Analyse the effect of Soil Structure Interaction on Seismic Response of Building Cluster by Variation in Soil and Building Properties

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Shubham Srivastava[*] and Rajesh Kumar[**]

[*]PhD Scholar, Department of Civil Engineering, IIT BHU Varanasi, Uttar Pradesh 221005, India

[**]Professor, Department of Civil Engineering, IIT BHU Varanasi, Uttar Pradesh 221005, India

[*]Corresponding Author: shubhamsrivastava.rs.civ19@itbhu.ac.in

ABSTRACT

The seismic response of a building is dependent on the foundation flexibility, soil properties as well as the interaction between the soil and structure. The frequency and amplitude of the seismic response depends on the soil properties. For simpler calculations, the soil is usually assumed to be rigid which is unrealistic mostly. The buildings are designed on basis of idealized conditions taking fixed base or on Winkler foundations. Until recently, the efforts to ascertain the effect of Soil-Foundation-Structure Interaction (SFSI) on the response of structure have been limited. This study aims at investigating the nature of soil-structure interaction and investigate the effect on the response of building owing to variation in soil stiffness, depth of foundation and building mass ratio using numerical method. The analysis shows that the response of building cluster decreases with increase in soil stiffness. Heterogeneous cluster proved better during earthquake than homogenous cluster. The results indicated that the soil and building properties have major influence on the dynamic response of building cluster and thus may be given due consideration during design and seismic analysis.

Keywords - Soil structure interaction, building cluster, Soil stiffness, Seismic response, SFSI, building mass ratio.

INTRODUCTION

In seismic design of building structure, usually, the soil is assumed to be rigid, which is realistic only if the foundation is on solid rock or when soil stiffness is very high. For all other cases, the soil surface interaction (SSI) constitutes of two distinct effects – kinematic and inertial interaction, which is complex. The soil-structure interaction (SSI) refers to the action in which the response of the soil influences, the response of the structure and the response of the structure influence the motion of the soil (Kramer, 1996). The buildings are considered isolated with fixed base while designing for simpler calculations. However, the buildings are not built in isolation in reality. The seismic response of buildings, especially when closely spaced, do not act independently and, considering that their foundations are in the same soil, the response is affected by each other. Further, contradictory to the belief that Soil-Foundation-Structure Interaction (SFSI) increases natural time period of structure and is beneficial, as assumed while designing, studies have shown that the increase in natural period of structure due to SFSI can lead to resonance. Additionally, the ductility can also significantly increase with increase in natural period of structure due to SSI. The seismic response of the structure may be further aggravated by the permanent deformation and failure of soil.

Kinematic and Inertial interaction are the main mechanism involved during SFSI. Kinematic interaction considers free-field motion. According to Van Nguyen et al., 2016, the foundation size impacts the interactions largely by varying the mass and stiffness of the soil-foundation system and the decrease in size of foundation resulted in reduction in base shear. If the foundation dimensions are small compared to wavelength of seismic waves, kinematic interaction has negligible effects on the response of the structure; whereas if the foundation dimensions are of the same order as the wavelength, a base slab averaging effect will result (Clough, 1995). Several transfer functions between translational and torsional foundation motions and free field ground motions were developed (Veletsos et al., 1997) and calibrated against observed foundation and free field behaviour (Kim et al., 2003). The soil allows some movement due to its natural flexibility. This reduces the overall stiffness of system and increases the natural period. This is very much dependent on size of foundation (Gazetas et al., 1998). Kinematic interactions are important for structures on large, stiff soils (Kramer, 1996), however, the inertial effect considers presence of soil underneath the foundation, taking deformation of soil into account. The soil deformation influences the motion and behaviour of foundation and superstructure. One approach to soil-structure interaction models is to model soil compliance with springs and viscous dampers. When the system responses with and without springs and viscous dampers is compared, the effect of SSI becomes evident. Studies have also been carried out on the impact of different type of foundation (Chu et al., 2004) and effect of foundation size (Van Nguyen et al., 2016).

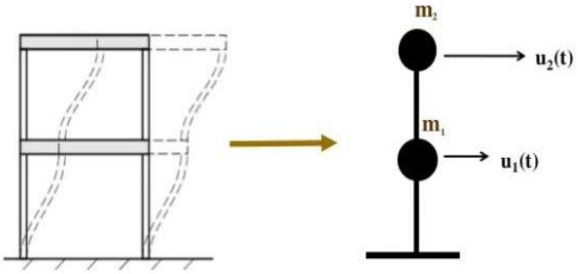

Fig. 1: Schematic diagram of structure with fixed and flexible base

Further, the type of soil is equally important in analysis of SSI. The properties of soil i.e. its stiffness, plasticity etc. also have great influence on the response of building. Soil plasticity can dissipate the earthquake energy and result in lesser deformation while more deflection and rotation of foundation is observed when soil reaches its shear strength due to seismic loading (Xu et al., 2017). Choi et al., 2004 used the shear moduli of near field soil region and young's moduli of structure to predict the response during earthquake which was observed to be close to measured responses. Rock have very high stiffness and structure on such soil behave as with fixed base (as assumed during simple analysis without considering SSI) however, the structures behave differently on softer soils (Jayalekshmi et al., 2016). According to Gazetas et al., 2001, ground motions at soft soil sites are typically defined by long predominant periods and result in resonance condition for period-lengthening with fixed based period less than predominant period. Although, the study on seismic response of mid-rise building assuming nonlinear SSI has been carried out (Adam et al., 2016) and Numerical methods have also been used for analysis of SSI (Sbartai, 2015; Sameti et al., 2014; Chen, 2015) but the study on the response on building cluster and specially mixed group of small and large buildings has been limited.

METHODOLOGY

Simplified methods are the first alternative for step by step SSI analysis. The simplest way to consider the SSI effects and to account for frequency dependency of interaction is by using Frequency-independent spring stiffness and damping coefficient. In direct methods of analysis, the entire soil-foundation-structure system is modelled and response to free-field motion applied at boundaries is analysed in a single step.

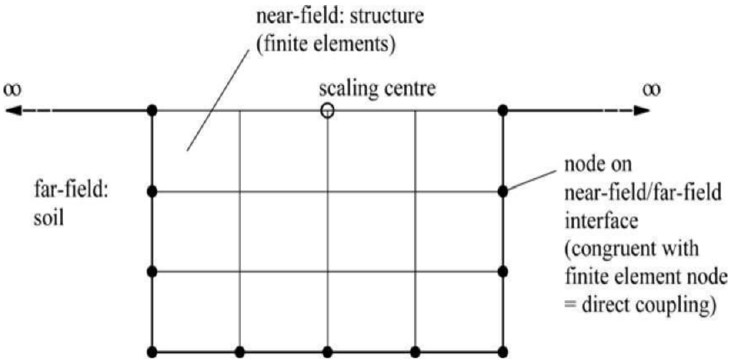

Fig. 2: Direct method of soil-structure interaction analysis.

The Multistep methods are limited to the analysis of linear (or equivalent linear) systems as they rely on superposition. The principle of superposition is utilised to isolate the 2 primary causes of soil-structure interaction that are the effect of the dynamic response of the structure-foundation system on movement of supporting soil and inability of the foundation to match the free-field deformation. The coupling methods, also known as hybrid methods, have been developed where FEM is used to analyse the near-field while the unbounded soil (near-field) is modelled by Boundary Element Method (BEM), taking into account the influence of the infinite half-space.

The basic equations for static deformation of a soil body are formulated within the framework of continuum mechanics. A restriction is made in the sense that deformations are assumed to be small. This enables a formulation with reference to original un-deformed geometry. The basic equation for static equilibrium of a continuum is as follows:

$$L^T\sigma + p=0 \qquad \text{(i)}$$

The equation relates vector σ, which assembles the spatial derivatives of the six stress components with vector p which amasses the three components of body forces. L^T is the transpose of a differential operator. The continuum description is then discretized to the finite element method (FEM). In FEM, a continuum is group of elements, element is group of nodes and each node has a number of degree of freedom. The displacement components correspond to the degree of freedom. For accurate analysis, not just the soil properties but groundwater flow is also required to be studied. The steady flow continuity equation (equation iii) represents that there is no net inflow or outflow in an elementary area. On a global level, contributions of all elements may be added and boundary conditions (either on the groundwater head or on the discharge) shall be imposed. In case of groundwater, the degree of freedom is the head of water.

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = 0 \qquad \text{(ii)}$$

The basic equation for time-dependent movement of a volume under the influence of a dynamic load is:

$$M\ddot{u} + C\mathring{u} + Ku = F \qquad \text{(iii)}$$

Where, M is the mass matrix, u is the displacement vector, C is the damping matrix, K is the stiffness matrix and F is the load vector. The displacement, u, the velocity, $\mathring{u}$, and the acceleration, $\ddot{u}$, can vary with time. Prescribed boundary displacements are introduced at the boundaries of FEM in case of static deformation analysis. The boundaries can be completely free or fixities can be applied in one or two directions. To counteract reflections, special measures are needed at the boundaries such as absorbent boundaries, dampers etc. For the current study viscous dampers have been implemented.

MODELLING

The soil element was modelled using Mohr- Coulomb model which involves five parameters: Young's modulus E, cohesion c, Poisson's ratio ν, friction angle ϕ and dilatancy angle ψ. Soil damping accounted by considering Rayleigh coefficients. A triangular soil element having 15 nodes is chosen for analysis. SSI was modelled using interfaces at junctions between foundation and soil. A suitable value for the strength reduction factor is chosen for modelling the interface. This factor relates the interface strength (foundation friction and adhesion) to the soil strength parameters (friction angle and cohesion). Each 15 node soil element is connected to interface element at 5 nodes of one of its sides.

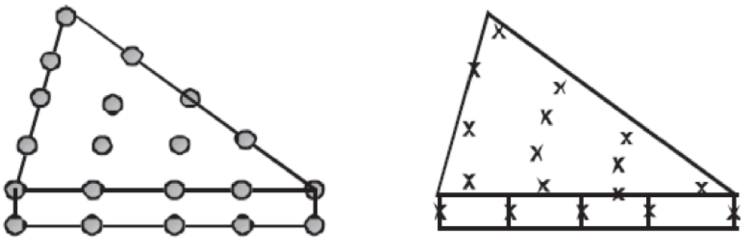

Fig. 3: Distribution of node and stress points in interface elements and connection with soil elements.

The vibrations caused by earthquakes pass through the soil, creating a dynamic excitation due to interaction between soil and foundation. This dynamic soil-structure interaction problem at the interface is required to be solved for analysing the behaviour. The interaction is modelled by using interfaces, by adopting a suitable value for the strength reduction factor. Interfaces are connected to soil elements and elements to nodes. In FEM, the interface element has zero thickness. Rayleigh's co-efficient are used for considering soil damping. For modelling the elasto-plastic behaviour coulomb criterion was used. For small displacements, the interface shear stress τ is given by:

$$|\tau| < \sigma_n \, tan \, tan \, \o_i \, + \, c_i \quad \text{(iv)}$$

For plastic behaviour τ is given by:

$$|\tau| = \sigma_n \, tan \, tan \, \o_i \, + \, c_i \quad \text{(v)}$$

The strength properties of interfaces are linked to the strength properties of the soil layer. The boundary conditions used in this study are based on the method described by Lysmer and Kuhlmeyer (Rosset, Kausel 1976). The normal and shear stresses absorbed by a viscous damper are:

$$\sigma_n = -c_1 \rho V_p u_x \quad \text{(vi)}$$

$$\tau = -c_2 \rho V_s u_y \quad \text{(vii)}$$

The proposed analysis model was studied for dynamic response due to harmonic excitation for building cluster, the numerical results were obtained using Plaxis program. The area near the buildings and the boundary is expected to observe a higher strain gradient and therefore, to achieve improved accuracy the mesh density has been increased in these areas. Response spectrum analysis is used to evaluate the mass of a building during an earthquake. It shows how the structure responds to vibrations. As per building codes, response spectra are generally smooth and straight, while ground motion recordings provide a rugged and sharp response (Naresh et al., 2021).

ANALYSIS

Simultaneous effects of soil and many adjacent structures sitting next to each other is known as the site–city interaction which is affected by several parameters such as dynamic properties of soil and constructed dwellings (Norouzi et al., 2021). A soil-structure model of span 1250m was made with 25m depth of soil. Five node line element was used as plate element. The plate properties are given below in table 1.

Table 1: Structural properties used in model.

No.	**Identification**	**EA** [kN/m]	**EI** [kNm²/m]	**W** [kN/m/m]	**v**
1	Concrete Beam	2.25 x10^6	16875.00	15.12	0.17
2	Concrete Column	2.25 x10^6	16875.00	2.16	0.17

Four layers of soil of total depth of 25 m have been modelled to represent realistic site conditions. The first layer is clay with depth of 13m, then sand (2m depth), deep sand (5m depth) and lastly deep clay with another 5 m depth. The depth of water table has been fixed at 3 m. The various properties of the soil layers are tabulated in Table 2 below.

Table 2: Soil properties for four soil layers used in the model.

Depth	**Type**	**c**	**φ**	γ_{unsat}	γ_{sat}
0-13	Clay	5.5	24	15	18
13-15	Sand	1	31	16.5	20
15-20	Deep Sand	1	33	17	21
20-25	Deep Clay	4	25	16	18.5

Variation in soil stiffness

Xu et al., 2017 examined the influence of soil stiffness on the seismic response of a moment-resisting building by adopting a fully nonlinear direct method for an end-bearing pile foundation for a single building. Seismic codes recognise the finite stiffness and the finite bearing capacity of the foundation, without taking into account their ability to deform (Al-Ameri et al., 2020). The nature of the dynamic load applied to the soil or foundation is determined by the source. However, during an earthquake, the amplitude of soil deformation can change from small (elastic) to large (plastic) values (Richart, 1962). The behaviour of soil under dynamic loads is different from that under static loads due to the soil's stress-strain relationship, which is always nonlinear.

In this study, the response spectra of building cluster with 9 buildings was analysed for varying soil stiffness from 5000kN/m^2 to 120000kN/m^2 in 12 simulations. First at 5000 kN/m^2 and 11 simulations from 10000 kN/m^2 to 120000 at interval of 10000 kN/m^2 increase. The meshing as constructed in the Plaxis software is shown in figure 4. Each of the nine buildings are five storeyed. The displacement response spectra were studied for variation as achieved at the centre of the cluster and at the edges of the building cluster. Simulation was observed and compared with displacement response spectra at infinite soil stiffness. The displacement response spectra with varying soil stiffness at the centre of building cluster is produced in figure 5 while the response at the edges of the cluster is as shown in figure 6.

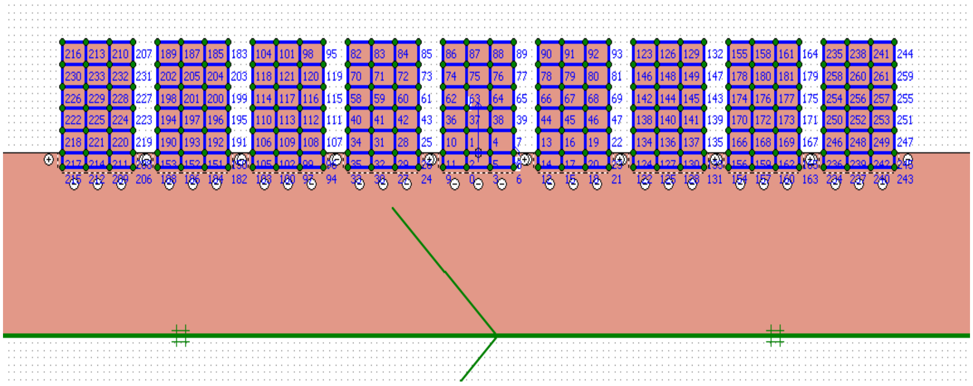

Fig. 4: Meshing in computational model of building cluster in Plaxis software

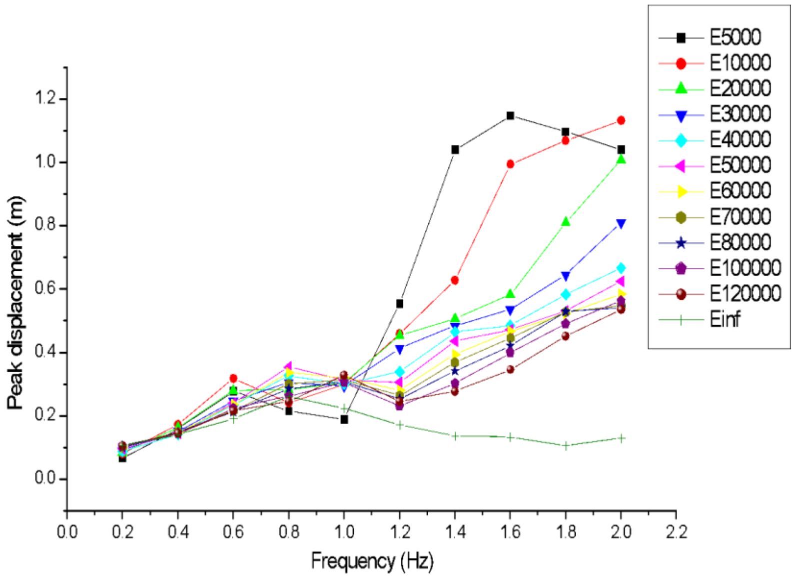

Fig. 5: Displacement response spectra at center of cluster of nine ‘five storied’ buildings at varied soil stiffness.

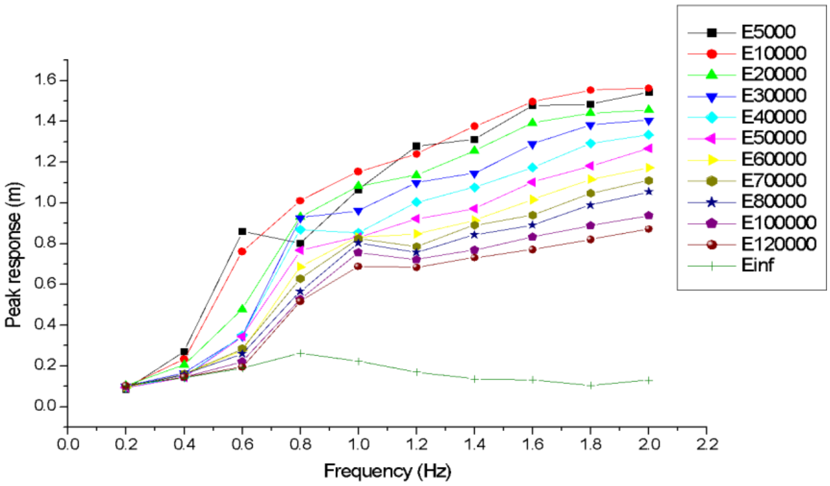

Fig 6: Displacement response spectra at edge of cluster of nine 'five storied' buildings at varied soil stiffness.

No clear trend is observed for frequencies of vibration less than 1 Hz at the centre. However, for frequency greater than 1Hz, the buildings' peak displacement response decreases with the increase in the soil's stiffness both at the centre and at the edges of the building cluster. The peak acceleration response is also not observed to follow any particular drift for the case. The displacement response of buildings considering SSI is observed to be always more than for the buildings with fixed base. Lower soil stiffness will lead to more deformation by dynamic response of building during earthquake. The soil properties will help determine the response accurately for buildings to be constructed and accordingly required provisions could be made for ensuring lesser damage to the structure under seismic conditions. Lower displacement will be observed in structures situated on hard soil compared to medium soil and maximum displacement will occur in structures on soft soils. Further, larger lateral drift is also observed in soft soils and therefore, in case of building clusters (especially closely spaced as mostly found in urban areas) the lateral displacement of one building can cause more damage to adjacent buildings. From the above observations it can be concluded that the spectral acceleration will be higher in soft soils in comparison to hard and medium soils.

Variation in properties of mixed building group.

Most major urban cities follow the practise of locating tall skyscrapers at city centre, where it is surrounded by smaller building clusters around it. To study the seismic performance for this case, a building cluster with three 10 storeyed buildings at centre and three 5 storeyed buildings at each edge (as shown in figure 7) was taken. The variation in building properties was brought by changing in depth of foundation and altering the building mass ratio to analyse the effect on dynamic response of the cluster. The model was analysed for following two conditions:

1. Varying building mass ratio of the cluster.
2. Varying depth of foundation of ten storeyed tall buildings at the centre of the cluster.

Varying building mass ratio of the cluster

The building mass ratio of the cluster was varied by changing the heights of smaller buildings at both ends of the cluster. The height of smaller buildings was varied from 2 to 5 storey. The building mass ratio was varied from 0 to 0.5 and 1 for analysing the response spectra of building cluster with mixed building group. A total of 6 simulations were carried out taking building mass ratio 0, 0.2, 0.3, 0.4, 0.5 and 1.0.

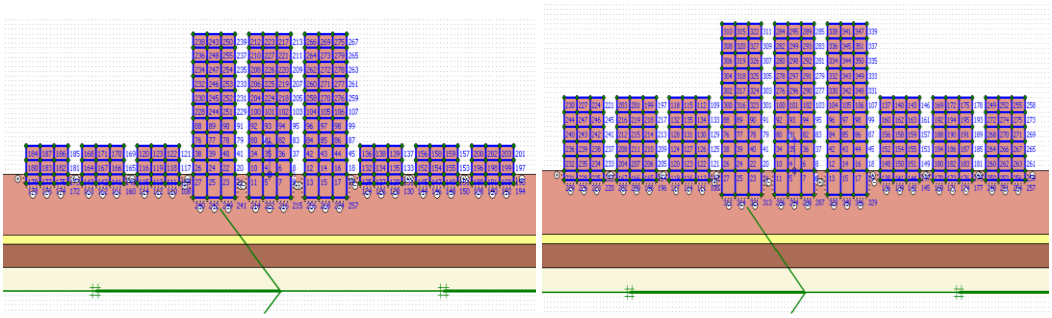

Fig. 7: Meshing of mixed building cluster with variation in building mass ratio.

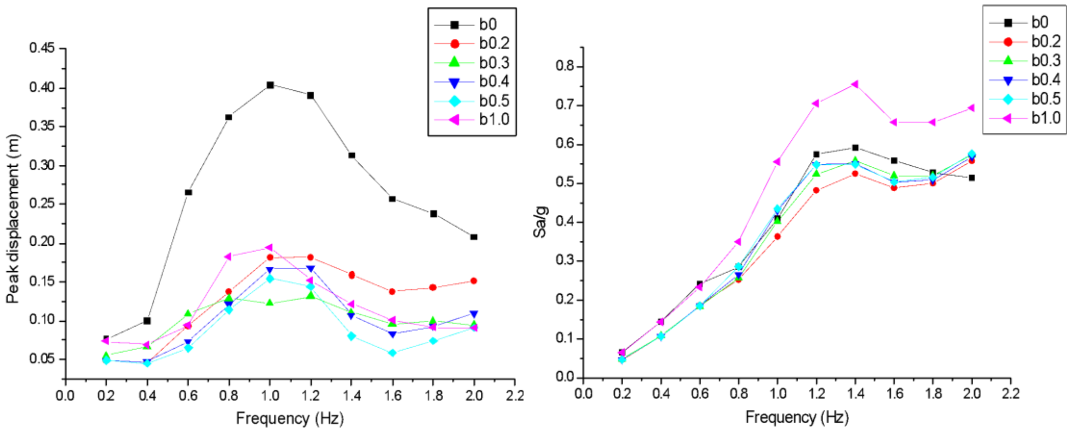

Fig. 8: (a) Displacement response spectra (b) Acceleration response spectra at center of mixed building cluster with varying building mass ratios.

Figure 8(a) shows the displacement response at the center of mixed building cluster with varying building mass ratios. The Acceleration response spectra at center of mixed building cluster with varying building mass ratios is shown in figure 8(b). In comparison to isolated building, the displacement response of central building of cluster was observed to be less. Further, the building cluster with mixed buildings i.e. buildings with different height and different number of storey perform better in seismic conditions than homogeneous building cluster (group of buildings with equal height).

Varying depth of foundation of ten storeyed tall buildings at the centre of the cluster.

Response spectra of building cluster with mixed building case, with varying building foundation depths from 2m to 10m. The mesh for mixed building cluster is shown in figure 9. The displacement and acceleration response spectra of small buildings adjacent and at the edge of cluster with variation in depth of foundation of tall buildings the mixed building cluster as obtained is shown in figure 10 and 11 respectively.

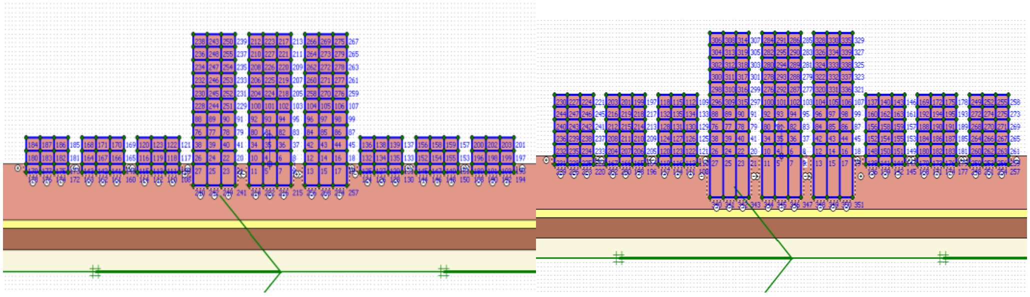

Fig. 9: Mixed building cluster with varying depth of central tall buildings.

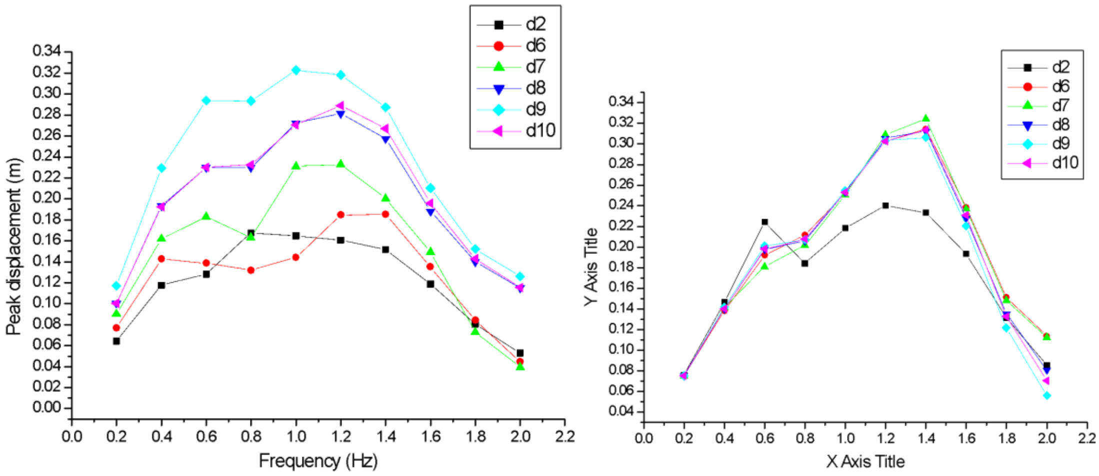

Fig. 10: Displacement response spectra of small buildings adjacent and at the edge of cluster with variation in depth of foundation of tall buildings the mixed building cluster.

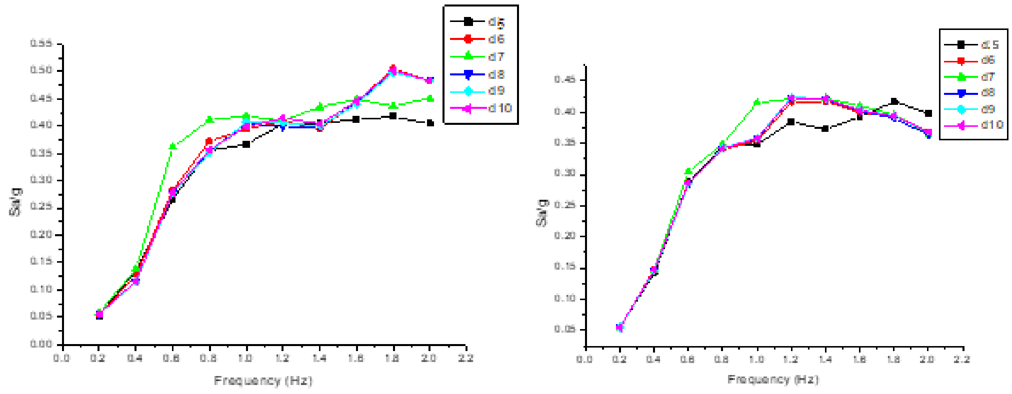

Fig. 11: Acceleration response spectra of small buildings adjacent and at the edge of cluster with variation in depth of foundation of tall buildings the mixed building cluster.

Greater the depth of foundation, lesser are the displacements and building response as deep foundation act stiffer than shallow foundations. Further, in context to the building cluster, the effect of parameters on the dynamic response of adjacent foundations is non-negligible. Small buildings adjacent to tall buildings generally show higher displacement response with increasing foundation depths of tall buildings. However, small buildings at the edge of the cluster seem to be unaffected by foundation depths of tall building at the middle of the cluster and show higher displacement response than small buildings closer to the centre of the cluster. No such clear trend exists for acceleration response spectra of small buildings adjacent to tall buildings as they generally tend to be less affected by various cluster and soil parameters.

CONCLUSION

In this paper, SSI analysis of a building cluster is conducted using PLAXIS to investigate the effect of soil and building properties on the response of the cluster when subjected to seismic loading. The soil and foundation properties have impact on dynamic response of building and therefore, they should be given due consideration during design.

- From the response spectra obtained it was concluded that the displacement response of central building in cluster is always lower than a similar isolated building.
- Building clusters with mixed building types perform better in seismic conditions than homogenous building cluster or isolated buildings as is evident from their acceleration response spectra.

- Short buildings adjacent to tall buildings in a mixed cluster are vulnerable and may need structural retrofitting. They show higher displacement response that increases with the depth of foundation of tall building. However, other short buildings in the cluster are unaffected. As the depth of foundation increases the displacements also increase.
- Small buildings in the vicinity of tall buildings generally exhibit higher displacement response due to increasing foundation depths while the buildings at the edges of the cluster remain unaffected.
- The heterogeneous building cluster perform better than homogeneous building cluster or isolated buildings under seismic conditions and should be preferred while planning and designing.

Additionally, there is a need for developing a catalogue of building performance case histories in order to truly understand SFSI effects in building clusters and analyse it. SSI can be studied with different approaches viz. structural, geotechnical and seismological. Andreotti et al., 2021 proposed a formulation based on the database of real ground motion and simulated accelerograms which revealed the crucial role of non-linearity of soil. The same requires an extensive study for developing a code based guidance system for the professional design community to effectively design building clusters. The field of SFSI effects in building clusters is expected to be both challenging as well as a rewarding field with plenty of scope in improvement of current understanding.

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