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Soil–Foundation–Structure Interaction Effects in Seismic Behavior of Bridges

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Abstract

Presented here is an analysis of the effects of soil-foundation-structure interaction (SFSI) on seismic response of highway bridges. Of particular importance is the issue of input motions, their scaling and application to the SFS models. The analysis presented in this paper addresses the influence of inelastic behavior of both the soil and the structural components during seismic response evaluation of highway bridge systems. At the system level, the additional flexibility introduced by the soil-foundation system results in increased displacement demands under moderate to severe ground motions. Additionally, it is also demonstrated that that SFS interaction can sometimes have a beneficial effect on the superstructure response and sometimes produce detrimental effects on the system behavior and is dependent on the characteristics of the earthquake motion. It is shown that each SFS intearacton problem has to be analyzed fully and that it is almost impossible to draw general conclusions about the behavior of the SFS system during seismic motions.

Keywords: Seismic soil–structure interaction.

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1 Introduction

The issue of effects of soil-foundation-structure (SFS) interaction on behavior of bridges has been researched extensively in last couple of decades. For some reason, there is a general opinion between most structural engineers that the the effects of soil-foundation-structure interaction are beneficial to the behavior of the structural system under earthquake loading. That opinion has found it's way even in today's codes. For example the NEHRP-94 seismic code states that: "These [seismic] forces therefore can be evaluated conservatively without the adjustments recommended in Sec. 2.5 [i.e. for SFS interaction effects]". Eventhough design spectra are derived on a conservative basis, and the above statement may hold for a large class of structures, there are case histories that show that the perceived role of SFS interaction is an over–simplification and may lead to unsafe design.

Recent case studies suggest, however, that the soil–structure interaction can somethimes be detrimental to seismic behavior of structures (e.g. Gazetas and Mylonakis [5]). A number of papers in recent years have investigated the influence of the SSI on behavior of bridges [8, 10, 9, 15, 11, 3, 4]. In particular Sweet [15] and McCallen and Romstadt [11] performed finite element analysis of bridge structures subjected to earthquake loads. However, Sweet [15] approximated the geometry of pile groups as he was unable to analyze a full model with available computer hardware. On the other hand, McCallen and Romstadt [11] performed a remarkable full scale three-dimensional analysis of the soil–foundation–bridge system. The soil material (cohesionless soil, sand) was modeled using an equivalent elastic approach (using Ramberg–Osgood material model through standard modulus reduction and damping curves developed by Seed et al. [12]). The two studies by Chen and Penzien [3] and by Dendrou et al. [4] analyzed the bridge system including the soil but the developed models used very coarse finite element meshes.

This paper investigates a number of SFS interaction issues. Shown are results of a case study on simulating SFS interaction behavior for the I–880 viaduct in Oakland, California. Of particular interest is the investigation of beneficial and detrimental effects on structural response due to different input ground motions. To this end, the structure is modeled with and without SFS interaction effects and the resulting damage, in terms of disipated plastic energy is used to establish state of structure after the seismic load. The effects of ground motion scaling on the response of the structure is investigated.

Another very important issue related to SFS interaction is the question of input motions applied to the structure and their relation to the so called free field motions. Presented here is also a brief overview of some recent work on modeling seismic motion, taking into the account the effects of propagation from the source (hypocenter) through the top layers of soil. An enhanced version of the so called Domain Reduction Method (e.g. Bielak et al.[2, 16]) is used with inelastic models for soil. A set of examples is presented to exemplify the importance of SFS interaction, particularly in soft soils.

2 SFSI Case Study

A simple case study was performed in order to investigate SFS interaction effects during earthquakes (eg. Jeremić et al. [6]). A simplified SFS model, using soil springs was used to illustrate beneficial and detrimental effects of SFS interaction on performance of the structure. The prototype structure was a typical bent of the I–880 highway structure in Oakland, CA. The model is composed of inelastic fiber beams to represent the bridge piers where much of the inelastic behavior is expected to occur, elastic beams to represent the deck and equivalent zero-length foundation springs to represent the soil-foundation system. Figure 1 shows a plan view of the I-880 highway. The complete structure

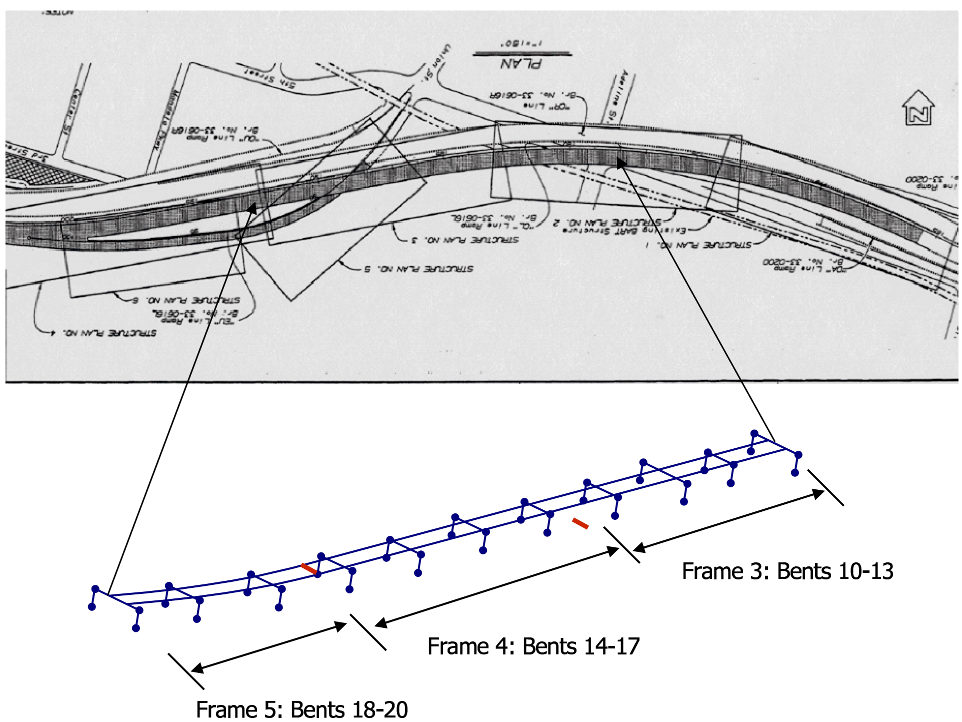


Figure 1: **Plan view of I–880 Viaduct and multiframe structural model.**

consists of seven frames and 26 bents. In the present study, three interior frames comprising 11 bents (Bent 10-20) were considered in the evaluation. A simpler model consisting of a single frame was also used in a series of simulation studies. Figure 2 shows the frame models, one without and one with the SFS interaction. Foundation springs for both models were obtained from a detailed

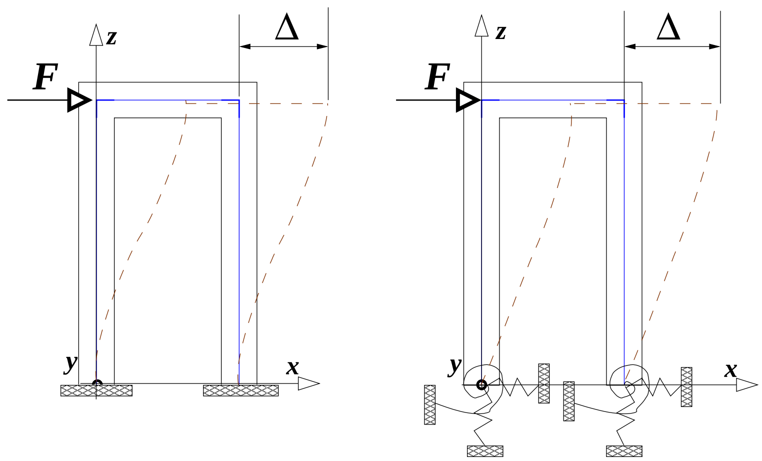


Figure 2: **Two frame models for the Bent #16,fully fixed and the model with soil springs.**

3D finite element model of the pile group foundation system using elastic soil properties. It is noted that the inelastic analysis of soil–foundation system was also performed for a limited number of load cases and it was shown that, at least for small deformations expected here, the response can be very well approximated with elastic soil behavior. The foundation system consists of a 5×5 pile groups connected with a massive pile cap. The piles are made of reinforced concrete and reside in a steel shell with a diameter of 0.6m. The schematic figure of the pile cap, the piles and the finite element mesh for the soil–foundation system is show in Figure 3.

A uniform hazard spectra for SD (soil) site conditions was derived for a site in Oakland which represents an event with a 10 % probability of exceedance in 50 years. The hazard is dominated by earthquakes on the Hayward fault which is located about 7 km east of the I–880 site. The ground motion model of Abrahamson and Silva [1] was used in generating the spectra (Somerville and Collins [13]). The spectra contains rupture directivity effects which were represented in the probabilistic hazard analysis using the empirical model proposed by Somerville et al. [14]. The spectra were generated for both fault-parallel (FP) and fault-normal (FN) directions.

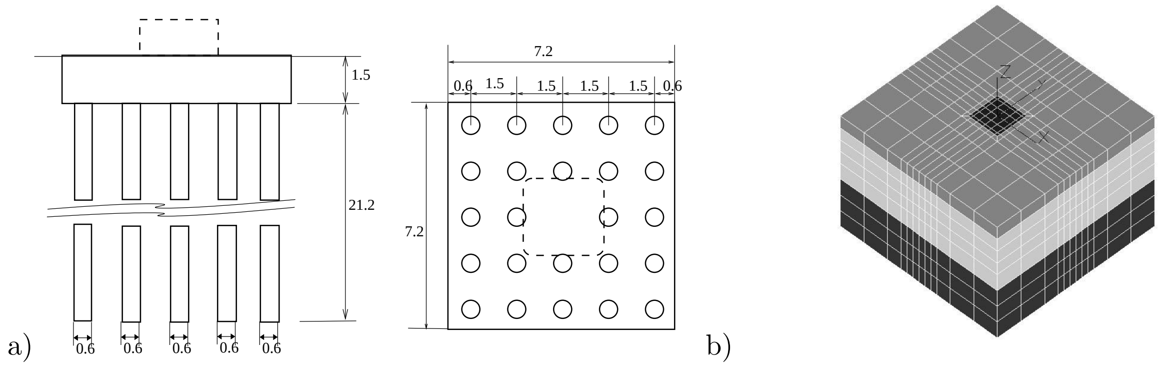


Figure 3: **(a) Schematics of the pile cap and the piles. (b) Finite element mesh for soil foundation system.**

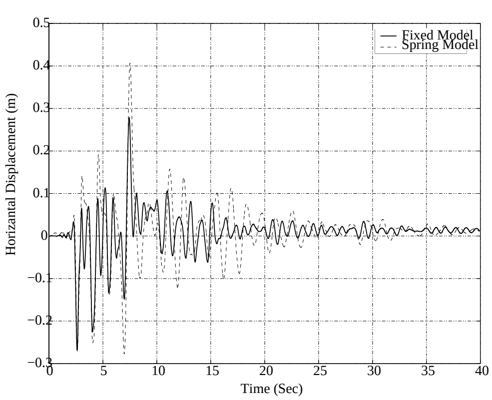
2.1 Response Results from Single Frame Model

Three time histories were selected: two from the modified suite of Loma Prieta motions (recorded at Gilroy and Corralitos) and one from Kobe. Detailed description of ground motion generation is given by Jeremić et al. [6]

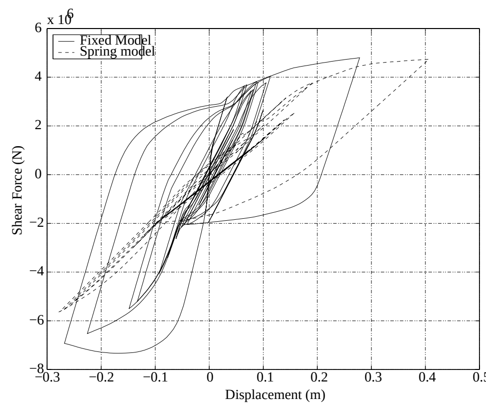
The main feature in evaluation of the two bent models is in different behavior of the same bent for chosen input motions. Presented here are result from two Loma Prieta motions (Corralitos and Gilroy). The effects of SFS interaction are considered to be beneficial to the structure under the following conditions:

- There are no significant permanent deformations in the structure resulting from yielding of the pier, or
- The energy dissipation (hysteretic loops) of the system with SFS interaction is smaller than that with fixed foundation, leading to the conclusion that there is less damage to the structure.

If any of the above criteria is not fulfilled, it is assumed that SFS interaction is detrimental to the structure behavior. Presented here are two examples of bent behavior, one representing beneficial effects and one for detrimental effects of SFS interaction. Figure 4 shows behavior of the bent subjected to the scaled Corralitos record. This record was scaled to match the hazard spectra at a period of 0.77 sec. As is evident from the spectra shown in Figure 4, the demands imposed by the earthquake are more significant in the short period range, hence the fixed base model experiences higher demands than the model with SFS interaction. Both SFS and non SFS interaction results show small permanent deformation (on the order of one to two centimeters). However, the hysteretic loops of the model considering SFS interaction effects are much smaller then those of the non SFS interaction model thus suggesting much smaller levels of damage for the SFS interaction model. Results in Figure 5, on the other hand, clearly indicate that the SFS interaction model subjected to



a)



b)

Figure 4: LP–Corralitos Record : a) displacement time history for fixed and spring supported models, b) horizontal displacement vs shear force for fixed and SFS interaction models.

scaled Gilroy earthquake is dissipating more energy and also being subjected to larger deformations than the non–SFS interaction model. The spectral demands are initially higher in the short period range for this record, however, it is likely that the fixed base model moves into a region of slightly lower demands (just beyond 0.5 seconds) since the degree of inelasticity is not severe. The shift in the period from 1.24 seconds of the SFS interaction model takes it into a region of increased demand thus causing higher drifts.

2.2 Response Results from Multiple Frame Model

In this phase of the study, the complete response of the entire three-frame model shown in Figure 1 was considered. For the multiple-frame model it was necessary to provide spring elements between each frame to model the inter-frame connections. These spring elements represent the four components that make up the inter-frame connections; the longitudinal and vertical restrainers, shear keys and bearing pads. Three sets of 10 ground motions were selected for the bridge site corresponding to three hazard levels: events with a 50% probability of being exceeded in 50 years; events with a 10% probability of being exceeded in 50 years; and events with a 2% probability of being exceeded in 50 years. Two model configurations were each subjected to each set of ground motions: the first model

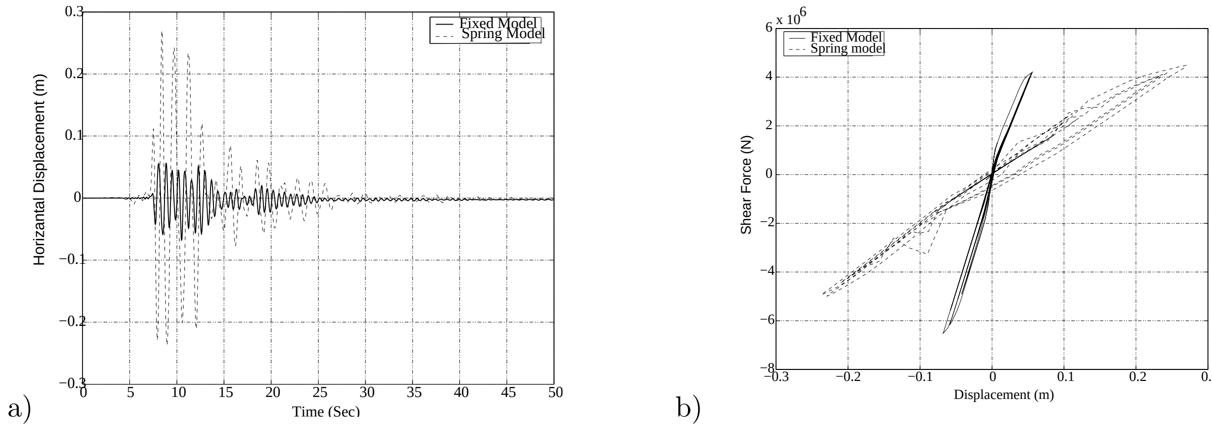


Figure 5: LP–Gilroy Record: a) displacement time history for fixed and SFS interaction models, b) horizontal displacement vs shear force for fixed and SFS interaction models.

assumed fixed base conditions while the second model incorporated the soil-foundation springs as described in the previous section. Since the ground motions were scaled to match the fundamental period of the model, another issue that was investigated in this study was the influence of ground motion scaling. The same set of ground motions was first scaled to match the hazard spectra at a period of 0.6 seconds (which represents the first mode period of the fixed base model) and then the ground motions were scaled to match the hazard spectra at 1.2 seconds (which corresponds to the model with soil-foundation springs). Results of the simulations are presented in Figures 6, 7. The peak drifts shown are the mean values of the 10 simulations for each hazard level. As is evident from these plots, the effect of ground motion scaling is not very significant. However, the mean response for all earthquakes indicate that soil-structure interaction effects lead to increased superstructure displacements. While increased displacements did not always result in nonlinear or detrimental behavior, certain ground motions produced more inelastic behavior in some of the bents. In general it was not possible to draw generalized conclusions on the effects of SFS interaction. As indicated in the previous section, both beneficial and detrimental effects of SFS interaction were observed which varied with bent location and ground motion.

3 Dynamic SFS Interaction Modeling

One of the basis for seismic analysis of soil–foundation–structure (SFS) system is appropriate formulation and implementation. The finite size of finite element models introduces many problems,

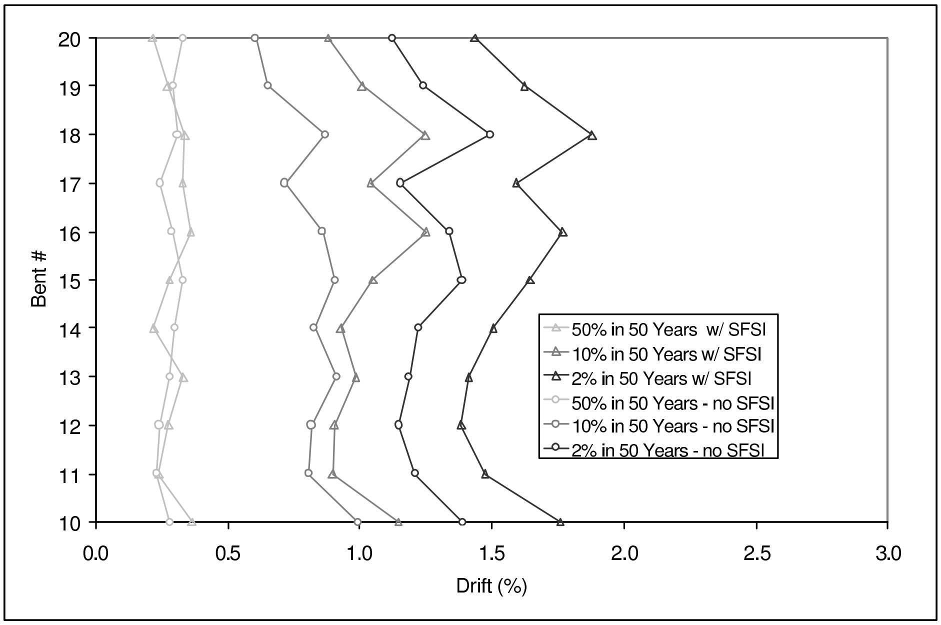


Figure 6: Mean of the peak bent displacements for all three hazard levels for records scaled to match hazard spectrum at fixed base period.

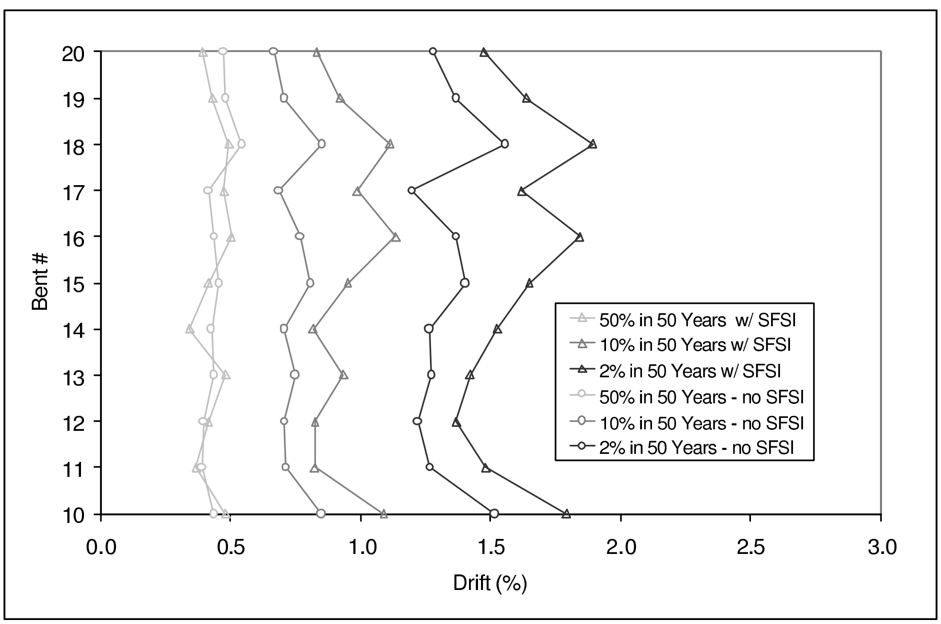


Figure 7: Mean of the peak bent displacements for all three hazard levels for records scaled to match hazard spectrum at fundamental period obtained using SFS interaction model.

including the input of seismic motions, arrest of wave energy in the finite size model to list just a few. Recently developed Domain Reduction Method (DRM) for elastic problems [2, 16] is used and adapted for SFS interaction problems. One of the best features of the DRM is that in addition to being applicable to elastic problems, close inspection of the formulation shows that it can be applied to inelastic problems as well. Detailed formulation and implementation details are given in [7]. Figure 8 shows the application of the DRM to SFS problems. The seismic wave field (free field) can be obtained using some of the available methods, including closed form solutions (Green's functions or large scale geophysical simulations) are used to provide input for the DRM. The input

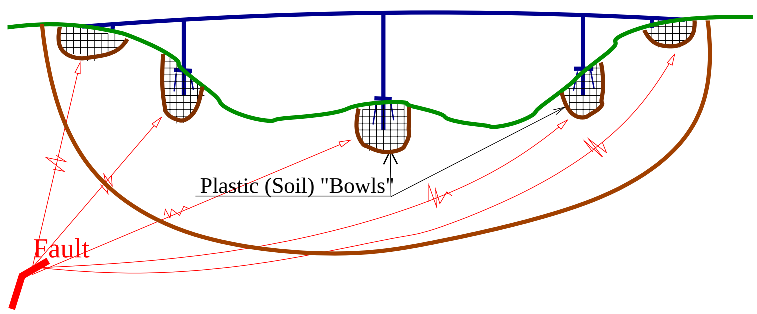


Figure 8: Seismic SFS interaction using large scale geophysical wave propagation and the DRM (soil islands) to assess the behavior of a bridge during an earthquake.

requires displacements and accelerations on a single layer of elements that completely encompasses the inelastic domain with the SFS system. The effective forces that are used to load the system are then

$$\left\{ \begin{array}{c} P_i^{eff} \\ P_b^{eff} \\ P_e^{eff} \end{array} \right\} = \left\{ \begin{array}{c} 0 \\ -M_{be}^{\Omega+} \ddot{u}_e^0 - K_{be}^{\Omega+} u_e^0 \\ M_{eb}^{\Omega+} \ddot{u}_b^0 + K_{eb}^{\Omega+} u_b^0 \end{array} \right\}$$

Seismic amplification of local, soft soil sites has been reported many times, yet robust and accurate 3D simulation techniques have not been fully developed to help analyze SFS interaction problems. For example, Figure 9, obtained by using our DRM implementation in OpenSees, shows vertical wave propagation through stiff (dense sand) and soft (soft clay) soils subject to the same earthquake. The result shows that the soft soil site has an increase in surface deformation of 3.5 times than that of the stiff site.

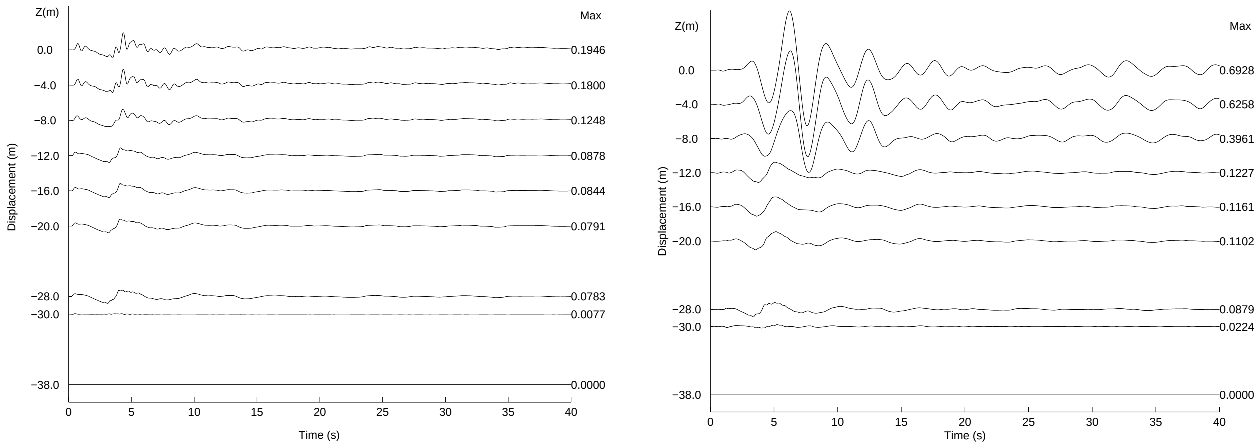


Figure 9: Seismic wave propagation resulting from the same earthquake acting on a stiff and soft soil site.

4 Summary

In this paper, the influence of soil–foundation–structure interaction (SSI) on behavior of structures was investigated. In particular, the notion that the SFS interaction is always good for the structure should be carefully evaluated on a case by case basis. In addition to that, a novel approach to simulating SFS interaction, using Domain Reduction Method was presented, as an alternative methodology to overcome current limitations in nonlinear analysis incorporating SFS interaction.

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