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Seismic response analysis of reinforced concrete frames including soil flexibility

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Abstract. The seismic response of RC space frame structures with isolated footing resting on a shallow soil stratum on rock is presented in this paper. Homogeneous soil stratum of different stiffness in the very soft to stiff range is considered. Soil, footing and super structure are considered to be the parts of an integral system. A finite element model of the integrated system is developed and subjected to scaled acceleration time histories recorded during two different real earthquakes. Dynamic analysis is performed using mode superposition method of transient analysis. A parametric study is conducted to investigate the effect of flexibility of soil in the dynamic behaviour of low- rise building frames. The time histories and Fourier spectra of roof displacement, base shear and structural response quantities of the space frame on compliant base are presented and compared with the fixed base condition. Results indicate that the incorporation of soil flexibility is required for the realistic estimate of structural seismic response especially for single storey structures resting on very soft soil.

Keywords: seismic response; transient analysis; natural period; soil flexibility; Fourier spectra; base shear

1. Introduction

Mac Murdo (1824) stated that "buildings situated on rock were not by any means so much affected as those whose foundations did not reach to the bottom of the soil" relating to the 1819 earthquake in Cutch, India. The effect of local soil conditions on ground motions have been illustrated in earthquakes around the world from many observations. The response to earthquake motion of a structure founded on a deformable soil will not be the same as if the structure were supported on a rigid foundation. The influence of the flexibility of the soil on the response of low rise structures subjected to earthquake motion is the general subject of this study.

Significant progress has been made in the last three decades in developing methods to analyse the interaction between structure and its foundation medium. In most studies the soil is idealized as a linear, homogeneous, isotropic, elastic half space and in many instances the dynamic properties

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of the half space are further approximated by discrete springs and dashpots. Oliveto *et al*. (1995) have checked certain approximations that have been made in the engineering literature in dealing with the soil-structure interaction problems and it is shown how the complex frequencies and modes of vibrations are derived. Yang *et al*. (1996) have demonstrated that the condensation technique can in reality be employed to formulate the soil-structure interaction problems in a rather straightforward manner. A new fixed base model possessing classical normal modes for a general multi degree of freedom soil structure interaction system has been developed by Wu *et al*. (2001) for conducting simplified soil-structure interaction analysis in a more efficient way. Rambabu *et al*. (2002) examined the appropriateness of representing open-plane frames on isolated footings and subjected to horizontal seismic excitation by Parmelee model. The current state-of-the art of the modeling of soil as applied in the soil–structure interaction analysis is presented in a review article by Dutta and Roy (2002) stating that resort to the finite element modeling may be taken for the important structure where more rigorous analysis is necessary. Investigations by Bhattacharya *et al*. (2004) is a limited effort to find the effect of soil–structure interaction on lateral natural period, seismic base shear and fundamental torsional to lateral period ratio of building frames resting on raft foundation on different types of clayey soil. The role of soil structure interaction on the response of an open plane frame is examined by Parmelee model and a frame model by Basha and Allam (2004). Dutta *et al*. (2004), Bhattacharya and Dutta (2004) considered low-rise building frames resting on shallow foundations, viz. isolated and grid foundation to examine the influence of soil–structure interaction on elastic and inelastic range responses due to seismic excitations. RezaTabatabaiefar *et al*. (2013) studied the effects of dynamic soil-structure interaction on seismic behaviour and lateral structural response of mid-rise moment resisting building frames using finite difference method. Chandrashekhar *et al*. (2005) presented the analysis of multistorey buildings with raft foundations resting on soft and medium stiff soils to evaluate the variation of natural period and base shear with various parameters like different types of soil, number of storey and beam to column stiffness ratios. Christos *et al*. (2011) focused their study on the seismic response of a 3-storey building supported on strip footings on soft soil that suffered severe column damage in the longitudinal direction under the Lefkada earthquake (2003) in Greece and observed that soil-structure interaction may affect inelastic seismic response and alter the dynamic behaviour of such buildings.

Since its appearance, the finite element method has proven to be one of the most important analytical tools in the interaction investigation but often it appears uneconomical due to the large number of degrees of freedom necessary to describe the behaviour of the soil-footing system. In order to overcome this drawback and to reduce the size of the problem researchers have tried several approaches and various techniques, using translational and/or rotational springs, “fictitious members”, line and/or surface elements to simulate the soil-footing system.

Kutanis *et al*. (2001) suggested an idealized two-dimensional plane strain finite element seismic soil-structure interaction analysis based on the substructure method. The boundary element method is coupled with the finite element method to study the dynamic response of flexible massive strip–foundations embedded in layered soils (Spyrakos and Xu 2004). The dynamic analyses for a soil layer by itself and for a complete soil structure system using a finite element discretization of the soil in cylindrical coordinates and structures modeled as equivalent single degree of freedom systems with an approximate linear iterative procedure to simulate nonlinear behavior were performed by Kim and Roesset (2004). A new numerical procedure was developed and implemented into a three-dimensional dynamic soil–structure interaction analysis program (DSSIA -3D) (Wegner *et al*. 2005). Wong (1975) suggested that because of the limitations of two dimensional approximations three dimensional models must be developed for the introduction of soil-structure interaction computations into engineering design. But only a limited number of studies have been conducted on soil-structure interaction effect considering three dimensional space frames since analyses remain quite expensive from a computational standpoint. A full three-dimensional dynamic soil–foundation–structure interaction analysis of a famous landmark in Luxor, Egypt, the South Memnon Colossus, was performed by Casciati *et al*. (2004) to investigate the response of this historical monument to seismic excitation.

From numerous studies on the effect of soil-structure interaction under dynamic loading it is seen that the dynamic characteristics of a structural system gets modified when the supporting medium of soil is also considered as an integral part of the structure compared to those with the conventional completely restrained supports. The two idealizations of the extreme soil profiles are the homogeneous half space extending to infinite depth and soil stratum underlain by very stiff material or bedrock at a shallow depth (Mylonakis *et al*. 2006). For a soil site approaching an elastic half space, the radiation of energy of the propagating waves away from the structure will result in significant increase of the damping of the final dynamic system leading to a strongly reduced response. For a soil site consisting of a shallow layer, it is possible that no waves propagate away from the structure. In this case, only the material damping of the soil will act, and no beneficial effect on the seismic response by radiation damping is to be expected (Wolf 1985). With regard to damping, Stewart *et al*. (1998) found out that there is a lack of radiation damping at frequencies less than the fundamental frequency of the finite soil layer. Half space damping ratios can be used for frequencies greater than the soil layer frequency, and a transition to zero radiation damping at smaller frequencies can be defined. However, this under-prediction of radiation damping may be tolerable in some situations, because at the low frequencies, typical of many building structures, radiation damping effects are small relative to hysteretic soil damping.

In the present study, a full three dimensional finite element simulation of a soil-foundation-structure system in a shallow soil site under real earthquake time histories is examined. Single bay structure models with one, two, three and four storey with isolated footing resting on four types of soils ranging from very soft to stiff and subjected to two different acceleration time histories of real ground motions, modified to peak ground acceleration of 0.5g are analyzed. A parametric numerical study of the integrated system is carried out with a linear mode-superposition transient dynamic analysis. The strain dependence and shear modulus degradation in soil is not considered. The effect of stiffness of soil and frequency content of input motion on the seismic response of the overlying structure is examined by the direct method of soil-structure interaction analysis. The earthquake response of the building frames considering the flexibility of the soil is compared with that of the structure with fixed base.

2. Modeling of soil-foundation-structure system

2.1 Structural idealization

The building frame elements have been idealized as three dimensional space frames consisting of two node three dimensional beam elements with 6 degrees of freedom (DOF) at each node. The floor Slabs are modeled with four node plate element with 6 DOF at each node. The foundation, which supports the superstructure, is also discretized as 4 node plate–bending element. The behavior of superstructure and foundation is assumed as elastic and is modeled using two

Table 1 Values of Modulus of elasticity (*E*) and Poisson's ratio (*ν*) for different types of soils

Designation	Soil Type	E (kN/m^2)	ν
soil20	Very soft	20000	0.3
soil40	Soft	40000	0.3
soil60	Medium Stiff	60000	0.25
soil80	Stiff	80000	0.2

parameters, the modulus of elasticity E and Poisson's ratio ν. Structural members are considered to be reinforced concrete of grade M20. Value of E is taken as 22.36GPa, ν is taken as 0.15 and density of concrete as 25kN/m^3. The bay length of the building is taken as 4.0 m and height as 3 m for all the cases. Sizes of beams and columns are 230mm × 400 mm. Thickness of slab is taken as 150mm and wall as 230mm with density of 20kN/m^3. The geometric sizes and loadings on the frames have been arrived on the basis of general requirement confirming to Indian design codes. The live load over floors is taken as 3kN/m^2. Square footing of size 2m × 2m with 500mm thickness is considered for all structures. The space frames considered for transient analysis are single bay structure with 1 storey, 2 storey, 3 storey and 4 storey designated as 1×1×1, 1×1×2, 1×1×3, 1×1×4 with fixed base and resting on different types of soil models. The structure with fixed support condition is designated as Fixed in the study.

2.2 Idealization of soil

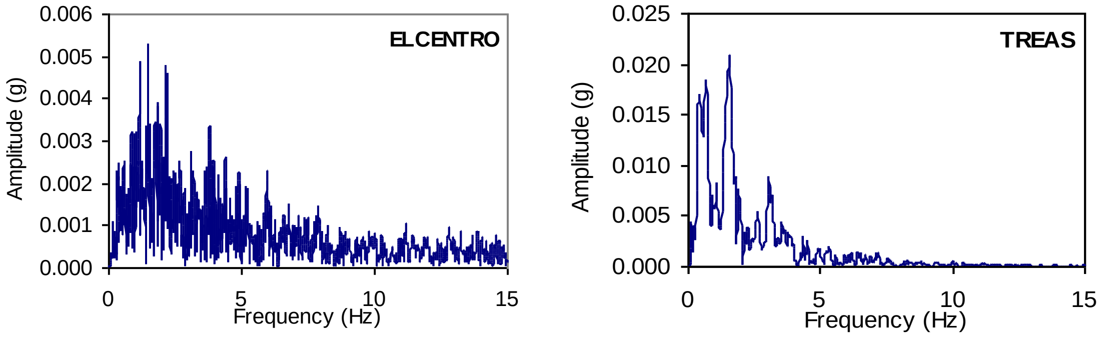
The structures are assumed to be resting on different types of soil models, in the very soft to stiff range, based on soil parameters, the modulus of elasticity E and Poisson's ratio ν (Bowles 1997). They are designated as soil20, soil40, soil60 and soil80 as shown in Table 1. The density of the soil is taken as 18kN/m^3. The soil is assumed to be linear, elastic and isotropic material. A finite soil mass is considered with width of the soil mass beyond the outermost footing as 4 times the width of isolated footing considered as the zone of influence (Bowles 1997) with an elementary boundary condition.

Free vibration analysis of the soil strata alone is carried out to determine the maximum depth for a shallow soil site underlain by bedrock with a fundamental frequency higher than the fixed base structure and the combined soil-structure system such that the radiation damping effects are negligible. And the depth to the bedrock is placed at 8 times the width of isolated footing. Soil is discretized using 8 node solid element with 3 translational DOF at each node.

2.3 Ground motions

For the purpose of this study, two acceleration time histories were selected so that the strong shaking frequency components of these records are lying in the range of the natural frequency of the structure. The two recorded ground motions, Imperial Valley Earthquake, Station Elcentro (1940) and Treasure Island (Loma Prieta) earthquake, Station Treas (1991) are selected and referred as Elcentro and Treas in the study.

The analysis has been carried out for the modified acceleration time histories that correspond to a scaled peak ground acceleration of 0.5g with a loading time step at 0.02sec. Elcentro motion is rich in high amplitude 0.5Hz to 4Hz frequency components with maximum spectral amplitude at



(a) EL CENTRO (b) TREAS

Fig. 1 Fourier spectrum curves for the Elcentro and Treas ground motions

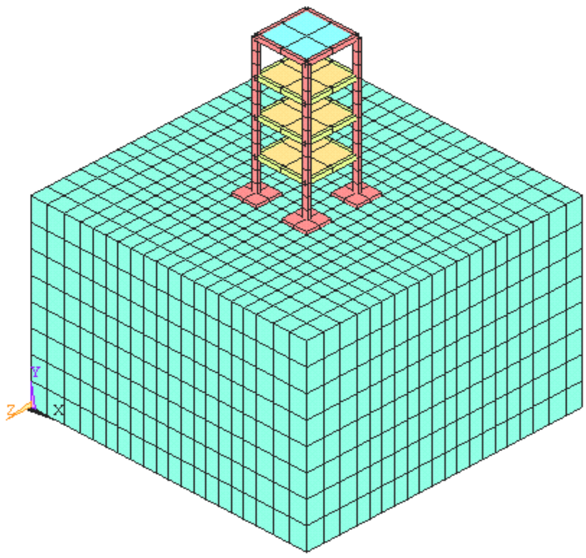


Fig. 2 Finite element Model of a 1×1×4 RC frame - foundation - soil system

1.53Hz and Treas rich in 0.3 to 3Hz frequency components with maximum spectral amplitude at 1.47Hz (Fig. 1).

2.4 Modeling

Three dimensional finite element model of the whole structure foundation soil system is generated using finite element software ANSYS and shown in Fig. 2. The seismic analysis of the building frames is carried out with transient dynamic analysis using mode superposition method. For the mode superposition type of transient analysis in ANSYS, the mass and stiffness matrix multiplier for damping are specified for a range of frequencies corresponding to the first ten modes of vibration assuming the critical damping as 5%. (ANSYS documentation R11).

Table 2 Values of natural period for different buildings with fixed base and with consideration of soil flexibility

No. of storeys	Natural period (sec)					Variation in natural period (%)			
	Fixed	soil 80	soil 60	soil40	soil20	soil 80	soil 60	soil 40	soil 20
1	0.369	0.381	0.385	0.397	0.530	3.29	4.46	7.70	43.81
2	0.480	0.496	0.500	0.510	0.555	3.31	4.27	6.24	15.59
3	0.794	0.818	0.824	0.837	0.879	3.00	3.82	5.44	10.70
4	0.985	1.151	1.160	1.178	1.234	16.86	17.80	19.63	25.33

3. Seismic analysis results

Transient analysis results for fixed base as well as soil supported models of different space frames subjected to scaled earthquake excitations are presented here. Response in each case is studied with and without considering the effect of soil flexibility. The variation of natural period and seismic structural response parameters like roof displacements, base shear, bending moment and shear force for the first floor beams and ground storey corner columns of the building models resting on different types of soil represented with their time histories and Fourier spectra are presented and comparisons are made with those obtained from the analysis of a fixed base structure.

3.1 Variation in Natural period

The variation in natural period due to the effect of soil flexibility is tabulated in Table 2. The analysis of the results reported in Table 2 shows that the fundamental natural period of the soil structure interacting model is always larger than the natural period of the same structure on a fixed base. It is observed here in the integrated system that, natural period increases as the number of storey increases in all types of soil. The percentage variation of natural period with respect to a fixed base structure is more than 16% for a four storey building supported on all soil models. The variation in natural period is less than 7.8% for the building models up to three storeys resting on soils except on very soft soil, soil20. The maximum variation of 43.8% is observed for a single storey building in soil20 whereas the variation is 3.3% for support on stiff soil. Percentage variation decreases with increase in stiffness of soil. It is seen that the natural period increases by the incorporation of soil flexibility and the variation is maximum for very soft soil.

3.2 Variation in roof displacement

The percentage variation in roof displacement for different buildings with consideration of soil flexibility is tabulated in Table 3. It is observed that the maximum roof displacement increases by the incorporation of soil flexibility. It is seen that for the case of a 1×1×1 building resting on very soft soil, soil20, the variation in roof displacement is 414% when subjected to Elcentro motion whereas it is 158% for the excitation with Treas motion. But for all other stiffer soil supports the variation ranges from 10% to 80% in general for all the frames. Representative time history of roof displacement of 1×1×2 building for Elcentro and Treas motions is shown in Fig. 3. The time history of roof displacement shows that the roof displacement of the structure founded on soil is more than that of the fixed base structure with the highest increase for frames on very soft soil.

Table 3 Percentage variation of roof displacement for different buildings with consideration of soil flexibility

No. of storeys	Ground motion	Percentage variation of roof displacement			
		soil 80	soil60	soil40	soil20
1	Elcentro	43.84	42.87	79.17	414.29
	Treas	39.56	40.62	87.07	158.43
2	Elcentro	52.05	59.38	67.55	132.48
	Treas	70.25	73.40	112.06	184.91
4	Elcentro	54.86	58.01	59.63	71.16
	Treas	9.47	11.46	14.08	60.18

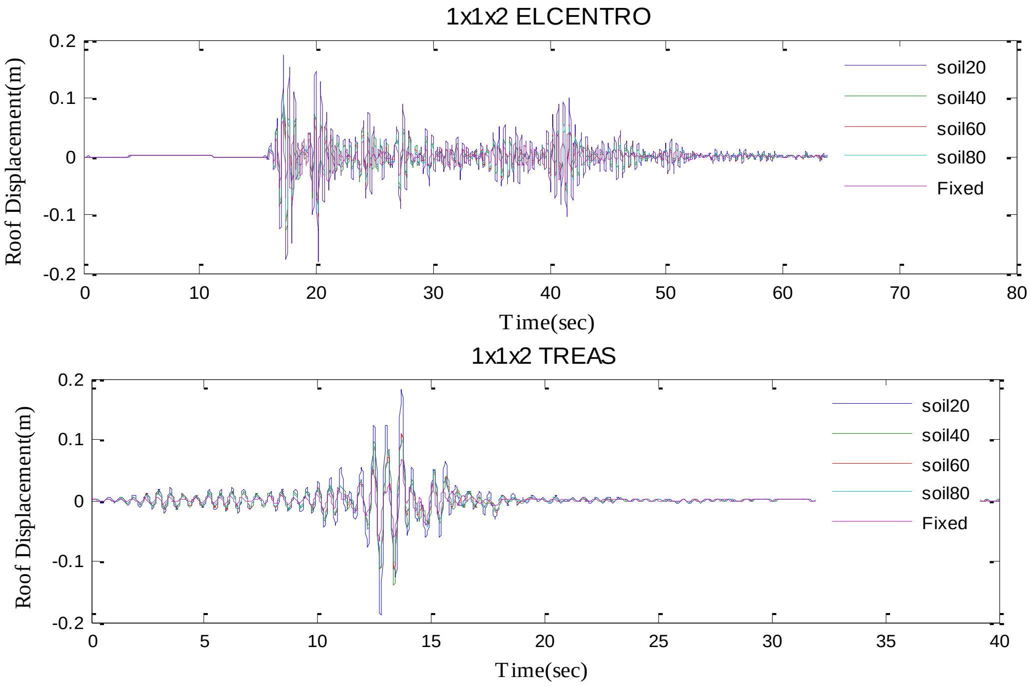


Fig. 3 Time history of roof displacement of 1×1×2 building for Elcentro and Treas motions

The representative Fourier spectrum for roof displacement of single and four storey structures is shown in Fig. 4. The variation in roof displacements shows a one to one correspondence with the variation of the amplitude of Fourier spectrum of the excitations of Elcentro and Treas motion, corresponding to the natural frequency of each model. This amplitude variation is the maximum for the case of 1×1×1 frame on soil20 as compared to fixed base support and hence shows a high variation in the roof displacement. The amplification of roof displacement of 1×1×1 structures lies in the frequency range of 1.7Hz to 2.9Hz for Elcentro motion and 1.8Hz to 2.7Hz for Treas motion. The frequency content range decreases as the number of storeys increases and it is mainly concentrated in the range of respective natural frequency of the building models. It is evident in the case of a four storey structure that the amplification is the maximum at the excitation frequency 1.47Hz for a fixed base structure and the amplification is more at the system natural frequency of 0.9Hz for the compliant base system.

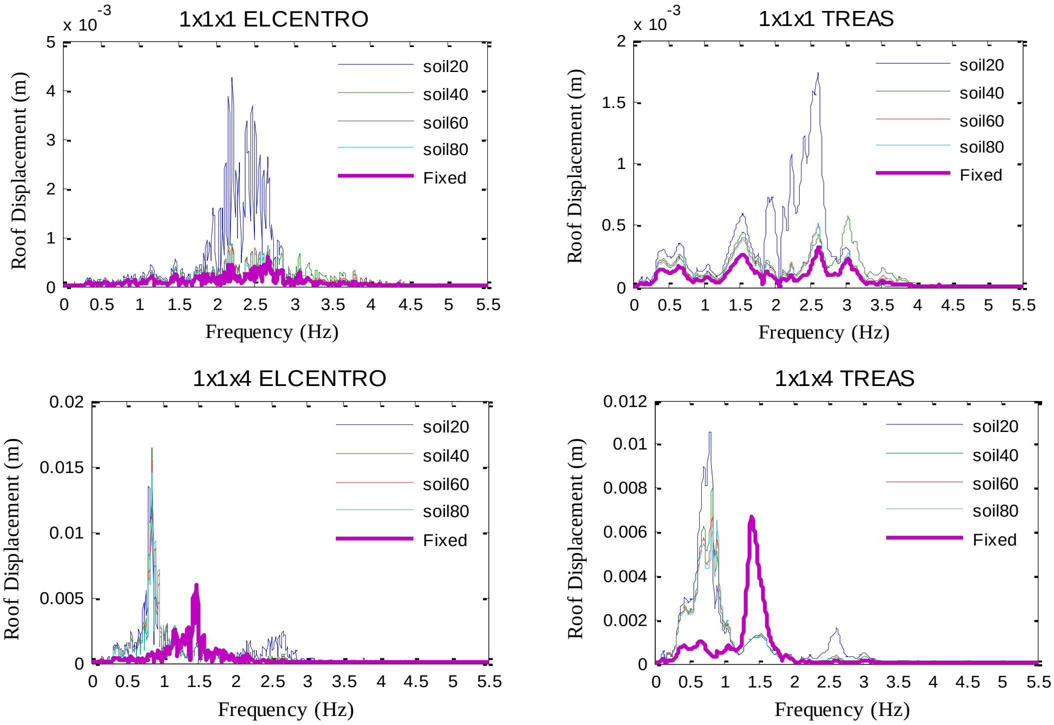
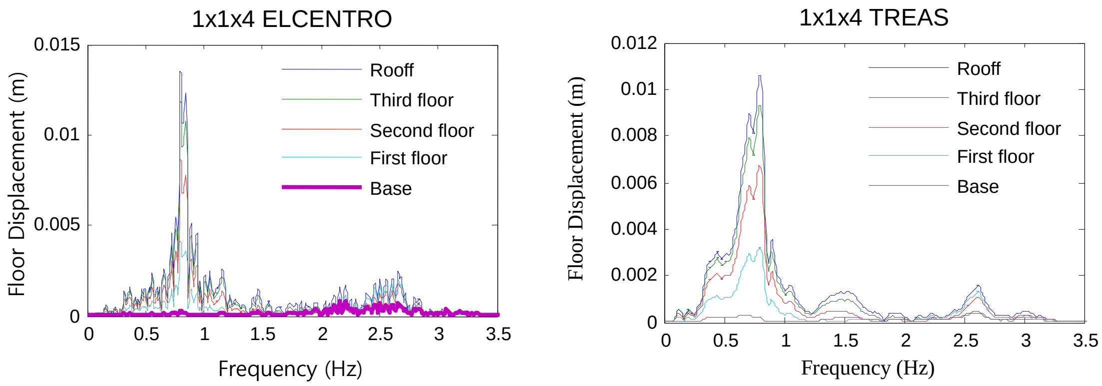


Fig. 4 Fourier Spectrum of roof displacement for single and four storey structures for Elcentro and Treas motions



(a) ELCENTRO (b) TREAS

Fig. 5 Fourier spectrum of floor displacement at different levels of 1×1×4 building on soil20

3.3 Variation in floor displacement

The variations of displacement values at various floor levels for single bay, 1 to 4 storey building models for Elcentro and Treas ground motions are analysed. It is observed that, displacement increases as the number of storeys increases and the percentage variation decreases with increase in number of storeys. The Fourier spectrum of displacement at different floor levels of a representative 1×1×4 building on soil20 for Elcentro and Treas motions is shown in Fig. 5. The Fourier spectra represents the frequency content of the displacement amplification for very soft soil lying in the range of 0.65Hz to 0.9Hz and the peak value is concentrated near to the natural frequency of the building i.e., at 0.8Hz.

3.4 Variation in base shear

Variation in base shear for various building frames with different soil support models subjected to Elcentro and Treas motion has been studied and the percentage variation as compared to the fixed base is given in Table 4. It is seen that for a single storey building in very soft soil, the base shear increase is 288% for Elcentro motion and 180% for Treas motion. The percentage increase decreases as the number of storey increases. Fig. 6 shows the Fourier spectra of base shear for all building models with respect to the two input motions. The influence of excitation frequency is more in four storey building with fixed base and this effect is more in structures subjected to Treas earthquake with a higher peak spectral acceleration at 1.47Hz.

Table 4 Percentage variation of base shear for different buildings with consideration of soil flexibility

No. of storeys	Ground motion	Percentage variation of Base Shear			
		soil 80	soil60	soil40	soil20
1	Elcentro	32.73	41.04	108.04	288.56
	Treas	24.73	24.85	79.66	180.02
2	Elcentro	52.51	61.36	68.55	144.34
	Treas	59.14	67.11	85.65	163.66
4	Elcentro	-29.95	-28.1	-22.68	1.11
	Treas	-62.18	-60.4	-57.94	-31.65

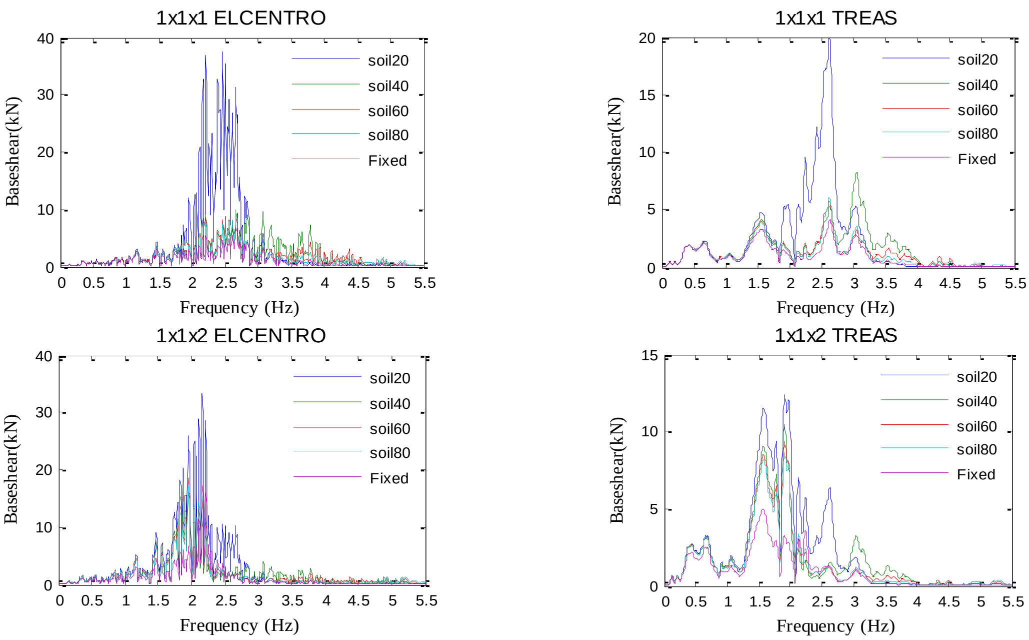


Fig. 6 Fourier spectrum of base shear for Elcentro and Treas motions

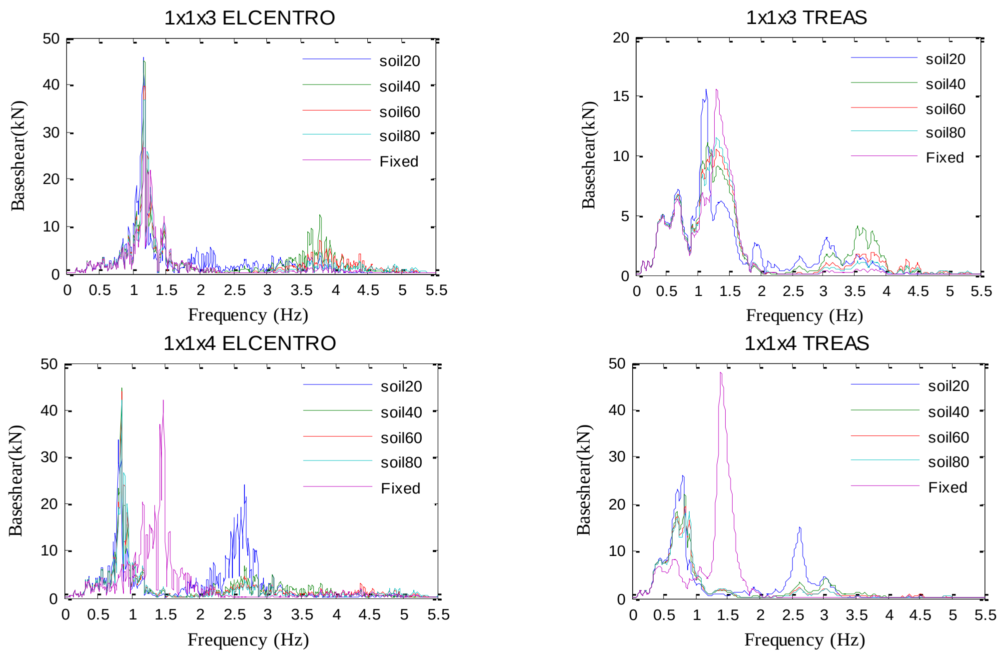


Fig. 6 Continued

3.5 Variation in bending moment and shear force in beam

Figs. 7 and 8 show the variation in maximum values of first floor beam shear force and bending moment for different building models. In general it is observed that, the structures resting on soil20 show considerable increase in force values compared to other soil supports but a four storey building resting on soil shows a reduction in beam forces compared to a fixed base structure. The analysis of response values shows that for a 1×1×1 building in very soft soil, the increase in beam shear force is 312 % for Elcentro motion compared to 133% in the case of Treas motion. It is observed that for 1×1×1 building model in soil20, an increase in beam bending moment of about 307% is seen for Elcentro motion as compared to 274% in the case of Treas motion. It is also observed that the percentage increase decreases as the stiffness of soil increases and it decreases as the number of storeys increases which is attributed due to increased flexibility of structure with higher number of storeys.

3.6 Variation in bending moment and shear force in column

Table 5 shows the percentage variation in maximum values of ground storey corner column shear force and bending moment for different building models with consideration of soil flexibility. It is observed that, all buildings resting on soil20 show considerable increase in these values compared to other soil bases. An increase in shear force of about 294 % is seen for excitation with Elcentro motion compared to 261% in the case of Treas motion for 1×1×1 building model. Four storey building models show a reduction in the column shear force with consideration of soil flexibility. A similar variation is observed in the column bending moment also. For both

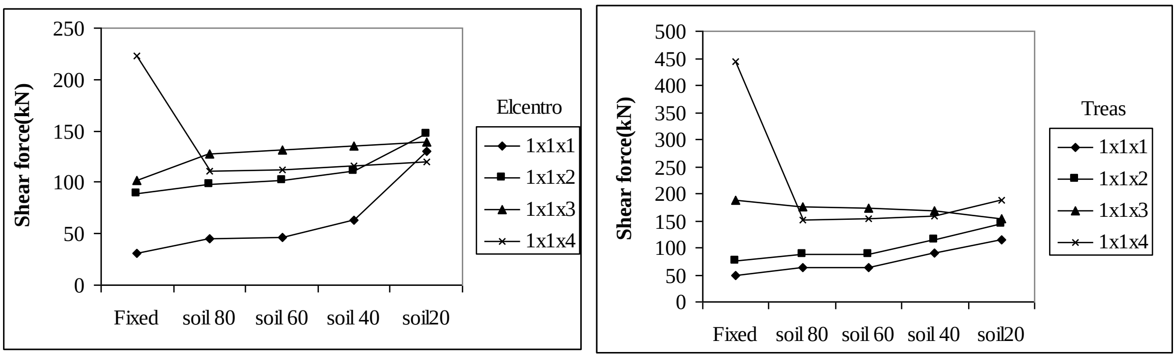


Fig. 7 Variation of beam shear force with the flexibility of soil for Elcentro & Treas motions

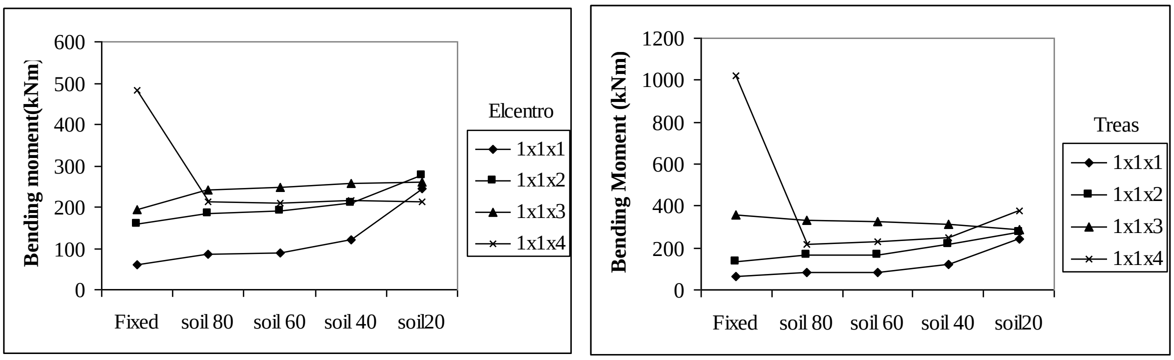


Fig. 8 Variation of beam bending moment with the flexibility of soil for Elcentro & Treas motions

Table 5 Variation of maximum column shear force & column bending moment

No. of storeys	Ground motion	% Variation of column shear force				% Variation of column bending moment			
		soil 80	soil60	soil40	soil20	soil 80	soil60	soil40	soil20
1	Elcentro	38.67	42.99	95.91	293.73	38.12	44.01	95.37	282.79
	Treas	23.24	23.99	78.99	261.36	22.27	22.86	76.24	251.59
2	Elcentro	45.73	56.73	72.07	143.14	42.05	53.15	66.93	128.18
	Treas	73.59	73.52	122.98	183.18	39.86	54.38	43.29	134.37
4	Elcentro	-33.06	-29.1	-27.9	-1.68	-38.72	-35.7	-34.72	-17.28
	Treas	-70.44	-68.1	-66.2	-35.0	-72.94	-70.7	-69.07	-43.01

motions, single storey and double storey building show increase in column forces and the highest variation is caused by the very soft soil support compared to other soil models.

Since the fundamental natural period of single storey building models are lying in the rising part of the response spectrum curve of the two motions, the values of response quantities increase as the flexibility of the soil increases and the values are the highest for the structure resting on very soft soil. The fundamental natural period of double storey building models, are in and around the peak amplitude region of the input ground motions. Hence a considerable increase in response quantities is seen due to the development of resonance and the values being more than three storey building for very soft soil. Response results corresponding to three storey building models decrease as the flexibility of soil increases since the fundamental natural period values for these building models are lying on the falling part of the response spectrum curve of both motions. But in the case of four storey building with fixed base the structural response is seen to be 1 to 2 times more than that of structure supported on very soft soil. This is due to the natural period of these buildings lying in the falling part of response spectrum curve with lower spectral amplitude for compliant base. The response of rigid base four storey structure to Treas motion shows considerable increase compared to Elcentro motion due to the higher response spectrum intensity of Treas motion than that of Elcentro motion.

The Fourier spectrum of member forces of single storey and four storey buildings subjected to Elcentro and Treas motions are only presented in Figs. 9 and 10 as this seems to exhibit the representative trends of interaction behaviour when considered along with the Fourier spectra of base shear for all building models shown in Fig. 6. The frequency content of the structural response shifts to lower values as the number of storey increases and this closely follows the natural frequency of the structures. For a single storey structure with different base flexibility, the fundamental structural natural frequency lies in the range of 1.89Hz to 2.71Hz and that of a double storey structure lies in 1.8Hz to 2.08Hz. All the structural forces considered are amplified in this frequency range. The three storey structures have the fundamental frequency in the narrow range of 1.14Hz to 1.26Hz based on the support stiffness and the amplification of structural response in this frequency range is evident from the Fourier spectra.

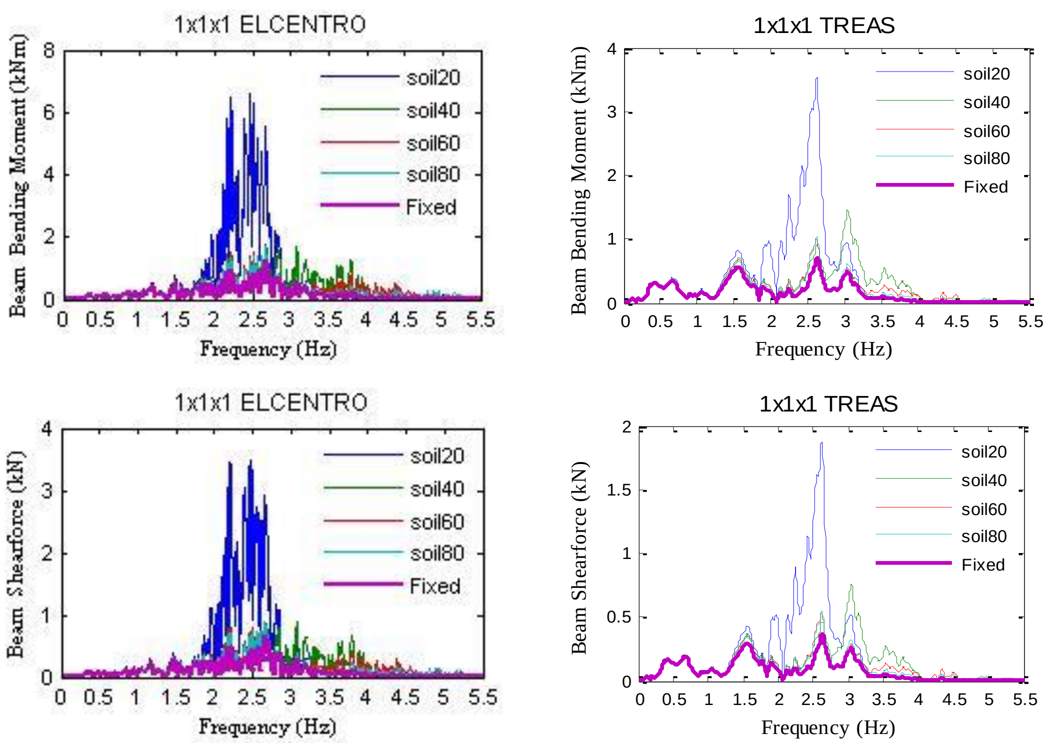


Fig. 9 Response of a single storey building for Elcentro and Treas motions

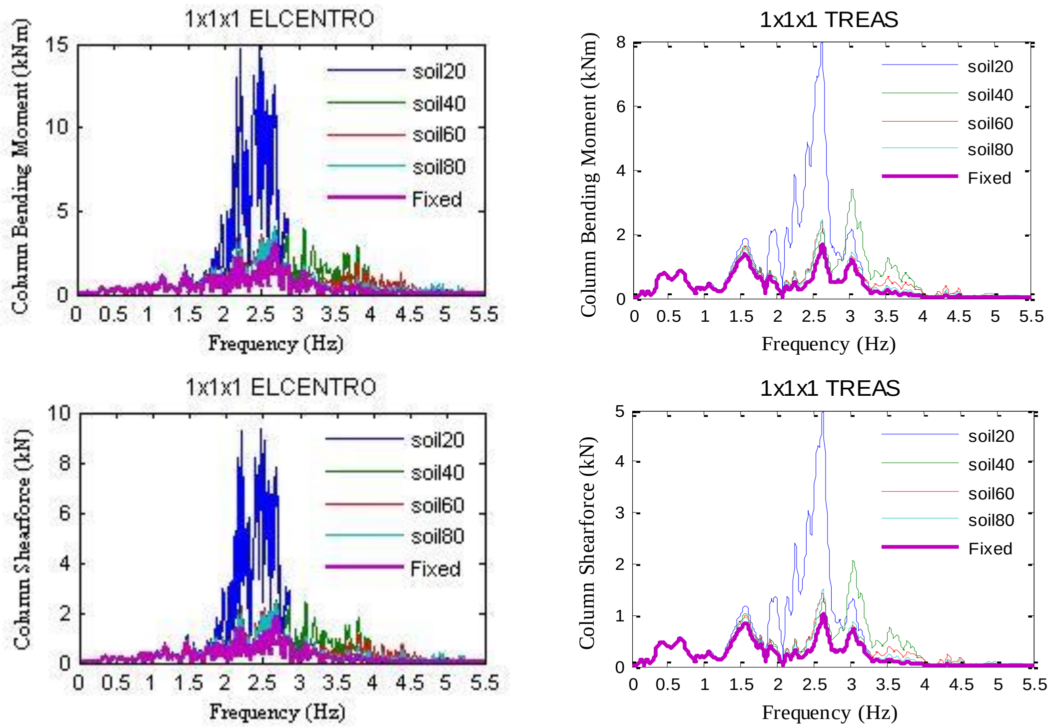


Fig. 9 Continued

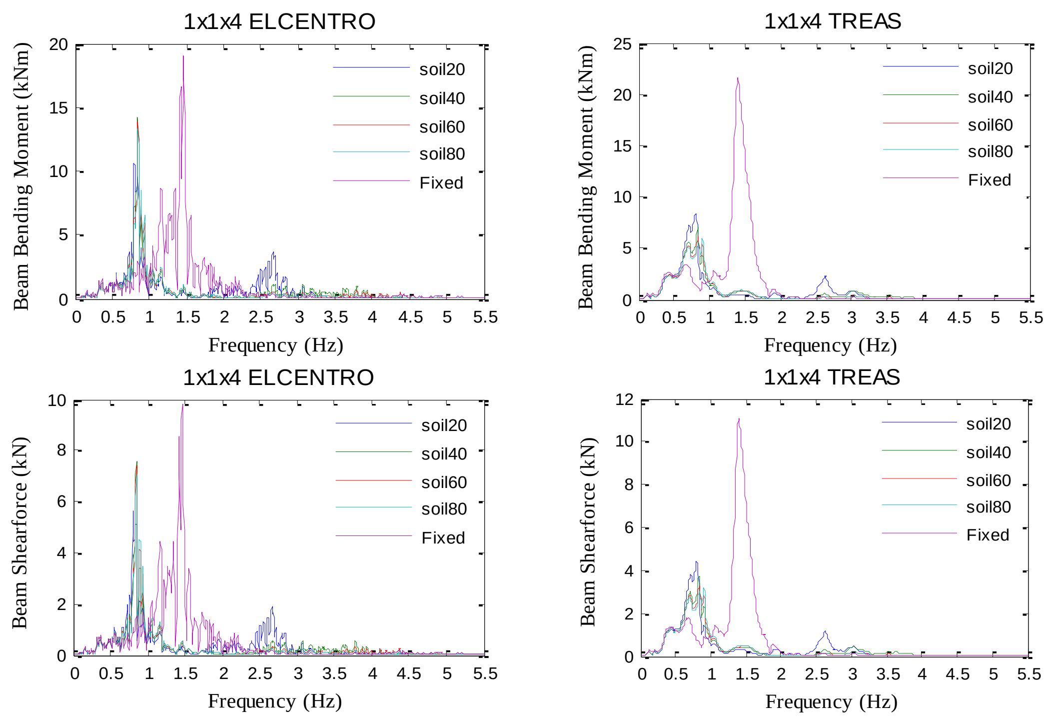


Fig. 10 Response of a four storey building for Elcentro and Treas motion

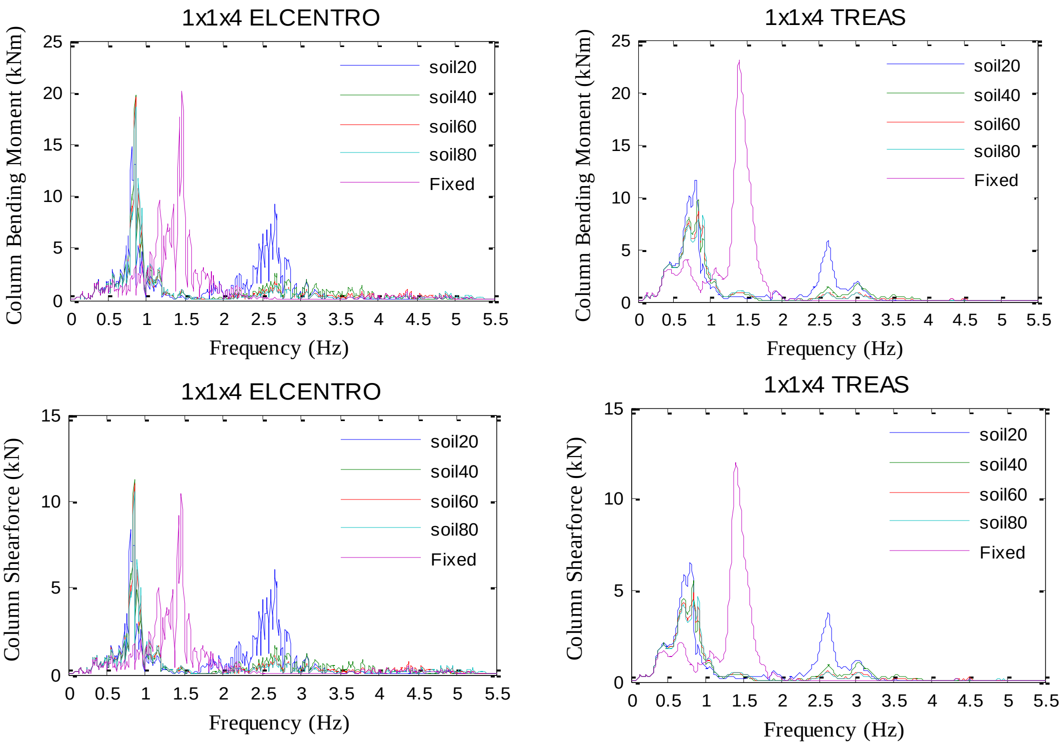


Fig. 10 Continued

The double peak and uniform peak spectral distribution of the excitations Treas and Elcentro are reflected as similar structural response amplification, and a clear picture of this is apparent in the response of a three storey structure. Apart from the general behaviour shown by the single storey to three storey structures in the frequency content of the structural response, the four storey structure with fixed base has highly amplified structural response at the excitation frequency of the ground motions whereas the same structure with compliant base has amplified structural response at the corresponding natural frequency of the structure. So, a reduction of structural response in the four storey structure with compliant base is seen in the tables 4 and 5. Hence the four storey building with fixed base subjected to these ground motions results in high structural response which leads to a very conservative design. Consideration of flexibility of supporting soil may lead to an economical design. It is seen that the incorporation of soil flexibility in the case of low rise buildings is required for the correct estimate of structural seismic response.

4. Conclusions

The effect of soil-structure interaction for low rise buildings with isolated footings resting on a shallow soil stratum on rock under transient loading is investigated here. The present investigation reveals that the effect of soil-structure interaction indicates the possibility of increase in the seismic response of low rise buildings up to three storeys. From the analysis of response results, it is concluded that the fundamental natural period of the soil-structure interacting model is always larger than the natural period of the same structure on a fixed base. The effect of soil structure interaction plays a significant role to increase the structural response of low rise building frames with high amplification for structures in very soft soil.

The seismic response of all the buildings considering soil flexibility exhibit variation based on the frequency content of the input motion and stiffness of soil. The maximum amplification of the response quantities is concentrated at and near the natural frequency of the building, as seen from the Fourier spectra. The time history shows that during the period of strong shaking, the response quantities show appreciable increase in its amplitude for structures on very soft soil. The influence of excitation frequency is more in four storey rigid base building and this effect is more when subjected to Treas earthquake which has the higher peak spectral acceleration. It is concluded that the incorporation of soil flexibility in the case of low rise buildings is required for the realistic estimate of structural seismic response especially for single storey structures resting on very soft soil. Since the seismic structural behaviour of four storey fixed base structure at the excitation frequency leads to very conservative response it is important to include the effect of soil flexibility for an economic design.

References

Basha, S.M. and Allam, M. M. (2004), "Response of open plane frames on isolated footings to an excitation characterized by a white noise", *Journal of Sound and Vibration*, **275**, 1085-1100.

Bhattacharya, K. and Dutta, S.C. (2004), "Assessing lateral period of building frames incorporating soil-flexibility", *Journal of Sound and Vibration*, **269**, 795-821.

Bhattacharya, K., Dutta, S.C. and Dasgupta, S. (2004), "Effect of soil-flexibility on dynamic behaviour of building frames on raft foundation", *Journal of Sound and Vibration*, **274**,111-135.

Bowles, J.E. (1997), *Foundation Analysis and Design*, McGraw Hill, New York.

Casciati, S., and Borja, R.I. (2004), "Dynamic FE analysis of South Memnon Colossus including 3D soil–foundation–structure interaction", *Computers and Structures*, **82**, 1719-1736.

Chandrashekhar, A., Jayalekshmi, B.R. and Venkataramana, K. (2005), "Dynamic soil structure interaction effects on multistoreyed RCC frame", *Proceedings of the international conference on Advances in structural dynamics and is applications*, ICASDA, 454-467.

Dutta, S.C. and Roy, R. (2002), "A critical review on idealization and modeling for interaction among soil–foundation–structure system", *Computers and Structures*, **80**, 1579-1594.

Dutta, S.C., Bhattacharya, K. and Roy, R. (2004), "Response of low-rise buildings under seismic ground excitation incorporating soil–structure interaction", *Soil Dynamics and Earthquake Engineering*, **24**, 893-914.

Dutta, S.C. and Roy, R. (2002), "A critical review on idealization and modeling for interaction among soil–foundation–structure system", *Computers and Structures*, **80**, 1579-1594.

Giarlelis, C., Lekka, D., Mylonakis, G. and Karabalis, D.L. (2011), "The M6.4 Lefkada 2003, Greece, earthquake: Dynamic response of a 3-storey R/C structure on soft soil", *Eartquakes and Structures*, **2**(3), 257-277.

RezaTabatabaiefar, S.H., Fatahi, B. and Samali, B. (2013), "Lateral seismic response of building frames considering dynamic soil-structure interaction effects", *Structural Engineering and Mechanics*, **45**(3), 311-321.

Kutanis, M. and Elmas, M. (2001), "Non-linear seismic soil-structure interaction analysis based on the substructure method in the time domain", *Turk. J. Eng. Environ. Sci.*, **25**, 617-626.

Mac Murdo, J. (1824), "Papers relating to the earthquake which occurred in India in 1819", *Philosophical Magazine*, **63**, 105-177.

Mylonakis, G., Nikolaou, S. and Gazetas, G. (2006), "Footings under seismic loading: analysis and design

issues with emphasis on bridge foundations”, *Soil Dynamics and Earthquake Engineering*, **26**, 824-853.
Oliveto, G.A. and Santini. (1995), “Time domain response of a one dimensional soil-structure interacting model via complex analysis”, *Engineering Structures*, **18**, 425-436.
Rambabu, K.V. and Allam, M.M. (2002), “Adequacy of the parmelee model to represent open plane frames on isolated footings under seismic excitation”, *Journal of Sound and Vibration*, **258**(5), 969-980.
Spyrakos, C.C. and Xu, C. (2004), “Dynamic analysis of flexible massive strip–foundations embedded in layered soils by hybrid BEM–FEM”, *Computers and Structures*, **82**, 2541-2550.
Stewart, J.P., Raymond, S.B. and Gregory, L.F. (1998), Empirical evaluation of inertial soil-structure interaction effects, Report No. PEER -98/07.
Structural Analysis Guide, ANSYS documentation Release 11.
Wegner, J.L., Yao, M.M. and Zhang, X. (2005), “Dynamic wave–soil–structure interaction analysis in the time domain”, *Computers and Structures*, **83**, 2206-2214.
Wolf, J.P. (1985), *Dynamic Soil-Structure Interaction*, Prentice- Hall Inc., Englewood Cliffs, New Jersey.
Wong, H.L. (1975), *Dynamic Soil Structure Interaction*, Ph.D. Report EERI 1975.
Wu, W.H. and Chen, C.Y. (2001), “An effective fixed – base model with classical normal modes for soil structure interaction systems”, *Soil Dynamics and Earthquake Engineering*, **21**, 689-698.
Yang, Y.B., Kuo, S.R. and Liang, M. (1996), “A simplified procedure for formulation of Soil-structure interaction problems”, *Computers and Structures*, **60**(4), 511-520.