental natural frequency of the whole SSI system.

Keywords: soil-structure interaction, Foundation impedance, Frequency dependency, Shallow foundations

1. INTRODUCTION

Substructure method have been commonly used to analyze soil-structure interacting systems. in this method the soil-foundation interaction is represented by spring and dashpot elements. properties of these spring and dashpot elements applied to simulate foundation impedance depend on soil, foundation and frequency of excitation. Unlike other ones the last parameter is not constant for a given system, this situation makes it difficult to conduct analysis in time domain. Some researchers asserted that this dependency has minor effect on final response of the SSI models. Tsai et al (1974). Other researchers such as Wolf, (1991), Wu & Chen, (2002). tried to introduce the frequency independent functions to compute the corresponding constant values of stiffness and damping. However inertial interaction of superstructure with the foundation can dramatically alter the efficiency of using those functions. Mansur Ghaffar-Zadeh & François Chapel (1983) tried to compensate it by introducing constant impedances based on fundamental natural frequency of the whole SSI system. Masato Saitoh (2007) presented a method making use of mass moment of inertia “gyro mass” in combination with spring and dashpot elements at the base to nullify frequency dependency of their properties. In this study, frequency dependencies of several structural responses are evaluated. Different types of structures resting on surface of soft soil (ground type D according to Eurocode 8) are examined.

2. FORMULATION OF THE PROBLEM

The use of simplified SDOF model to simulate soil-structure interaction is common in SSI problems Wolf (1985). In order to capture any possible effect of foundation mass two more dynamic degrees of freedom are added to the conventional SDOF 2D model, those are sway and rocking motion of the foundation.
In this study a simplified four degree of freedom (4DOF) system shown in Fig. 1.1. is introduced to

represent an actual system with soil structure interaction. The 1st degree of freedom (DOF) is obviously representing the horizontal displacement of the superstructure mass. 2nd and 3rd DOFs are considered because of the fact that mass of the foundation is usually not negligible comparing to that of superstructure, therefore its possible influence on the overall response is of interest to investigate. The 4th DOF seems to be negligible as it's been neglected in most previous studies but it should be noted that although the value of rotational inertia is not considerable in regular buildings, but in some structures such as elevated tanks can affect the shape of deformation and the overall mass matrix as well. Consequently the mode shapes and modal frequencies will be affected and that can influence impedance of foundation since it is frequency dependant.

Fig. 1.1. also shows the analytical representation of the 4DOF model. It can be an idealized multi-storey building or an elevated water storage tank. It consists of the top mass that is connected to the foundation by an element with a specific stiffness and damping matrix. The interaction of foundation with underneath ground is represented by spring and dashpot elements which their properties are calculated based on foundation properties and geotechnical properties of the soil. In this study these stiffness and damping coefficients which are influenced by foundation and soil relative displacement are to be calculated by program DYNA (1993) based on corresponding dynamic impedance of foundation. It should be noted that in this model the foundation mass and its mass moment of inertia are considered as lumped mass at the base.

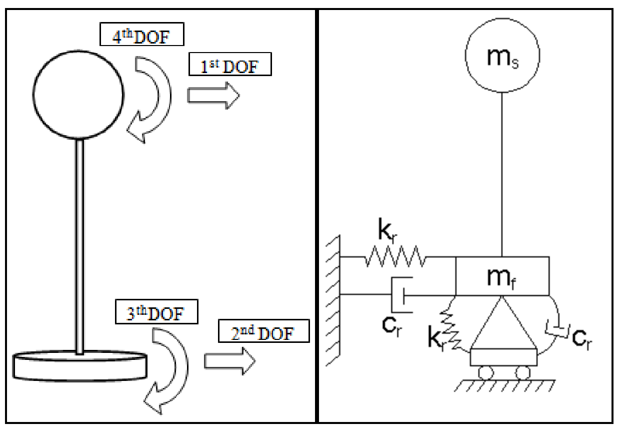

Figure 1.1. Simplified 4DOF SSI model and its mechanical representation

2.2. Frequency dependent impedance of foundation

Impedance functions represent the frequency-dependent stiffness and damping characteristics of foundation-soil interaction. Various numerical solutions for impedance functions are suggested by Gazetas (1991). Those presented methods usually assume rigid foundation and uniform soil of infinite depth in which the hysteresis damping is considered constant. Under these conditions, the soil profile is referred to as a viscoelastic half-space which is also the assumption in this study. Some equations have been proposed in order to account for foundation embedment (e.g., Apsel and Luco 1987), and non-rigid foundations (e.g., Iguchi and Luco 1982). However, some previous findings imply that accounting for foundation flexibility has minor effect on final SSI responses. Gulkan. P, Clough. R (1993) Moghaddasi M, et al (2010). It should be noted that to apply these frequency dependant impedances in analysis for earthquake loads, the frequency on which the properties are depended, is neither the input motion nor that of system but it is the frequency of foundation response in rocking and horizontal directions.

2.3. Response measures

Three parameters are selected as representative response measures in simplified SSI model:

- Relative displacement of foundation and the superstructure (top mass) divided by height that is an indication of internal elastic forces produced in super structure and is referred to as drift.
- Total acceleration of superstructure that represents the inertial forces and non-structural demand forces.
- Total displacement to monitor maximum lateral displacement of the whole system.

2.4. Generating realistic samples of 4DOF model

In order to hold realistic assumptions, number of realization of structures with typical ordinary dimensions and loads are assumed. Then the equivalent 4DOF model of each is produced. The following sections explain the process of selection of each parameter consistent with conventional engineering practice. Summary of all realization properties are presented in Table.2.2.

2.4.1. Fixed base superstructure fundamental period and stiffness

One of the major parameters is superstructure fixed base period which is a combination of mass and stiffness. To have realistic values of this period, some buildings with different heights are assumed then based on Eqn. 2.1. and Eqn. 2.2. Recommended by EC8 & FEMA 450, a rough estimation of fundamental period is achieved. Therefore some values within the range of engineering interest are obtained. Equivalent mass and height is calculated assuming uniform mass distribution along the height of MDOF system. Stiffness of the system is obtained using conventional structural mechanics equations.

$$T_1=0.05H^{(3/4)} \tag{2.1}$$

$$T_1=0.1N \tag{2.2}$$

T_1: Fundamental Period
H: Height of the structure
N: Number of stories

2.4.2. Ground type

Since soil-structure interaction is expected to be more significant on soft soil, according to Eurocode 8 ground classification, ground type D is considered. Reasonable values of unit weight and material damping are assumed as shown in Table 2.1.

Table 2.1. Considered ground type

Ground Type	V_s (m/s)	Unit weight (kN/m^3)	Poisson's ratio	Material damping (%)
D	150	15	0.3	5

2.4.3. Foundation characteristics

The area and thickness of foundations are designed based on Eurocode 8 provisions. To eliminate any effect of directivity only circular uniform foundation shape is considered. Foundations are designed based on Eurocode 8 provision, according to underneath ground type and properties of superstructure weight. Mass of foundation is calculated based on its area and thickness assuming unit weight of concrete equal to 24 kN/m^3. Gulkan. P, Clough. R (1993) and Moghaddasi M, et al (2010) found that foundation flexibility has minor effect on overall response, therefore foundations are considered as uniform rigid concrete mat resting on the surface of homogenous half space of ground type D.

Table 2.2. Characteristics of all realizations of SSI model.

Case num	Number of stories	Height (m)	Fixed base period (sec)	Superstructure mass (Tons)	Foundation Diameter (m)	Foundation thickness (m)	Structure Damping (%)
1	3	9	0.26	144	8	0.8	5
2	5	15	0.38	240	10	1	5
3	8	24	0.54	384	15	1	5
4	15	45	0.87	720	25	1.2	5
5	18	50	1.50	1000	30	1.5	5
6	20	60	2.00	2000	35	2	5
7	25	75	2.50	2500	40	2.3	5
8	30	90	3.00	3000	45	3	5

3. ANALYSIS IN FREQUENCY DOMAIN

In order to investigate the effect of frequency dependant elements at the base of 4DOF model different systems are excited with harmonic load with frequency range of 0.1 to 4.6 Hz which is roughly the range of structural engineering interest.

3.1. Frequency independent impedance of foundation

For the sake of comparison, frequency independent properties are also calculated using median of the frequency range and they are used as constant values throughout the whole time domain analysis.

3.2. Calculation of soil stiffness and damping by DYNA (1993)

Horizontal and rotational springs and dashpots properties depend on following parameters:

- Ground Type is D
- Soil material damping is assumed 5%
- Soil's Poisson's ratio 0.3
- Soil's layering pattern is assumed uniform
- Shape of the foundation is circular
- Foundation is located
- Foundation is assumed rigid resting on surface of elastic half space

The aforementioned parameters are inserted into Program DYNA and stiffness and damping coefficients can be calculated in any desired range of frequency. Depending on foundation response frequency the corresponding spring and dashpot properties are calculated. Provided that previous studies such as Salih Tileylioglu, et al (2011) and Kausel, E (2009) show that rocking impedance of the foundation is more frequency dependant than horizontal one, hence in this study properties of spring and dashpot elements at the base are calculated based on the rocking response of foundation through following iteration process.

3.2. Iteration algorithm

Spring and dashpot properties at the base are influenced by the base response, which in turn depends on frequency of excitation and natural frequency of the whole system that is a function of overall stiffness matrix that is also affected by local spring and dashpot properties of foundation. Therefore iteration is needed to find the accurate properties of spring and dashpot elements at the base. Practically the iteration converges quickly additionally, each analysis is repeated using constant foundation impedance at the base. The whole iteration process is shown in Fig. 3.1. The results are presented in Fig. 3.2 and in Fig. 3.3. The dash line showed with "-ind" extension in legend, distinguish the responses obtained by frequency independent properties of dashpot springs at the base. At top of each graph properties of the corresponding realization of SSI model are shown.

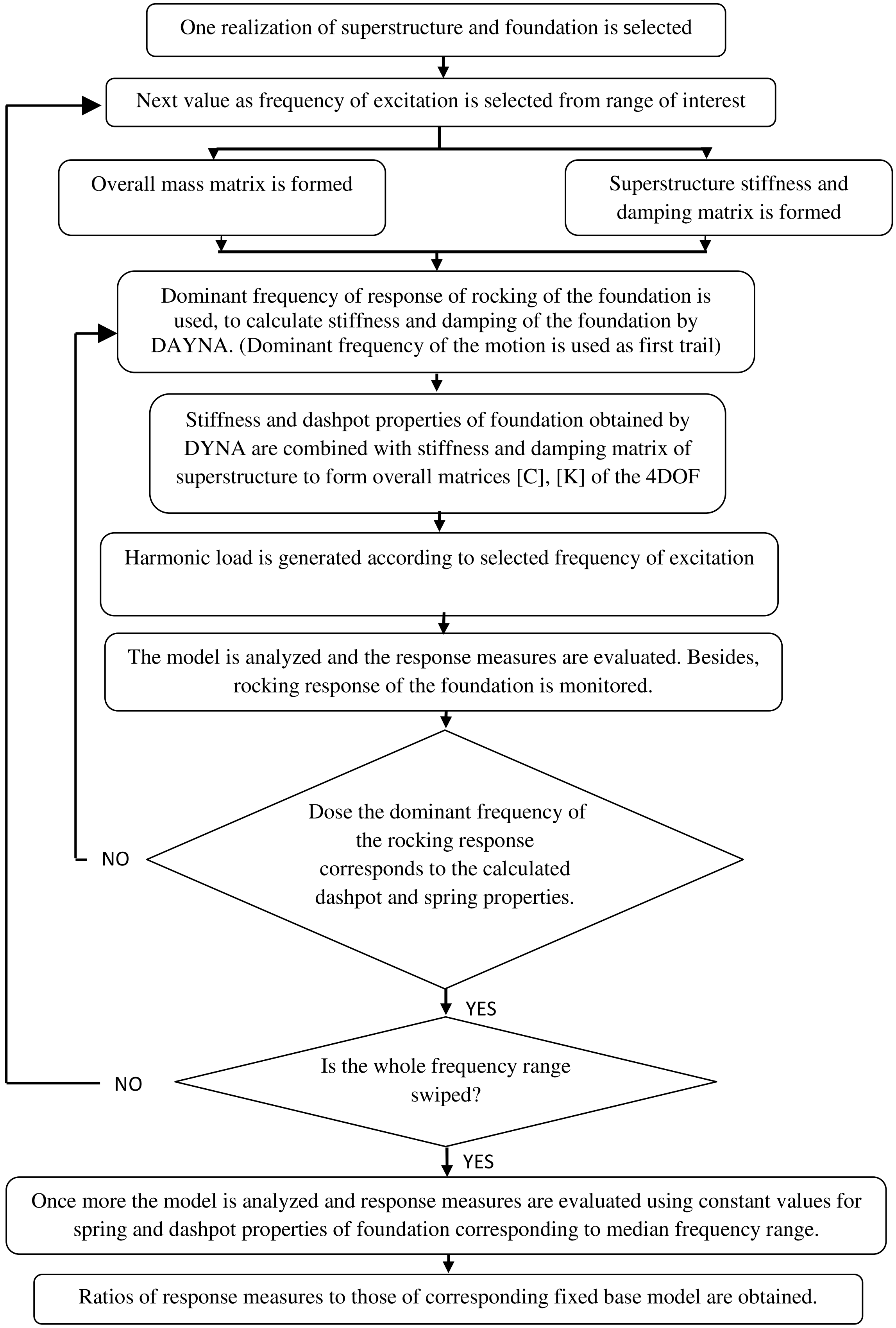

Figure 3.1. Iterative algorithm to analyze 4DOF model in frequency range of interest

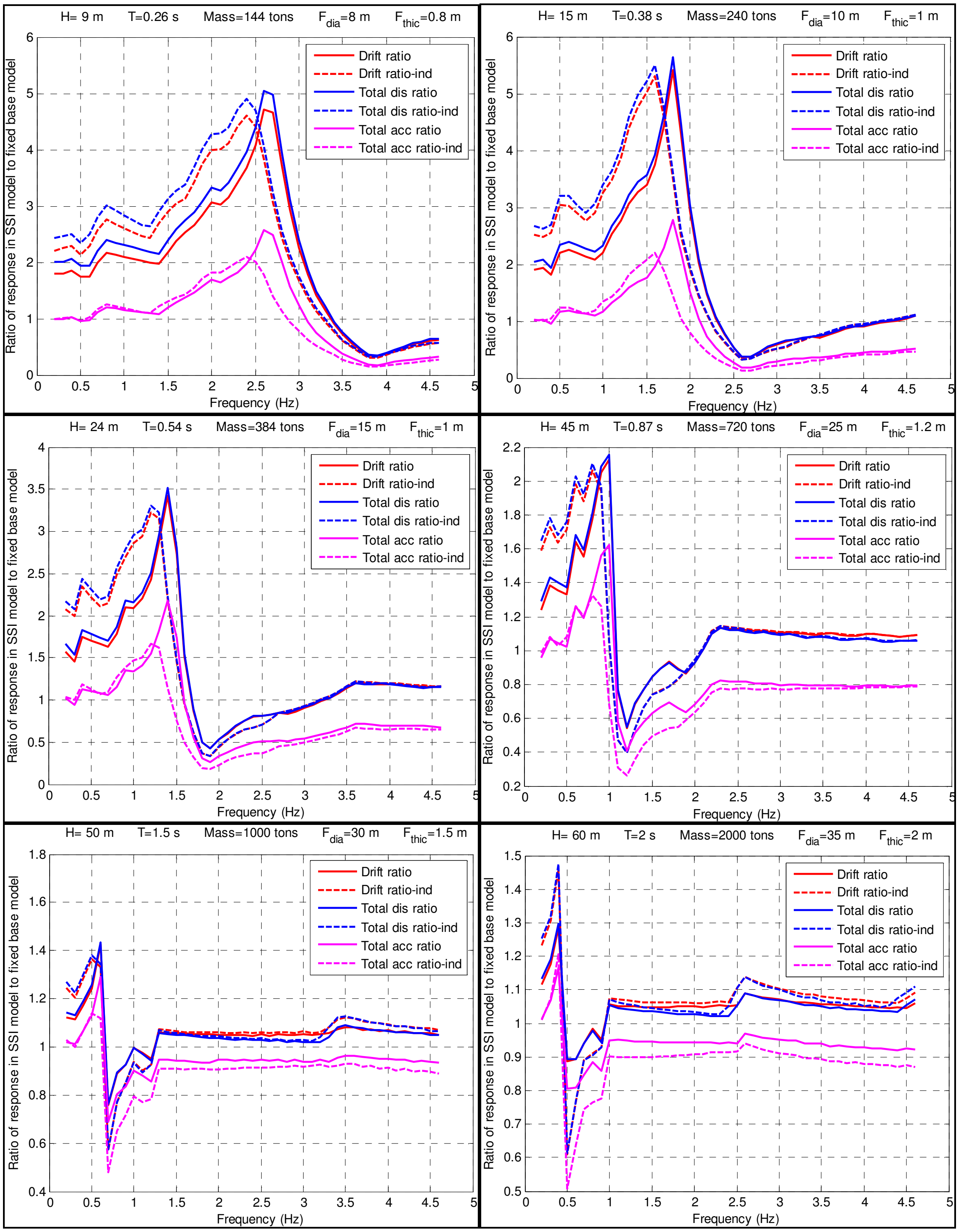

Figure 3.2. Ratio of representative responses in SSI model to that of fixed base model (SSI amplification factor) of different realizations of SSI model in frequency domain.

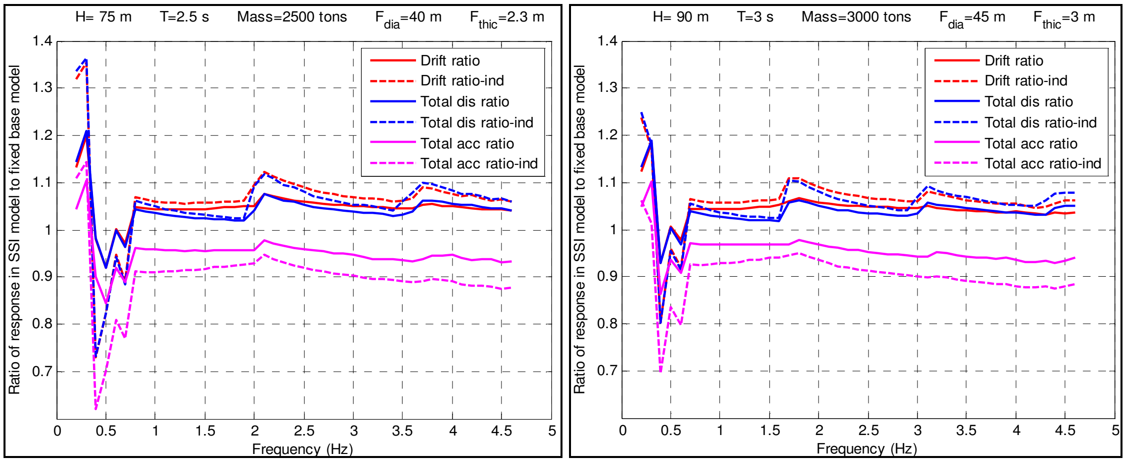

Figure 3.2.(continue) Ratio of representative responses in SSI model to that of fixed base model in different realizations of SSI model in frequency domain.

4. ANALYSIS IN TIME DOMAIN

In order to have robust results the realizations should be analyzed with real earthquake records.
Ten ground motions recorded on the ground type D (Vs<180 m/s) were carefully chosen. First, the ground motions are from different events in order to reflect the variety of motion characteristics. Besides, in terms of frequency content both narrow band and wide band motions are included. since the ratio of responses of SSI model to those of fixed base model are to be monitored the effect of ground motions intensity is automatically cancelled out, therefore the ground motions intensity do not need to be scaled with a design spectrum. Table 4.1. lists the selected ground motions.

4.1. Analysis procedure

The time domain analysis procedure is nearly the same as that of frequency domain; the only difference is that instead of generating harmonic motion with constant frequency now real records are used. As first trial frequency dependant properties of the system are set corresponding to dominant frequency of the motion. Then response is calculated and the frequency dependant properties are refined according to dominant frequency of rocking response of the foundation. The process quickly tends to convergence. Although the motions cover a broad range of frequencies but the foundation rocking response frequency content has a narrow band distribution around a specific value. This allows calculation of frequency dependant properties based on a specific value of frequency. The response amplification of each response measure is also obtained using frequency independent values. The results are shown in Fig. 4.1.

Table 4.1. Selected earthquake events.

Ground motion num	Earthquake Event
1	Imperial Valley
2	Loma prieta
3	Northridge
4	Chi-Chi, Taiwan
5	Duzce, Turkey
6	Gilroy
7	Morgan Hill
8	Kocaeli, Turkey
9	Yountville
10	Whittier Narrows

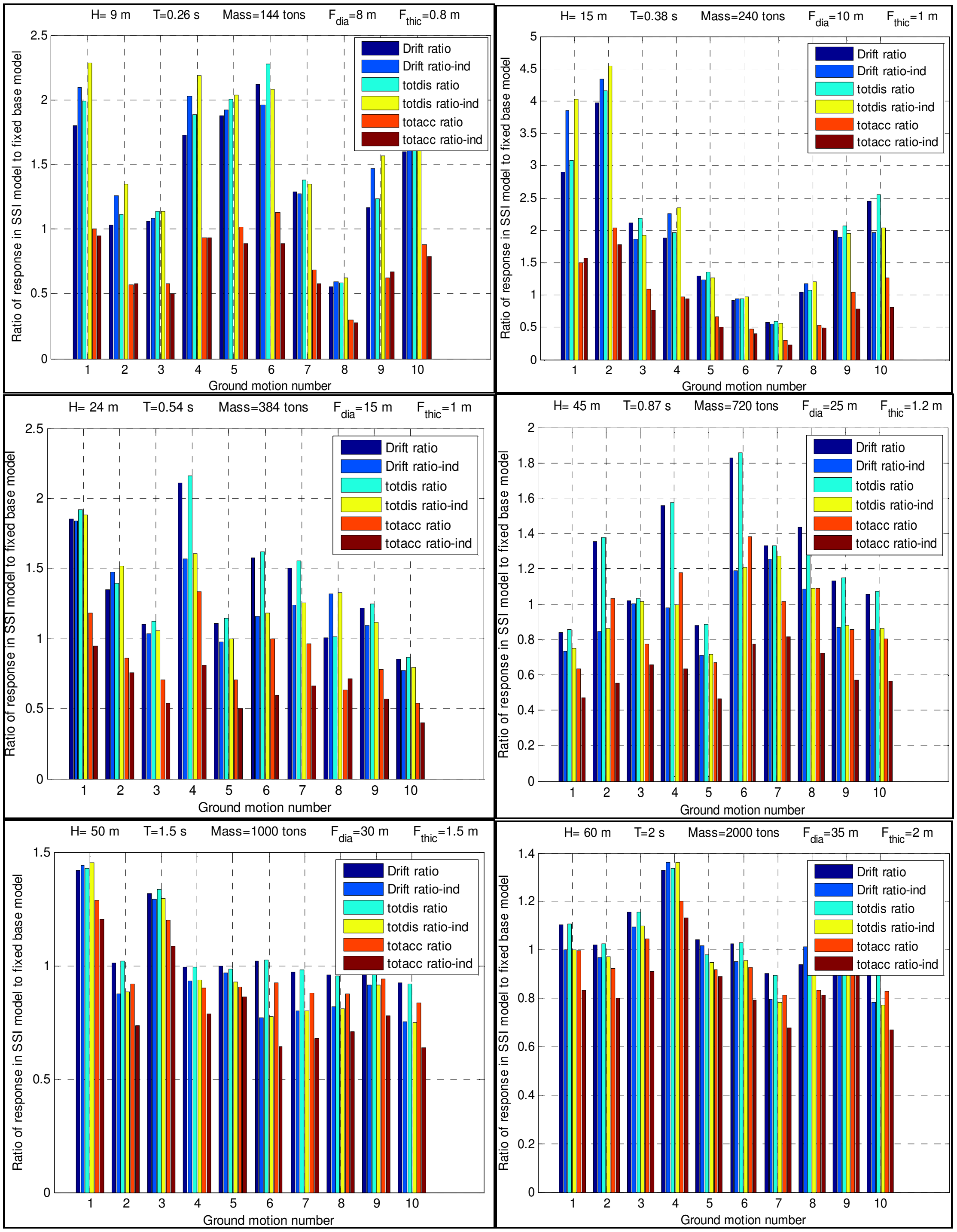

Figure 4.1. Ratio of representative responses in SSI model to that of fixed base model in different realizations of SSI model analyzed in time domain.

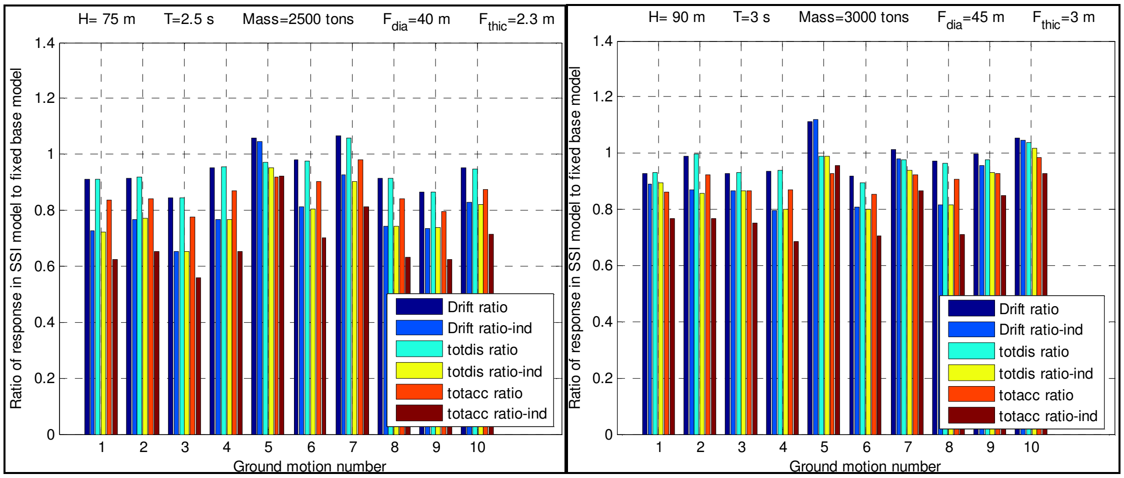

Figure 4.1. (continue) Ratio of representative responses in SSI model to that of fixed base model in different realizations of SSI model in time domain.

5. CONCLUSIONS

Amplification factor of 2 in drift response due to SSI is observed even in moderately stiff systems such as an eight story building resting on ground type D. The factor is around 5 in a system corresponding to a three story building.

Fundamental frequency of the whole SSI system plays a role as a threshold, considerable amplification due to SSI is observed when excitation frequency is below this threshold however there is a quick reduction in amplification of responses as soon as the frequency of excitation exceeds fundamental frequency of the SSI system.

As superstructure becomes more flexible obviously the amplification threshold shifts toward lower frequency and the amount of amplification gets smaller but still not negligible.

The amplification factor due to SSI is not the same for all structural responses. Displacement and drift are much more amplified whereas amplification in acceleration response caused by SSI is rarely seen in the selected earthquakes. This has to be considered in displacement based design procedures such as DDBD on soft soil. Since the target displacement (which corresponds to drift in this study) could be much higher than the ordinate obtained from displacement design spectrum.

Response amplification due to SSI is sensitive to spring and dashpot properties of the foundation in stiff systems located on ground type D, but as the system becomes flexible this sensitivity considerably decrease.

Amplification of displacement responses caused by SSI on ground type D, depends on ground motion but this dependency considerably diminishes in flexible structures. It seems complex to distinguish and quantify ground motion characteristics which influence SSI amplification the most.

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