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NUMERICAL INVESTIGATION OF POTENTIAL FOUNDATION INTERVENTION AS A MEANS FOR MITIGATING SEISMIC RISK

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ABSTRACT

Interventions at the foundation and the surrounding soil of existing buildings are commonly employed as a means to increase the foundation-soil system resistance and/or reduce excessive ground deformations under strong ground shaking. However, current research has highlighted the potential to improve the seismic performance of buildings by mitigating the imposed earthquake loading that is transmitted through the foundation. The scope of the present paper therefore, is to investigate whether such a potential modification of the soil-structure system dynamic characteristics could result to the upgrade of seismic safety while investigating the physical mechanisms that describe the behavior of the coupled SSI system. The examined foundation intervention methods include both commonly applied construction techniques, such as diaphragm walls and soil stiffening, as well as more innovative methods implementing low shear strength materials that are injected within the soil mass. All these solutions are studied with the use of advanced numerical tools through extensive experimental validation and parametric analyses that aim at investigating a specific beneficial or detrimental trend for various combinations of earthquake scenarios, soil conditions and SDOF and MDOF structural characteristics. The numerical analysis results derived reveal that, notwithstanding the significant complexity of the problem, particular interventions could potentially mitigate the imposed earthquake input, thus improving the anticipating building seismic performance under certain conditions.

Introduction

Interventions at the soil-foundation level of buildings are commonly applied over the last decades mainly in order to enhance soil resistance and bearing capacity and improve the structural response under both static and dynamic loading as well as towards the reduction of soil deformations. In this context, soil densification, pile reinforcement, jet grouting and several other techniques have been implemented to directly enhance resistance-related soil properties. Furthermore, in cases of critical soil behavior under dynamic loading, such as potentially

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liquefiable soils, alternative approaches have been proposed targeting indirectly at the decrease of phenomena that lead to failure (i.e. excessive pore pressure generation), a dissipation that is achieved by lowering of the ground water table, drainage systems construction etc.

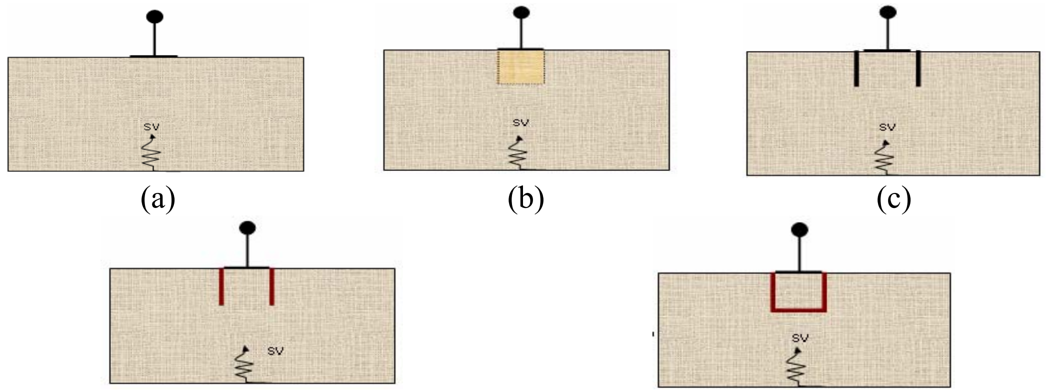
Apart from the improvement of the soil-foundation-structure behavior in terms of increased soil strength, foundation interventions impose a modification of the system dynamic properties, thus introducing an additional parameter to the examination of the overall seismic response. The contribution of this parameter could be beneficial, complementary to the already achieved soil resistance enhancement, or detrimental leading to unfavorable (modified) soil-structure dynamic behavior. Moreover, the complexity of the problem is increased due to the fact that the wave propagation characteristics within the soil media up to the soil-foundation interface caused by multiple reflections, refractions and superposition of the incoming wavefield are also affected by type and extent of the applied intervention technique.

From another point of view, the unavoidable modification of the system's dynamic properties after an intervention may constitute a mitigation technique on its own, as it can reduce the seismic load in particular cases (although not easily predicted in advance). Along these lines therefore, the scope of this paper is to investigate the potential beneficial or detrimental effect of the modified subsoil conditions and foundation characteristics on the overall dynamic response of the soil-structure system. Both simplified single-degree-of-freedom (SDOF) and more complicated multi-degree-of-freedom (MDOF) frame structures are examined, disregarding as a first stage soil strength related issues. Commonly applied techniques and theoretical investigations are analyzed and discussed in the following paragraphs.

Overview of the investigation procedure

Intervention methods examined

The intervention methods examined in this study are depicted schematically in Fig. 1. Soil stiffening of the foundation area (Fig. 1b), implementation of stiff or "soft" (flexible) diaphragms (Figs. 1c and 1d) as well as the introduction of a "soft caisson" isolation of the soil-structure system (Fig. 1e) are numerically simulated. First, the reference case (Fig. 1a) of the unmodified soil-structure response is determined for several configurations with respect to the structural dynamic properties. Then, the corresponding case including each intervention application is investigated and compared with the reference case response. A "modified" to "initial" response ratio is introduced (i.e. maximum response magnitude after mitigation divided by the maximum response magnitude of the reference case), to provide a comprehensive measure of the beneficial or detrimental effect of each particular intervention scheme. Consequently, ratios below unity indicate a beneficial mitigation effect of the applied intervention. Base and superstructure acceleration ratios, with base referring to the point at the center of the foundation level and superstructure to the top of the structure (mass location), as well as base rotations and column bending moments are selected as the most representative response parameters to determine the efficiency of each mitigation method. Base rotation represents the foundation rotation considering a rigid foundation herein. Soil stiffening and stiff diaphragms interventions are also commonly used in foundation engineering practice especially in problematic soil conditions, focusing primarily on the soil resistance upgrade and the reduction of the structural settlements and deformations.



(a) (b) (c)

(d) (e)

Figure 1. Schematic illustration of the intervention methods considered; (b) soil stiffening, (c) stiff vertical diaphragms, (d) “soft” vertical diaphragms, (e) “soft caisson” isolation

As a result, the potential secondary effect that such an interference could have on the dynamic properties of the system was also deemed interesting to be investigated in the framework of the present study. Another interesting case refers to techniques that aim at more flexible systems compared to the initial soil-foundation stiffness characteristics. Such techniques could seem rather challenging and difficult from a practical perspective but it is possible that such a substantial modification of the initial system stiffness (if indeed technically feasible) could result into an entirely different dynamic response. Of course the technological implementation of these techniques is still at the stage of research. Yet, several steps have been taken in this direction, which are gradually forming suggestions towards earthquake risk mitigation. As an example, this kind of premature soil seismic isolation of the entire foundation-soil volume, has been introduced employing innovative materials that create an interface of low friction (Yegian and Kadakal 2004, Yegian and Catan 2004). Moreover, alteration of the wave propagation pattern using flexible diaphragms or even trenches as well as pile barriers has also been already examined successfully for reducing train-induced structural vibrations (Leung et al 1989, Adam and Estorf 2005, Kattis et al 1998, Andersen and Nielsen 2005). Clearly, the main objective in these cases is to modify the surface wavefield only, differing substantially from the body wave propagation phenomena that carry a major percentage of seismic energy. Still though, it is definitely a progress towards solutions that implicate seismic motion alteration rather than soil-structure strength enhancement.

Numerical modeling

Numerical modeling of the examined soil-foundation-structure system is initially performed using simplified single degree of freedom (SDOF) oscillators with rigid spread foundation resting on a homogeneous soil profile of finite depth, assuming rigid bedrock conditions at the base. A more complicated multi degree of freedom frame structure (MDOF) is then employed, in an effort to extend the conclusions of SDOF performance to more realistic structure cases. For all examined interventions, the selected soil deposit corresponds to soil type C of the Eurocode 8 (EC8), characterized by shear wave velocity equal to Vs=200m/sec. The only exception was the stiff diaphragms intervention, where a softer soil of Vs=100m/sec was examined.

Numerical investigation of the intervention influence was performed in the time domain, implementing SV wave seismic motion introduced at the base of the soil profile, whereas review of the results was more comprehensive using the frequency domain. Evaluation of results is focused on a limited frequency range (periods between 0.1 and 1sec), which is considered of greatest interest for most common civil engineering projects.

The widely used FE codes, ADINA (ADINA R & D Inc. 2004) and ANSYS (ANSYS Inc, 2000), were comparatively employed for the numerical investigation of the soil-foundation-structure system. Appropriate consideration of the lateral boundaries averts undesirable effects from (analysis-induced) refracted waves, while the FE mesh was adequately defined according to the anticipated wavelength of the considered input motion. Based on the above modeling considerations, the parametric analysis of the intervention effect focused on the structural fixed base period T_s and the superstructure mass m_s, normalized in the case of the SDOF system according to the relationship:

$$m_{norm} = \frac{m_s}{\rho \cdot B^3} \qquad (1)$$

where ρ is the soil density and 2B the foundation length (Wolf, 1985). Two values of normalized mass have been considered (0.5 and 2) whereas several intervention properties regarding stiffness and geometric configuration have been also parametrically investigated.

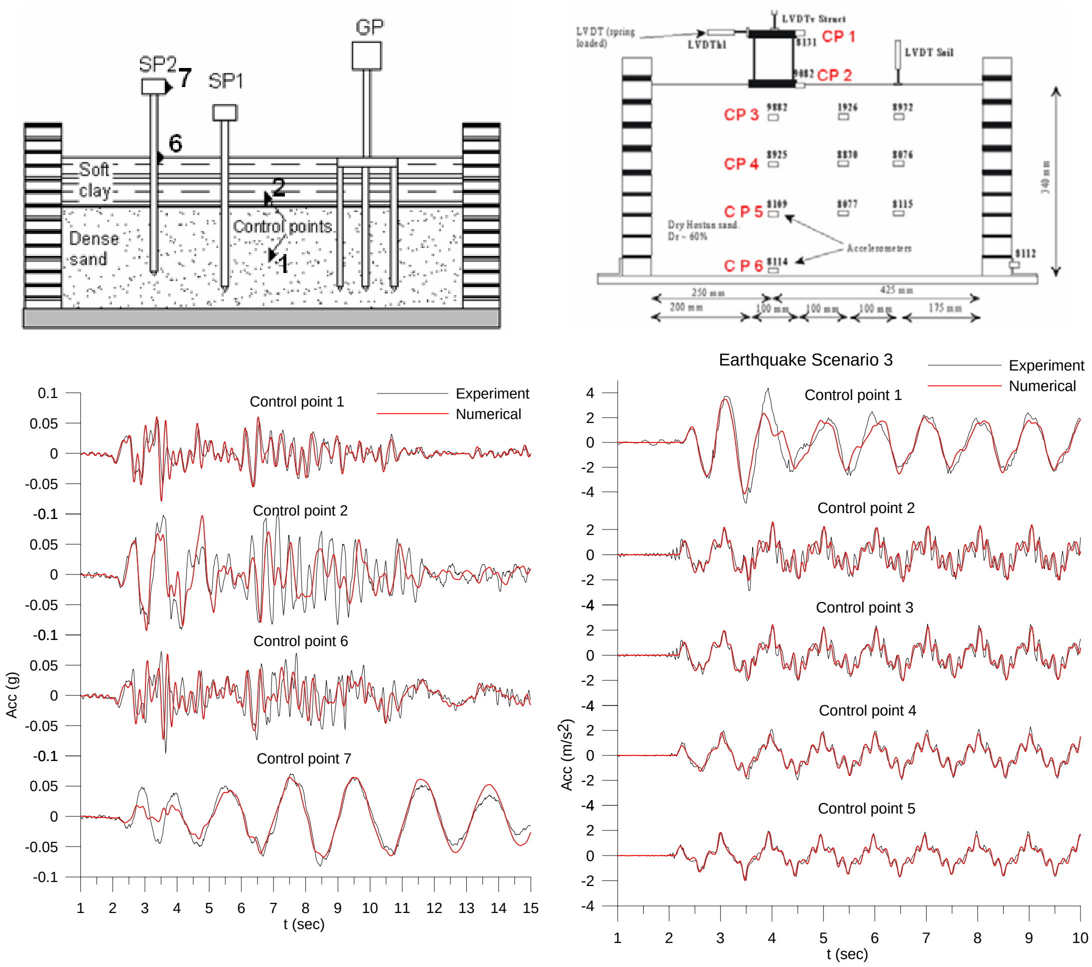
Anticipated mitigation mechanism

The fundamental role of soil-structure interaction in the seismic response of structures has been widely studied and well established by several researchers (Wolf, 1985, Gazetas, 1987 among others). Different natural vibration characteristics and additional energy dissipation mechanisms are among the basic parameters that modify in general the response of flexible supported structures contrary to the rigidly supported ones. Although soil-structure interaction usually (but not exclusively) leads to lower levels of seismic forces mainly due to the elongation of the fundamental period, the beneficial or detrimental effect of soil structure interaction on the final seismic response of the structures can not be identified a priori (Mylonakis and Gazetas, 2000). Given the significant role of soil-structure interaction, it becomes evident that interventions to subsoil conditions alter the dynamic properties of the overall system, thus affecting the soil-structure interaction mechanism and in turn modifying the seismic structural response. More specifically, the presence of stiff vertical diaphragms at the foundation soil is expected to modify the structural response due to the diaphragms stiffness interfering with wave propagation and increasing the overall stiffness of the soil-structure system. The strong kinematic interaction between the stiff diaphragms and the adjacent relatively soft soil may result in different excitation imposed at the base of the structure. Further modification of the base input motion is anticipated when the soil stiffening technique is employed. The introduction of an increased stiffness zone uniformly applied under the foundation is expected to modify substantially the soil-foundation-structure interaction mechanism since neither the relative soil-structure stiffness nor the energy dissipation mechanisms remain the same as in the initial soil structure case. Consequently, the response of the modified soil-structure system is anticipated to shift to higher frequencies, with the intervention effect (probably detrimental) being more pronounced with increasing ground improvement stiffness.

On the other hand, the "soft" diaphragms intervention aims at the alteration of the dynamic characteristics of the soil-structure system by shifting the response in higher periods. Furthermore, a modification of the input motion at foundation level is anticipated, due to the soil column response bounded between the "soft" diaphragms. Finally, "soft caisson" intervention technique employs the principles of seismic isolation. Filtering of the input motion as well as alteration of the dynamic characteristics should also be expected, with the modified soil-structure system response in higher periods. Consequently, modification of the amplitude and frequency content of the propagating motion that finally reaches the structure's base is anticipated.

Validation of the numerical tools

Since the effect of the foundations interventions on the overall structural response is analyzed with general purpose FE codes, it is necessary to establish a degree of confidence on the numerical tools efficiency to adequately reproduce both wave propagation and SSI effects. Centrifuge physical experiments are widely recognized as a reliable method of soil testing, being able to reproduce the prototype stress field in scaled experimental configurations and constitute therefore the framework of numerical modeling validation for soil response simulation cases. The particular centrifuge tests used for the validation of the FE codes herein (Fig. 2), were selected to correspond to different soil conditions and foundation type. For each case, the dynamic behavior of the soil was modeled using an equivalent linear procedure, a detailed description of which can be found in Pitilakis et al, 2004 and Pitilakis et al, 2005.



(a) (b)

Figure 2.Centrifuge and simulation data used for the validation of (a) ANSYS (b) ADINA code.

More specifically, for the validation of the ANSYS code a well-documented series of dynamic centrifuge tests of pile supported structures in soft ground was implemented. The tests were performed in the 9-m-radius centrifuge at the University of California at Davis (Wilson et al. 1997b, Boulanger et al, 1999). The double layer soil profile consisted of a 6m thick soft clay overlying a 11m thick dense sand. In the case of ADINA code, the validation procedure employs the simulation of a frame SDOF structure with spread foundation resting on a homogeneous soil profile. The soil model consisted of a dense layer of Hostun S28 sand, with 34cm depth corresponding to 17m at prototype scale considering the 50g environment applied. The experiments layout along with indicative validation results are presented in Fig. 2. It is obvious that with both codes a fair reproduction of wave propagation and SSI phenomena is achieved, making their implementation to numerical investigation of intervention effects possible.

Numerical investigation of the intervention cases

The obtained numerical analyses results are presented and compared in order to define the different levels of the beneficial or detrimental effect of each intervention method on the overall structural response.

Evaluation of intervention effects on SDOF system

The modification of the SDOF response due to the interventions at the foundation soil was first examined for two different fixed base periods (Ts=0.2 and 0.4sec). The main objective of this parametric study is to determine whether the superstructure dynamic properties affect the way that the interventions modify the soil-structure system response. Thus, in Fig. 3 the base acceleration ratio is plotted against the fundamental period of the input motion, for each one of the considered SDOF fixed base periods and for the two considered levels of superstructure mass. The respective ratios corresponding to the superstructure acceleration are plotted in Fig. 4.

It should be mentioned here that several different application configurations have been examined during the numerical investigation. The comparative diagrams of the following figures correspond to the particular cases that resulted in the most pronounced intervention effect. Those refer to an intervention depth equal to the foundation base length for the stiff (concrete equal) and flexible (E=200KPa) diaphragms and the soil stiffening method (Fasoula 2005, Trevlopoulos 2005). In the case of the “soft caisson” method, the respective curves were obtained using an equivalent shear modulus of very low rigidity (G=100KPa) to model the horizontal layer able to develop large shear strains under low values of seismic shear stresses.

The effect of each intervention on the structural response is not always on the conservative side depending mainly on the frequency content of the input motion and the dynamic characteristics of the superstructure. Furthermore, it is observed that in general the superstructure acceleration is modified without necessarily following the same trend with variation at the base of the structure. The effect of techniques related to soft material inclusions in the foundation soil is generally more pronounced compared to the stiff diaphragms or the soil stiffening method. Construction of soft vertical diaphragms or inclusion of the foundation soil introducing a soft caisson seems to affect the structural response over the entire frequency range of the considered input motion. On the other hand, stiff diaphragms or soil stiffening interventions modify the response of the system mainly under high frequency excitations, as Figs. 3 and 4 illustrate.

Different values of superstructure mass result into different modification patterns of the structural response. Especially in the case of flexible diaphragms and “soft caisson” it is obvious that increasing structural mass, for the same fixed base period, has a beneficial effect in terms of the resulting superstructure accelerations (Fig. 4).

On the contrary, when soil interventions that are related to stiffness upgrade are examined, larger superstructure mass may lead to higher seismic forces imposed on the structure (detrimental effect) for specific frequency range of the input motion. More specifically, construction of stiff vertical diaphragms results in increased base acceleration especially for low period structures (Fig. 3). Furthermore, increase of the structural mass amplifies the beneficial or detrimental effect of the intervention. Soil stiffening on the other hand reduces the computed seismic ground acceleration at the foundation level for low periods of motion whereas the intervention effect is less important with increasing superstructure mass.

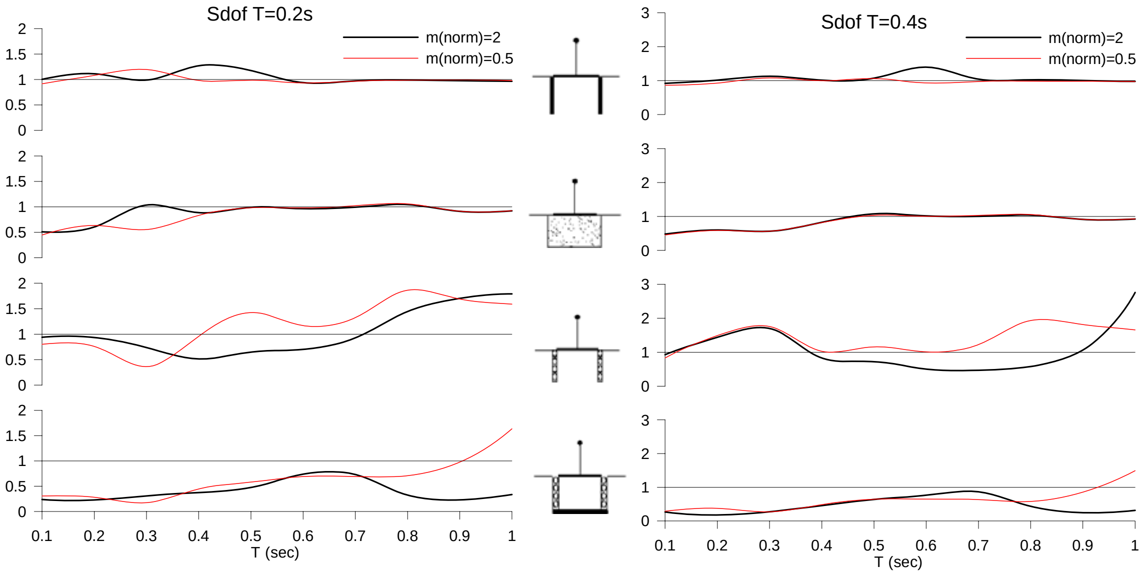


Figure 3. Variation of base acceleration ratios for T_{sdof}=0.2sec (left) and T_{sdof}=0.4sec (right).

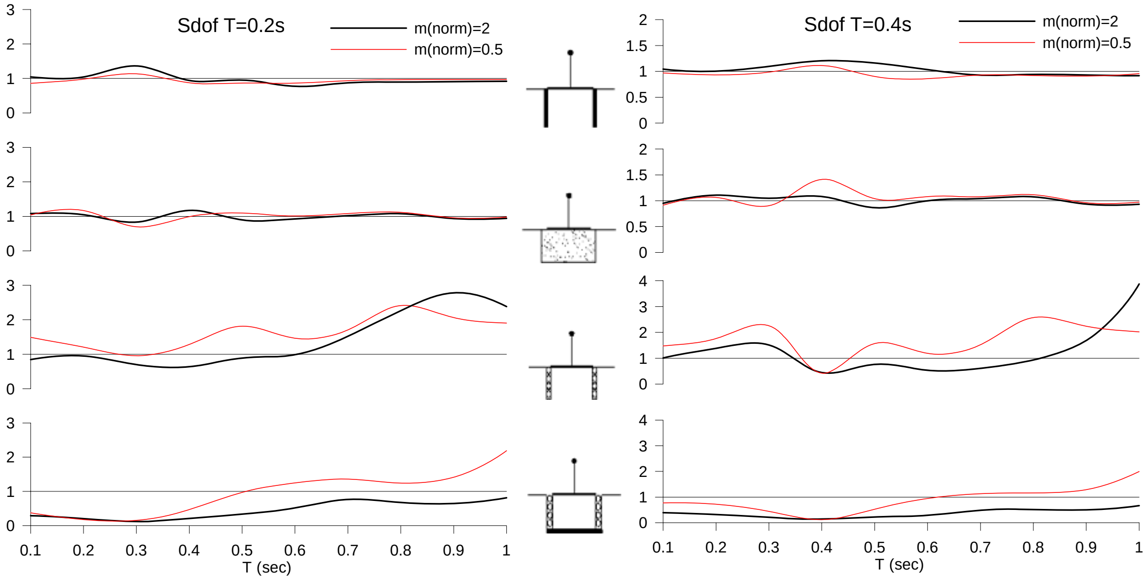


Figure 4. Variation of superstructure accel. ratios for T_{sdof}=0.2sec (left) and T_{sdof}=0.4sec (right).

Fig. 5 presents the comparative results in terms of the rotation ratio at the base of the SDOF structure. The beneficial effect of the stiff diaphragms intervention is quite obvious resulting in base rotation ratios below unity. On the contrary, the other examined methods significantly increase base rotations in some cases more than an order of magnitude. Yet, the magnitude of absolute base rotation values may still be insignificant.

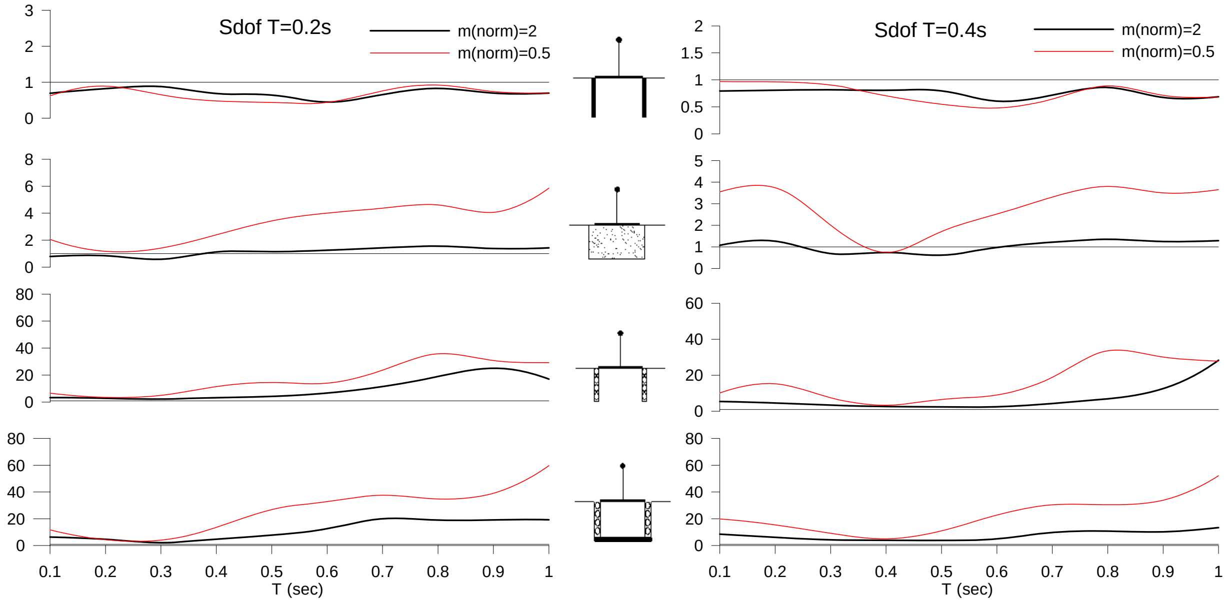


Figure 5. Variation of base rotation ratio for T_{sdof}=0.2sec (left) and T_{sdof} =0.4sec (right).

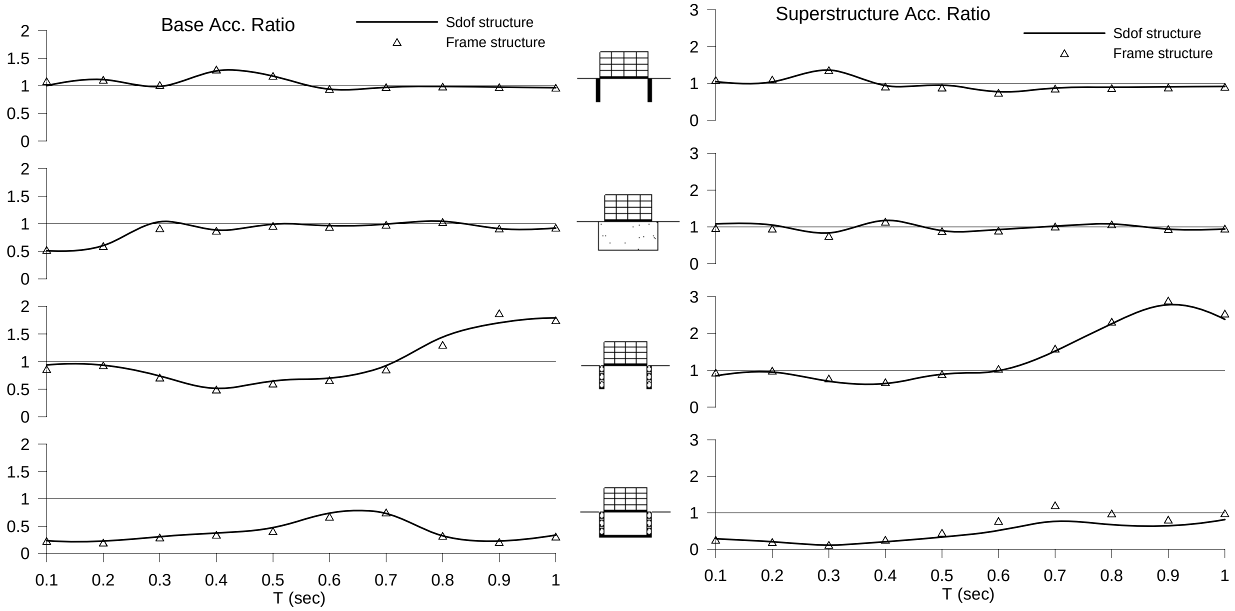


Figure 6. Base and superstructure acceleration ratio of frame structure compared to SDOF results (Notice the different scale between figures).

Comparative evaluation of intervention techniques on MDOF and SDOF systems

The next step of the study was to investigate whether the effect observed of each intervention on a SDOF modification ratio presented before could be extended for the case of a MDOF frame system. The fundamental period of the frame structure implemented herein is equal to T=0.2sec, having a mass participation ratio of the first mode approximating 87%. For the determination of the equivalent SDOF properties, the corresponding mass and height of the SDOF structure can be obtained according to the following well known relationship (Wolf, 1985):

$$m = \frac{(\sum_j m_j \varphi_j)^2}{\sum_j m_j \varphi_j^2} \; , \; h = \frac{\sum_j m_j \varphi_j h_j}{\sum_j m_j \varphi_j} \tag{2}$$

where m, h correspond to the mass and height of the SDOF structure, m_j and h_j are the mass and height of each j storey of the MDOF frame structure whereas φ_j represents the modal storey displacements of the first fundamental mode of the MDOF structure. Taking into consideration that the frame structure height and mass are equal to 12m and 3168t (792t per floor) respectively, calculations using Eq. 2 yield a SDOF equivalent of normalized mass equal to 2 and height equal to 9m.

Comparative results, in terms of base and superstructure accelerations (at the top storey level of the frame), are illustrated in Fig. 6, highlighting a strong resemblance to the simplified SDOF structure ratios. The trend of the intervention effect on the frame structure is accurately predicted in each investigated case by the SDOF ratios. The same observation is also reached when the bending moments of the base columns are examined. It is therefore a good indication that when the effect of the soil intervention on the seismic response of a frame structure is sought, a SDOF system could provide an acceptable first estimate of the overall system modified performance.

Conclusions

The effect of various intervention methods to subsoil and foundation conditions on the seismic response of structures was numerically investigated. Both commonly used and innovative intervention techniques have been employed, whereas numerical analyses of several different configurations of a single-degree of freedom structure were performed. Soil stiffening, stiff and flexible vertical diaphragms as well as soil isolation systems have been studied numerically using a soil-intervention-structure finite element model. Identification of intervention effects was subsequently extended to multi-degree of freedom frame structures. The extensive parametric analysis scheme performed indicate that whereas ‘classic’ soil intervention techniques, related to soil stiffness increase and strength upgrade, may lead to limited alteration of the seismic response and only under specific conditions. On the other hand, it is shown that the innovative techniques examined such as flexible diaphragms and the “soft caisson”, could potentially result into the mitigation of seismic loading at a wide frequency range provided that they are technically feasible and given a set of soil, earthquake and structural uncertainties.

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