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A new approach in simulation of soil-structure interaction problems including damper effects

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Abstract: In this paper, numerical simulation of the issues related to soil-structure interaction (SSI) in the structures equipped with prestressed damping device (PDD) is presented. More specifically, this research examines the impacts of dampers on the interaction between the soil and the structure, considering a variety of conditions, including the effects of the soil boundaries simulated by infinite elements. Comparative analysis of the results with different disposition of the dampers is made using ANSYS nonlinear platform. It could be observed from the results of the numerical analysis that regarding the impact of dampers in the structure on SSI, the selection of the damper type has a significant role.

Keywords: soil-structure interaction; SSI; seismic excitations; prestressed damping device; PDD; boundary conditions; infinite element.

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1 Introduction

For the time being, significant progress has been achieved in terms of numerical simulation software for bare frame structures considering time history record as a seismic input. However, what are not paid enough attention are the effects of the soil-structure interaction (SSI), both on the transmission of the strong movements from the ground to the structure and on the dynamic response of the structure (Fu, 2009, 2010; Guo et al., 2013; Fu et al., 2017; Fu and Parke, 2018).

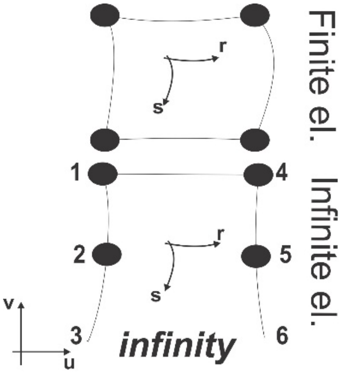
Furthermore, in the numerical simulation of the soil environment as a wide region, special attention should be given to the boundaries between the layers in order the influence of the reflection of the travelling waves from the soil environment to be avoided. Regarding the dynamic analysis and the consequential inertia parameters that should be taken into account, the circumstances are more complex in such a way that the emission of the waves should be also considered. In this paper, the effect of the seismic dampers on the SSI for a four-storey frame is investigated. In order to obtain more generalised results, the reference structure is analysed as both reinforced concrete structure as well as steel structure (Salvi et al., 2015; Elias and Matsagar, 2017; Amini et al., 2018).

Time history analyses are carried out for the whole complex problems, SSI and the effect of the dampers on the internal forces of the structural elements are investigated.

2 Infinite elements

Infinite elements are created in the same way as the finite elements beside the mapping domain. Firstly, the infinite elements are developed by Zienkiewicz et al. (1983) and until now they are developed both in frequency and time domain (Kumar, 2000; Liu et al., 2015; Kralik and Šimonovič, 2018). Häggblad and Nordgren (1987) have proposed infinite elements with absorbing characteristics that could be used in the time domain. In the development of an infinite element in this paper, some techniques take into account the time domain in which an infinite element is derived from the final element with six nodes, as depicted in Figure 1.

Figure 1 Coupling of finite and infinite element



The displacement of the element in both *u* and *v* directions is interpolated with the standard functions, N_1, N_2, N_4, and N_5:

$$\begin{aligned} u &= \begin{bmatrix} N_1 & N_2 & 0 & N_4 & N_5 & 0 \end{bmatrix} \mathbf{u} \\ v &= \begin{bmatrix} N_1 & N_2 & 0 & N_4 & N_5 & 0 \end{bmatrix} \mathbf{v} \end{aligned} \tag{1}$$

In expression (1), **u** and **v** are vectors with displacement of nodes in global coordinates.

$$\begin{aligned} N_1 &= -(1-s)r(1-r)/4 \\ N_2 &= (1/2)\left(1-r^2\right)(1-s) \\ N_4 &= -(1+s)r(1-r)/4 \\ N_5 &= (1/2)\left(1-r^2\right)(1+s) \end{aligned} \tag{2}$$

For coordinative interpolation in the coordinate system $r - s$, the one-dimensional mapping is used.

$$\begin{aligned} r &= \begin{bmatrix} M_1 & M_2 & 0 & M_4 & M_5 & 0 \end{bmatrix} \mathbf{r} \\ s &= \begin{bmatrix} M_1 & M_2 & 0 & M_4 & M_5 & 0 \end{bmatrix} \mathbf{s} \end{aligned} \tag{3}$$

where

$$\begin{aligned} M_1 &= -\frac{(1-s)r}{1-r} \\ M_2 &= -\frac{1}{2}\frac{(1-s)(1+r)}{1-r} \\ M_4 &= -\frac{(1+s)r}{1-r} \\ M_5 &= -\frac{1}{2}\frac{(1+s)(1+r)}{1-r} \end{aligned} \tag{4}$$

In expression (3), r and s are vectors of displacement of a node in local coordinates. It should be noted that on the infinity side ($r = 1$) no mapping of the nodes is appointed since it is assumed that the displacement is not possible in the infinity. Elements' matrices are designed following the standard procedures explained by Bathe (2006). Furthermore, Jacob's matrix takes into account the new coordinate interpolation functions, as described by Bettess (1992).

The Gaussian quadratic formulations are used to approximate the elements integration. The approach developed by Lysmer and Kuhlemeyer (1969) is utilised for the absorbing layer of the infinite element. Plane strain case has been considered in all cases.

The influence of the plane waves on the sides of the element produces normal and tangential stresses, as follows:

$$\begin{bmatrix} \sigma_n \\ \tau \end{bmatrix} = \begin{bmatrix} a\rho c_p & 0 \\ 0 & b\rho c_s \end{bmatrix} \begin{bmatrix} \dot{u}_n \\ \dot{u}_t \end{bmatrix} \tag{5}$$

Where c_p and c_s denote compression and shear waves and ρ represents the soil density. According to White et al. (1977), to obtain better numerical results considering the directions of the incident waves, coefficients a and b were used as multipliers. The transition from local to global coordinates was done automatically by the ANSYS (2007) software in such a way that does not require the definition of transformation matrices.

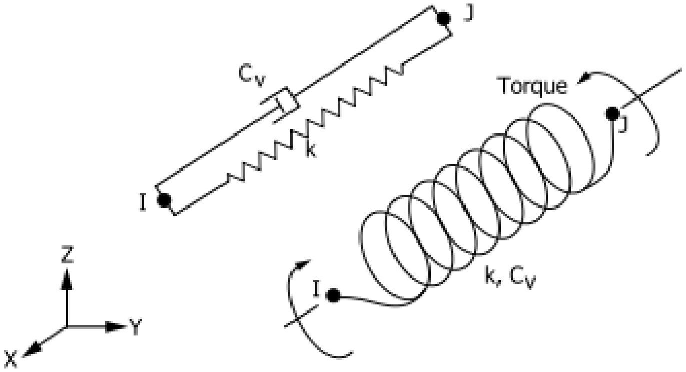
By collecting the contributions from each element, the main incremental equations for equilibrium in the dynamic analysis are obtained. Time derivatives are approximated using the Newmark's iteration equation method at each step as given in ANSYS finite element platform.

3 Characteristics of used dampers

The mathematical modelling of the dampers was carried out using *combin14* element, shown in Figure 2.

Dampers with the mass of 80 kilograms were simulated using a corresponding mass element, *mass21*. The element is defined by two nodes, a spring constant (k) as well as damping coefficients (C_{V1} and C_{V2}) and works on the basis of the Kelvin Vought model. The damping node participates only in the damping matrices of the structure.

Figure 2 Analytical model for the damper device used in ANSYS



The damping force (F) is then calculated by the following equation:

$$Fx = -C_v \frac{dUx}{dt} \tag{6}$$

where $C_v = C_{v1} + C_{v2}$ is the damping coefficient, whereas v is the velocity computed in the previous step.

Because the dampers are prestressed with a force of 30 KN (based on experimentally tested dampers), the pre-loading condition in the springs is specified as pressure by the input of an initial force (IFORCE) in the combin14 element.

In the optimisation process of the dampers, the following features were used: $k = 1{,}200$ kN/m, $C_V = 35$ kNs/m and prestressing force, $F = 30$ kN. This type of dampers gains additional structural damping up to 10%, decreasing the response and improving the performance under earthquake motions.

4 Coupled soil-structure system response

In order to consider the effect of soil boundaries on the construction to be explained, a comparison of different boundary conditions in the SSI problem was made. In this direct time domain method, the soil medium is modelled by two-dimensional quadrilaterals using the finite-element method.

To ensure complete insight, firstly, the soil side limit boundary is simulated as a fixed support applied to a truncated soil domain consisting of finite elements. Furthermore, the same soil medium is limited with viscous borders that could be easily simulated in the nonlinear platform (ANSYS, 2007).

Finally, the soil medium consisted of fewer finite elements is bypassed with the newly programmed infinite elements. Frame structural elements are idealised as two-dimensional elastic beam elements with three degrees of freedom in each node, translations in x and y directions, and rotation around the z-axis. Both steel and reinforced concrete frames were taken into consideration. It is assumed that the behaviour of the structure is elastic, so the input parameters for the modulus of elasticity and for the Poisson's coefficient are $E = 3.15 \times 10^7$ kPa, $n = 0.2$, and $E = 2.1 \times 10^7$ kPa, $n = 0.3$, for the reinforced concrete and the steel structure, respectively.

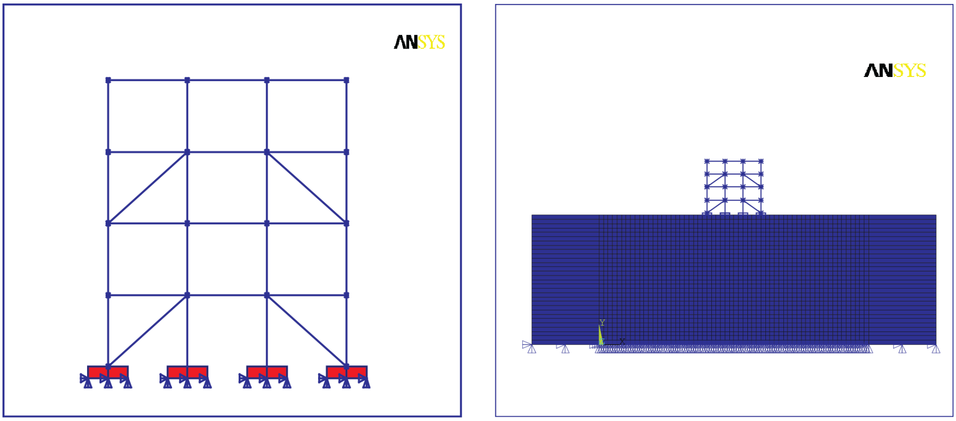
The span of the frame is considered as 4.0 m, with a height of 2.95 m. The cross-section of the columns and beams in RC structures are 40 × 40 cm^2 and 30 × 50 cm^2 respectively. The steel structure is analysed with elements with a corresponding moment of inertia comparing the reinforced concrete elements.

For each four-story frames, the reinforced concrete one and the steel one, the total mass of 44.0 tones is divided into four 11.0 tones per story and are assigned to centres of mass, for simulation of the real structural behaviour of the structure. The soil medium was represented as a two-dimensional model consisted of four different layers leaning on a bedrock, as shown in Table 1. It should be noted that the bottom two layers have better soil characteristics comparing the upper two layers.

Table 1 Soil medium properties

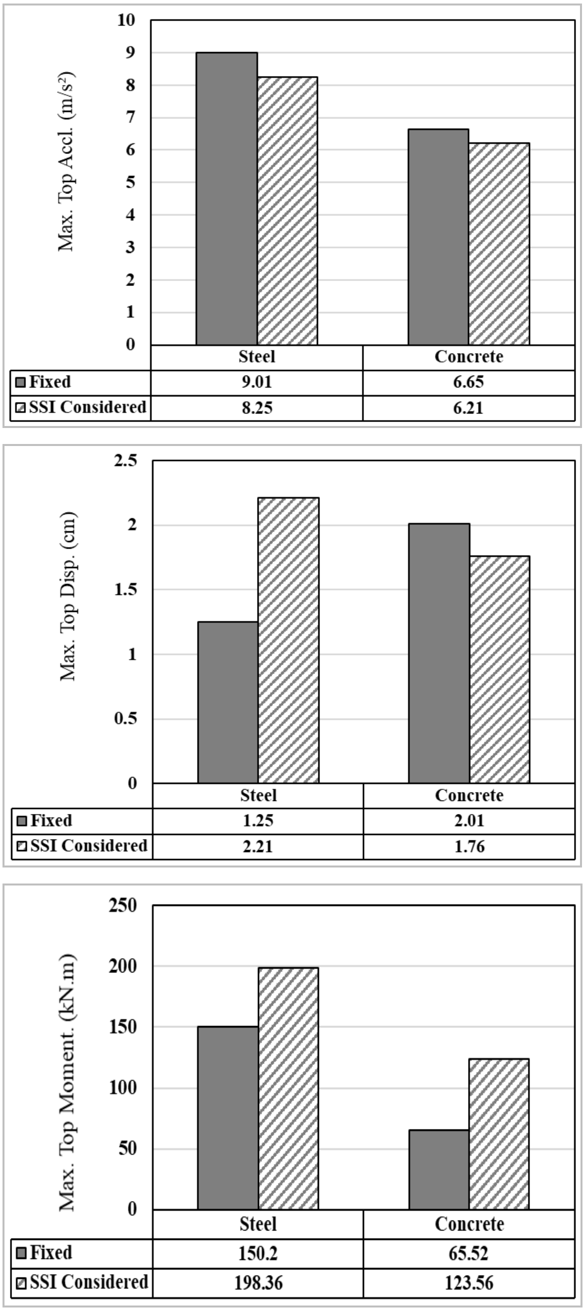
Number of layers	*Thickness (m)*	*Unit weight (kN/m^3)*	*Shear velocity (m/s)*
1	3	16.5	350
2	7	17.5	450
3	6	17.5	530
4	14	18.5	695

Figure 3 Four storey system with fixed foundation and soil layers foundation (see online version for colours)



It is assumed that the soil medium is represented by linear-elastic material and is discretised using plane strain elements with eight nodes. The NL time history analyses were carried out by transient analysis using the step by step integration method. The matrices of the viscous damping are defined as Rayleigh damping to be proportional to the mass and stiffness matrix. The finite element analysis was performed using (ANSYS, 2007). The mathematical software model, as well as the modelled SSI, is shown in Figure 3. The time history analysis was done using El Centro time history record with scaled PGA of 0.30 g. The column-foundation connection is designed using the constraint equation where the rotation of the beam is transferred as force couples to the plane element.

Figure 4 Variation of structural responses (without dampers)

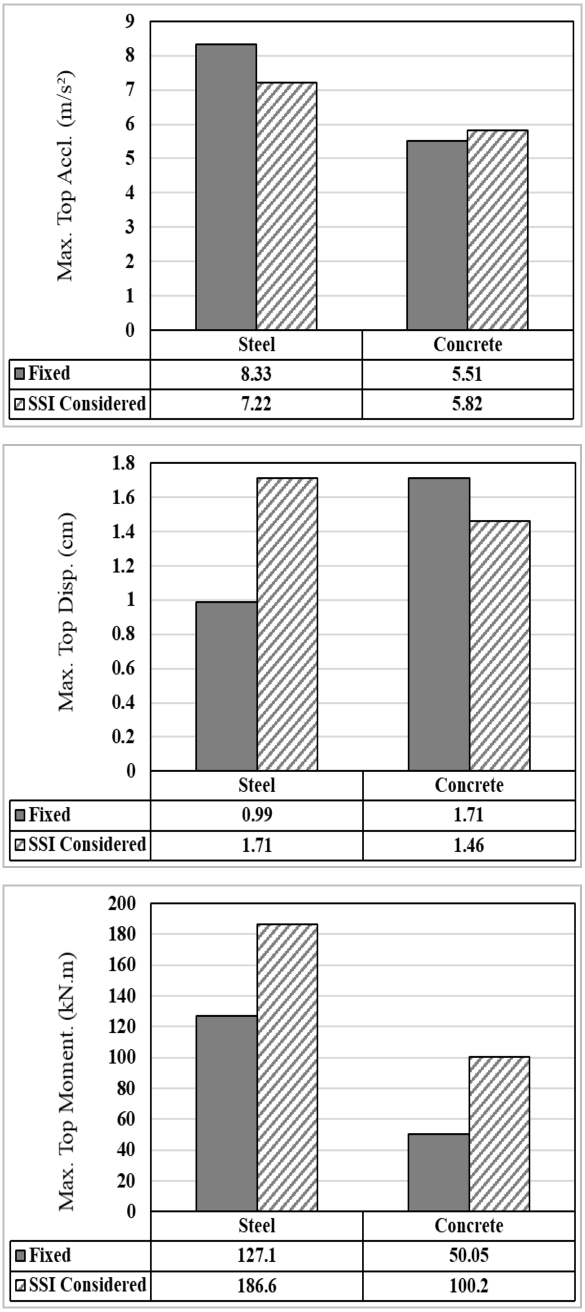


	Steel	Concrete
■ Fixed	9.01	6.65
▨ SSI Considered	8.25	6.21

	Steel	Concrete
■ Fixed	1.25	2.01
▨ SSI Considered	2.21	1.76

	Steel	Concrete
■ Fixed	150.2	65.52
▨ SSI Considered	198.36	123.56

Figure 5 Variation of structural responses (with dampers)



	Steel	Concrete
■ Fixed	8.33	5.51
▨ SSI Considered	7.22	5.82

	Steel	Concrete
■ Fixed	0.99	1.71
▨ SSI Considered	1.71	1.46

	Steel	Concrete
■ Fixed	127.1	50.05
▨ SSI Considered	186.6	100.2

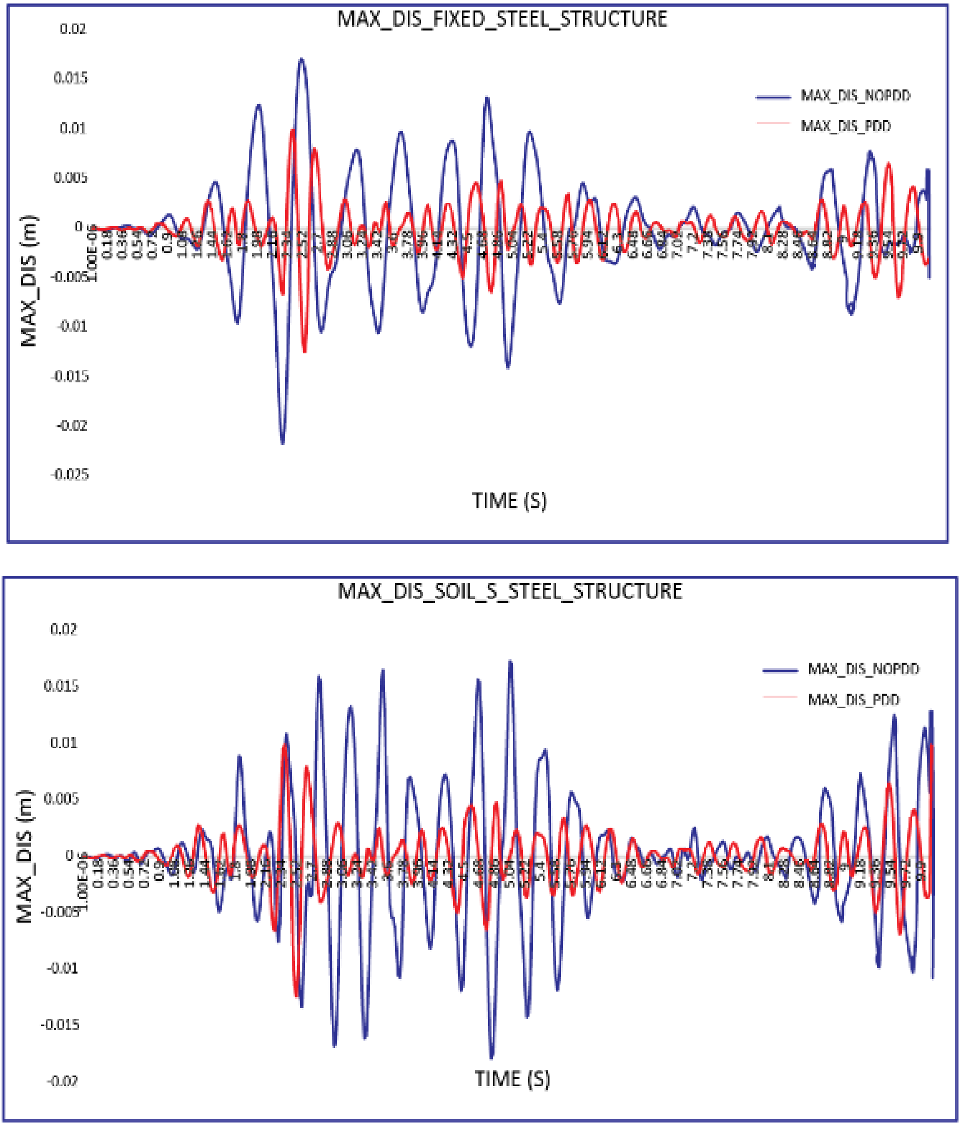
In the soil-structure modelling, the side boundaries are represented as fixed, viscous and infinite element boundaries.

In the case of an infinite element boundary, the domain of the soil medium is sampled with fewer elements (65%) compared to the analysis of fixed and viscous boundaries. In

Figures 4 and 5, the differences in the structural responses are presented considering both the fixed and the soil layers conditions.

Figure 5 clearly indicates that implementing structural dampers will significantly reduce the structural response (maximum top acceleration, maximum top displacement and maximum top moment).

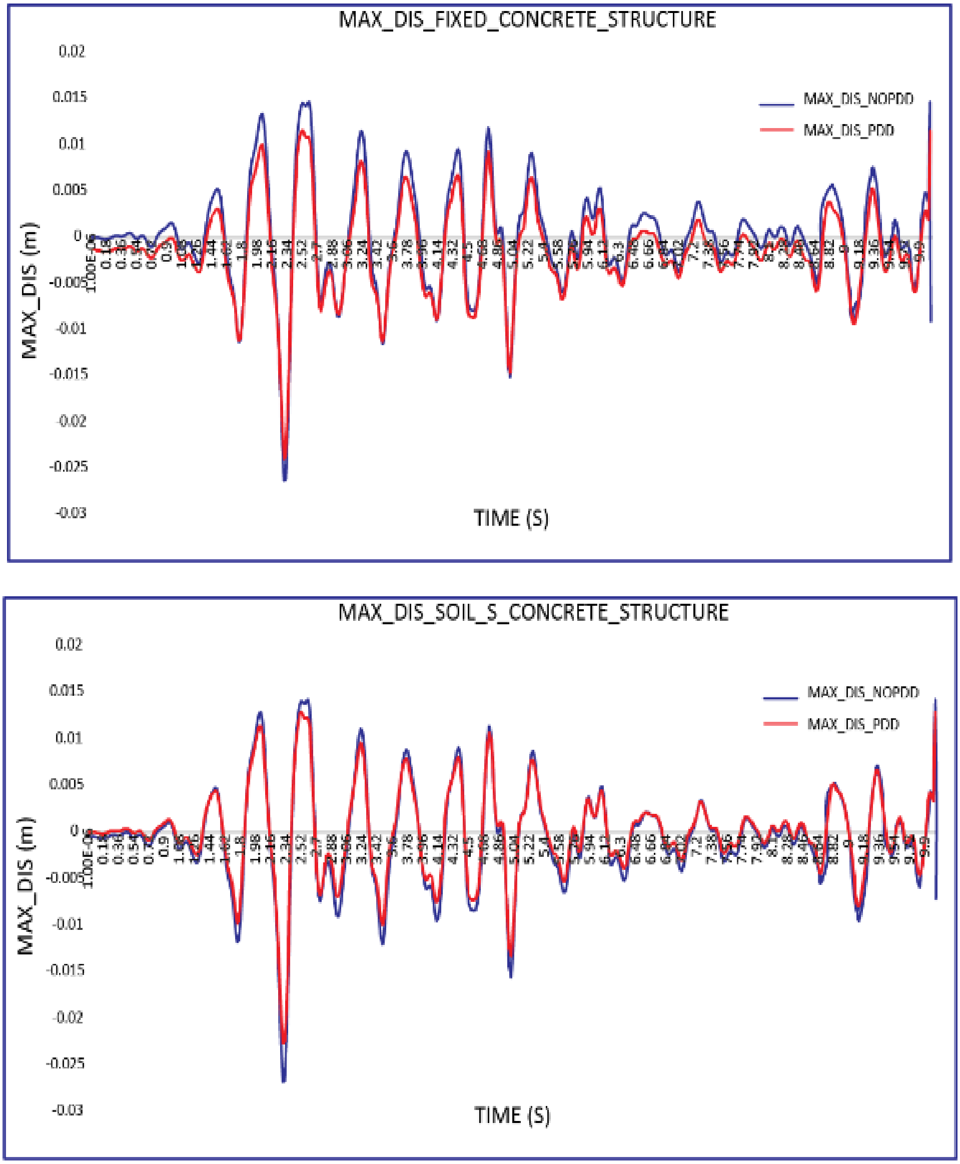
Figure 6 Comparisons of displacement TH for fixed and soil layers for steel structure with and without prestressed damping device (PDD) (see online version for colours)



Furthermore, when using viscous boundaries and infinite element boundaries, the structural responses including acceleration, displacement as well as the moment at the top of the frame elements show similar values. The essential difference is that when using the coupled finite-infinite elements, the number of finite elements is significantly decreased which leads to more computationally efficient models.

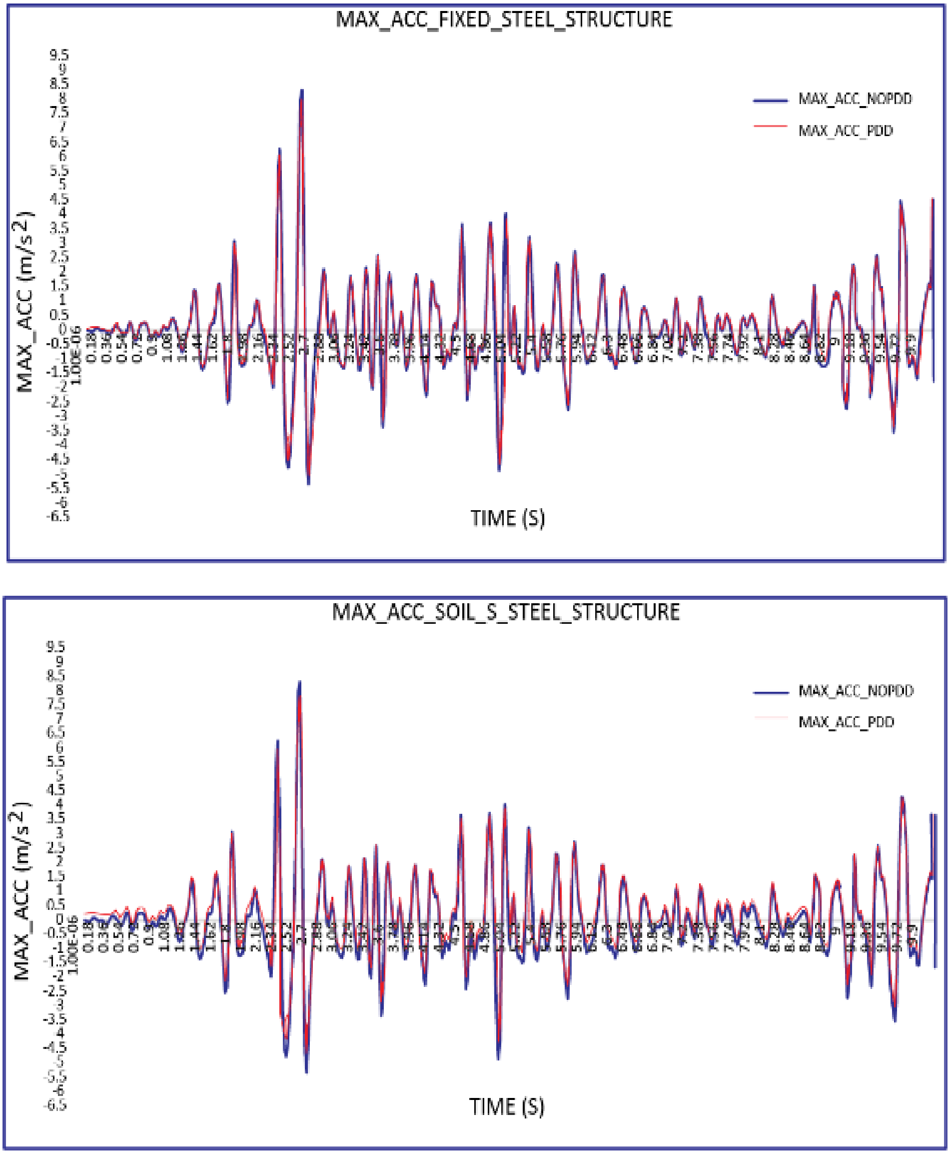
Comparing the stiffness of the soil medium it could be easily distinguished that for soft soils, the differences in the bending moments in the structural elements of the model with fixed boundaries is approximately two times of the model with the infinite element. Assessing the analysis results indicates that for the massive structures settled on a soft soil layer, the effect of SSI is more evident.

Figure 7 Comparisons of displacement TH for fixed and soil layers for RC structure with and without PDD (see online version for colours)



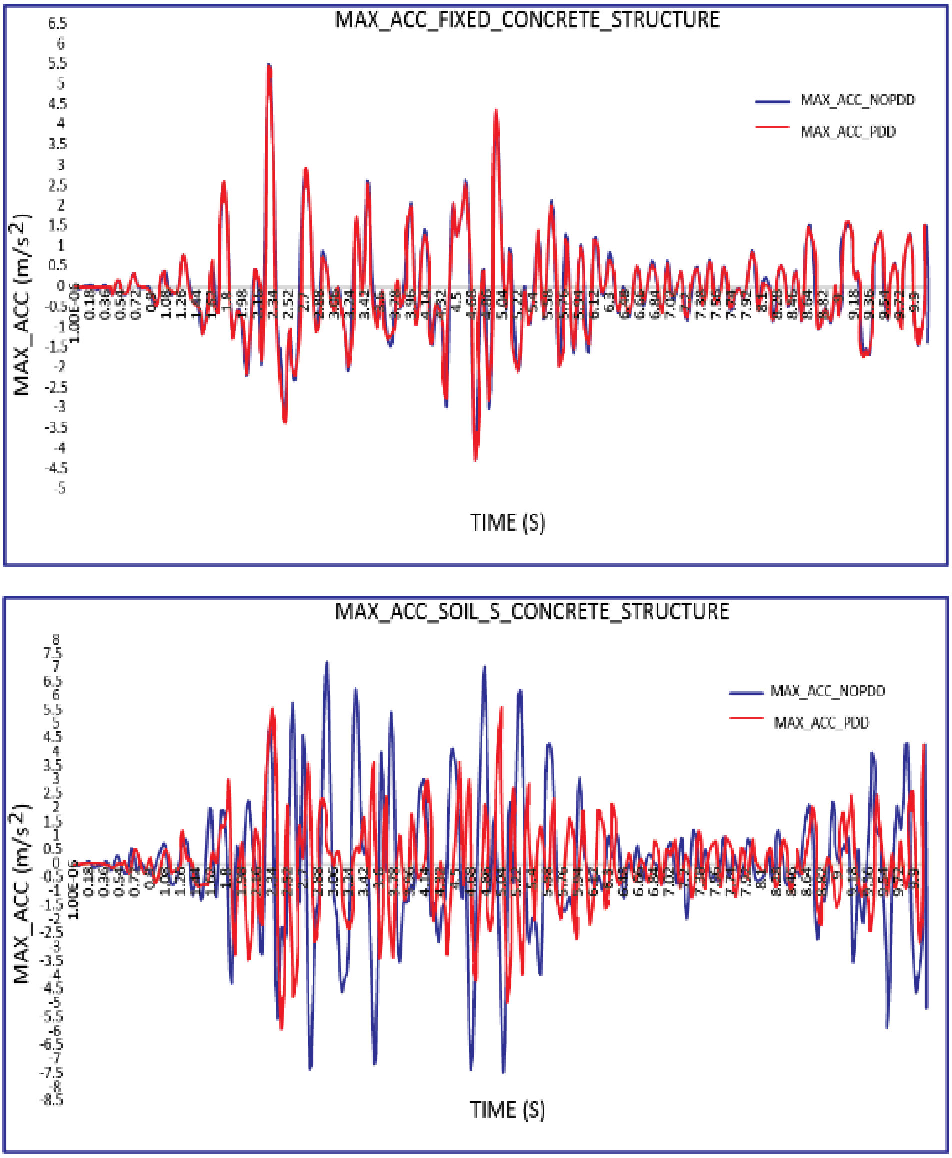
It can be concluded that using the mentioned infinite elements in SSI problems will significantly reduce the analysis time, while the accuracy of the final outcome is assured. Consequently, in the case of complex soil mediums, the proposed approach considering the combination of finite and infinite elements is strangely recommended.

Figure 8 Comparisons of acceleration TH for fixed and soil layers for steel structure with and without PDD (see online version for colours)



In Figures 6–9 the comparisons of response history analysis are presented in terms of displacement and acceleration. The comparisons are made for the case of steel and RC structures, with and without dampers and considering fixed and soft soil conditions.

Figure 9 Comparisons of acceleration TH for fixed and soil layers for steel structure with and without PDD (see online version for colours)



5 Conclusions

Coupled *finite* and *infinite* computational method for particular geotechnical issues is presented in this paper. For numerical simulation of the geotechnical problems, the local region of importance is mathematically modelled with finite elements that support complex geometries simulations. However, the field surrounding the domain is taken into account using infinite elements that have the ability to simulate the infinite region properly. Using ANSYS FE platform and its programmable features, for numerical simulations, it was possible that new *elements* such as the infinite elements to be programmed.

The obtained numerical results are consistent and could be further used for more advanced and sophisticated analysis of the coupled finite and infinite elements in the field of SSI.

Since the newly programmed infinite elements are in the time domain, the nonlinearity of the materials could be also taken into consideration where necessary (in the finite element region).

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