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INTERACTION ANALYSIS OF SPACE FRAME-SHEAR WALL-SOIL SYSTEM TO INVESTIGATE FOUNDATION FORCES UNDER SEISMIC LOADING

D. K. Jain and M. S. Hora
Department of Civil Engineering, Maulana Azad National Institute of Technology, Bhopal, India
E-Mail: dkjain63@gmail.com

ABSTRACT

The significance of incorporating soil-structure interaction effect in the analysis and design of RC frame buildings is increasingly recognized but still not penetrated to the grass root level owing to various complexities involved. It is well established fact that the soil-structure interaction effect considerably influence the design of multi-storey buildings subjected to lateral seismic loads. The shear walls are often provided in such buildings to increase the lateral stability to resist seismic lateral loads. In the present work, the linear soil-structure analysis of a G+5 storey RC shear wall building frame resting on isolated column footings and supported by deformable soil is presented. The finite element modelling and analysis is carried out using ANSYS software under normal loads as well as under seismic loads. Various load combinations are considered as per IS-1893 (Part-1):2002. The interaction analysis is carried out with and without shear wall to investigate the effect of inclusion of shear wall on the forces in the footings due to differential settlement of soil mass. The frame and soil mass both are considered to behave in linear elastic manner. It is observed that the soil-structure interaction effect significantly alters the axial forces and moments in the footings due to the differential settlement. The non-interaction analysis of space-frame-shear wall suggests that the presence of shear wall significantly reduces bending moments in most of the column footings but the interaction effect causes restoration of the bending moments to a great extent.

Keywords: soil-structure interaction, ANSYS, space frame, shear wall, linear analysis, differential settlement, isolated column footings, seismic forces.

INTRODUCTION

The conventional structural analysis of a RC space frame is carried out assuming foundation resting on unyielding supports. The analysis is carried out by considering bottom end of the columns fixed and neglecting the effect of soil deformations. In reality, any building frame rests on deformable soil resulting in redistribution of forces and moments due to soil-structure interaction. Thus, conventional analysis is unrealistic and may be unsafe. The interaction effect is more pronounced in case of multi-storeyed buildings due to heavy loads and may become further aggravated when such buildings are subjected to seismic loads. The shear walls are usually provided in such situation to resist seismic lateral loads. The behaviour of shear walls in the space frame during soil structure interaction is a matter of high concern.

In the present work, 3-D soil- structure interaction analysis has been carried out for a six storey RC framed building with isolated footings under normal as well as seismic loads using finite element software ANSYS. The analysis has been carried out considering space frame with and without shear walls oriented along the direction of seismic load. Various combinations of dead, live and seismic loads are considered as per IS-1893 (Part-1): 2002. The model is easily extendable to any configuration of space frame and shear wall as full 3-D space frame is considered for analysis. The results of conventional i.e. non interaction analysis (NIA) as well as linear interaction analysis (LIA) are compared for the space frame with and without shear wall to investigate the effect of total settlements and differential settlement on axial forces and moments in the footings. The results show that there is considerable redistribution of forces and moments in the space frame due to the interaction effect. The provision of shear wall significantly reduces bending moments in most of the column footings when structure is resting on unyielding supports like rock but in deformable soil this effect reduces considerably.

REVIEW OF LITERATURE

Several studies have been carried out in the past by many researchers to understand the soil-structure interaction effect on building frames and foundations and important conclusions are drawn. It is now a well-established fact that the soil-structure interaction effect causes redistribution of forces in the superstructure. The building frame as well as soils were approximated or idealised in various ways in most of the research work. Earlier research postulated 2-D idealisation of structure and soil, which gained momentum with the advent of more powerful tools like the finite element method. During recent few years, 3-D soil-structure interaction analysis with more realistic idealisation has been witnessed along with availability of increasing computing power and sophisticated modelling techniques. Yet, the soil structure interaction effect has not widely been penetrated from research to design offices owing to modelling and analysis complexities involved.

Noorzaei *et al*. (1995) carried out soil-structure interaction analysis of a plane frame-combined footing-soil system. A two-storey, two bay plane frame supported by combined footing-soil system was considered for analysis. The linear as well as nonlinear interaction analyses were carried out and compared with the non-interaction analysis. The analysis suggested that, in general, transfer of forces and moments take place from exterior columns to the interior ones at higher loads as a result of soil-structure interaction effect.

Arlekar *et al.* (1997) conducted an analytical study on moment resisting RC frame building with open first storey and brick masonry in the upper storey having isolated column footings and resting on medium soil. It was concluded that the drift and strength demands in the first storey columns were very high for buildings with soft ground storey and the soil flexibility needed to be examined carefully before finalizing the analytical model of a building. The possible solutions were suggested to provide stiffer columns in the first storey or to provide concrete service core in the building.

Mandal *et al.* (1998) presented a computational iterative scheme for studying the effect of soil-structure interaction on axial force and column moments. The results were validated from experimental studies made on a small scale 2 storey, 2 bay frame made of perspex kept on kaolin bed. The increase in axial force and moments in structural members due to interaction effect are predicted with the computational scheme.

Stavridis (2002) presented a simplified analysis approach for layered soil-structure analysis. An arbitrary structure was considered for analysis. The proposed procedure was based on a purely analytical treatment of the underlying soil models.

Yasuhiro and Ikuo (2004) studied soil-structure interaction effect on the earthquake response of buildings by carrying out a simulation analysis. 2-D finite element model was used. It was concluded that the damage reduction effects by soil-structure interaction greatly depend on the ground motion characteristics, number of storeys and horizontal capacity of earthquake resistance of buildings.

Edgers *et al*., (2005) modeled the effect of soil -structure interaction on a fifty storey building using ANSYS software. The structure was approximated by 2-D model to increase computational efficiency. The model was applicable to symmetrical buildings and for unsymmetrical buildings a full 3-D analysis was recommended. It was found that the analysis of building frame model pinned at rigid base greatly underestimated the bending moments at the lower floors in the frame and therefore, a model was needed for the foundation and deformable subsoil in order to capture the effect of SSI on the building structural response.

Hora (2006) proposed a computational methodology for nonlinear interaction analysis of infilled frame-foundation-soil system. The unbounded soil domain of soil mass was discretized with coupled finite-infinite elements to achieve computational economy. The non-linear behaviour of soil mass was modeled using hyperbolic model. The interaction analysis showed that apart from nonlinearity of soil mass, inclusion of infill walls in the frame also causes redistribution of forces in the members of a building frame. The vertical settlement below foundation beam was also studied.

Mahmoud *et al*. (2008) analyzed the effect of soil -structure interaction between two adjacent 32 storey buildings under seismic loading. A 2-D analysis of building frame, foundation and subsoil was carried out using ANSYS software. The interaction effects were investigated for variable distance between the buildings. It was concluded that the interaction effect increases time period of both of the buildings as well as base shear and lateral displacements.

Natarajan and Vidivelli (2009) examined the influence of column spacing on behaviour of a space frame raft foundation soil system under static loading using ANSYS software. The linear and nonlinear analyses were carried out. It was found that the higher values of settlements occur in case of nonlinear analysis and settlements increase with increase in column spacing. The uniform contact pressure distribution is found but lesser values of contact pressures are found in case of non-linear analysis.

Thangaraj and Illamparuthi (2010) compared interaction and non-interaction analyses for the space frame-raft foundation-soil system using ANSYS software. A detailed parametric study was conducted by varying the soil and raft stiffness for a constant building stiffness. It was found that the relative stiffness of soil plays major role in the performance of the raft.

Agrawal and Hora (2010) studied the effect of differential settlement of foundations on nonlinear interaction behavior of plane frame-soil system using coupled finite-infinite elements. The nonlinear constitutive hyperbolic soil model was used to model nonlinear behavior of soil mass. A two bay ten storey RC frame with unbounded soil mass was considered for analysis. It was concluded that differential settlements take place in the foundations causing significant increase in the forces in the frame members.

Shakib and Atefatdoost (2011) examined the effect of soil structure interaction on torsional response of asymmetrical wall type systems. A 3-D structure consisting of a slab supported on two asymmetrical walls with foundation and soil was considered. It was found that interaction effect increases the lateral displacement and decreases the rotational response.

Garg and Hora (2012) carried out interaction analysis of a three-bay three-storey RCC space frame-footing-strap beam-soil system using ANSYS software. The frame, foundation and supporting soil mass were considered to be linear elastic and to act as a single compatible structural unit for more realistic analysis. It was found that the interaction effect causes significant redistribution of forces and moments in the frame members. The interaction analysis also established importance of strap beams in controlling excessive moments in column bases for eccentrically loaded isolated footings.

Renzi *et al*. (2013) evolved a simplified empirical method for assessing seismic soil-structure interaction

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effects on ordinary shear-type buildings. A parametric analysis of the seismic SSI effects of a large number of idealised ordinary shear-type buildings was carried out with some simplifying assumptions. The results were compared with the corresponding classical fixed-base solutions. The structures were modelled as generalised single degree of freedom systems using the principle of virtual displacements and shallow squared foundations resting on different soil types were assumed. The outcomes of the numerical analyses were used as a statistical base in order to obtain simple analytical and non-dimensional relationships for estimating seismic SSI effects in terms of modified period and damping.

Hokmabadi *et al*. (2014) conducted assessment of seismic-soil-pile-structure interaction (SSPI) of mid-rise buildings sitting on floating pile foundations. A series of shaking table tests were conducted for three different cases, namely: (i) fixed-base structure representing the situation excluding the soil-structure interaction; (ii) structure supported by shallow foundation on soft soil; and (iii) structure supported by floating (frictional) pile foundation in soft soil. In addition, a fully nonlinear 3-D numerical model employing FLAC3D was adopted to perform time-history analysis on these three cases. Both experimental and numerical results indicated that soil-structure interaction amplifies the lateral deflections and inter-storey drifts of the structures supported by floating pile foundations in comparison to the fixed base structures. However, the floating pile foundations contribute to the reduction in the lateral displacements in comparison to the shallow foundation case, due to the reduced rocking components.

Usually in design offices full 3-D analysis of structures is carried out for all important RC framed buildings for design of its various components. Likewise a full 3-dimensional soil-structure-interaction analysis is needed to capture the interaction effect on various components of the structure for directly incorporating the same into the design. Present study is an effort in that direction in which a full 3-D soil-structure interaction effect is investigated on footings of a 6-storey RC framed building with and without shear wall.

PROBLEM FOR INVESTIGATION

A six storey RCC framed building with isolated footings resting on homogeneous soil mass has been considered in this study. The building consists of 4 bays in X-direction and 3 bays in Y-direction. For resisting lateral forces a dual system consisting of special moment resisting frames (SMRF) and reinforced concrete shear walls is considered. The shear walls are provided on outer frames along Y-direction i.e. the assumed direction of lateral seismic forces. The plinth beams are also provided. Such types of buildings are very common in urban areas. The space frame, shear walls and soil mass are considered as a single compatible structural unit for the interaction analysis. The interaction analyses are carried out with and without shear walls. The complete details of the problem under investigation are shown in Figures 1(a)-1(d). The building is considered to be situated in seismic zone V of India. For the present analysis, super-structure, foundation, as well as soil are considered to behave in linear elastic manner.

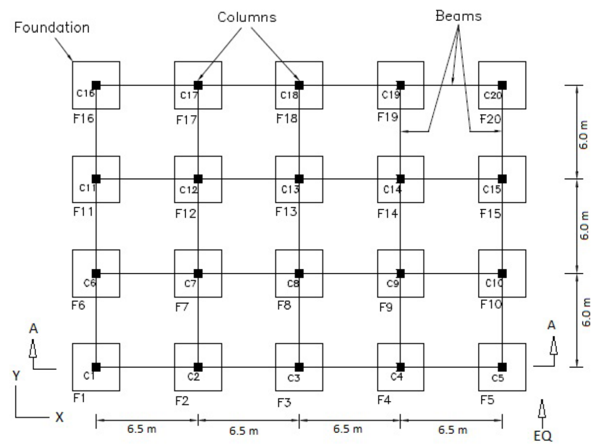

Figure-1(a). Plan of the space frame without shear wall.

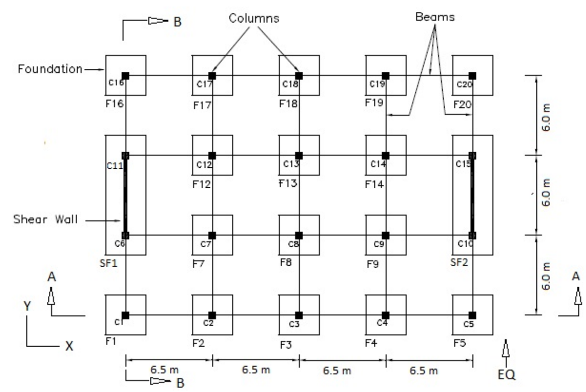

Figure-1(b). Plan of the space frame with shear wall.

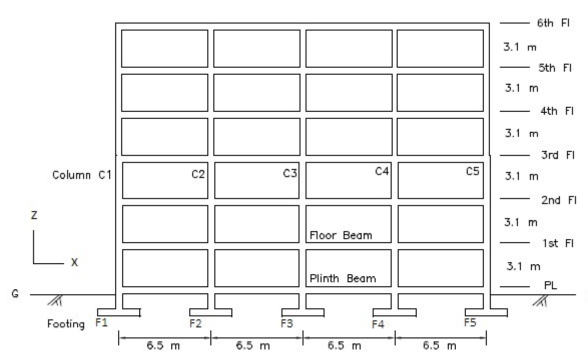

Figure-1(c). Sectional elevation at section A-A.

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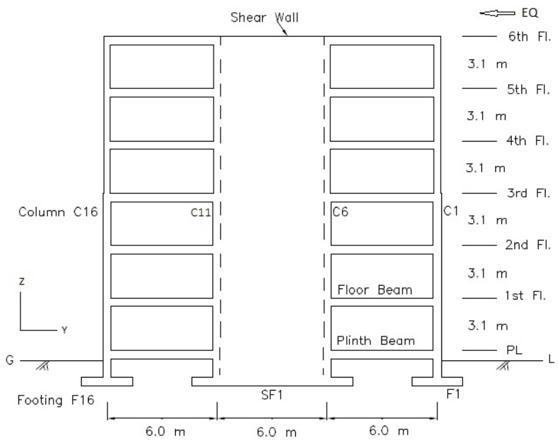

Figure-1(d). Sectional elevation at section B-B.

The geometrical properties of space frame-shear wall-soil system are provided in Table-1.

Table-1. Geometric parameters of space frame-shear wall-soil system.

Parameter	Value
Number of storeys	6
Number of bays in X direction	4
Number of bays in Y-direction	3
Bay width in X-direction	6.5 m
Bay width in Y-direction	6.0 m
Storey height	3.1 m
Slab thickness	200 mm
Beam size	300 mm x 500 mm
Column sizes: (i) Foundation to 3rd floor (ii) 4th floor to 6th floor	 500 mm x 500 mm 400 mm x 400 mm
Shear wall thickness	200 mm
Depth of foundation below G.L.	1.5 m
Height of plinth above G.L.	0.6 m
Footing size below column	3 m x 3 m
Footing size below shear wall	3 m x 9 m
Semi-infinite extent of soil mass	100 m x 100 m x 25 m

The elastic modulus of soil is taken as 14.78 N/mm^2 as per tri-axial test results reported in literature (Bishop and Henkel, 1962). The material properties of concrete and soil are provided in Table-2.

Table-2. Material properties of concrete and soil.

Property	Value
Grade of concrete for all structural elements	M25
Modulus of elasticity of concrete (N/mm^2)	$E_c = 5000\sqrt{f_{ck}}$
Poisson's ratio of concrete	0.15
Density of concrete	25000 N/m^3
Elastic Modulus of soil	14.78 N/mm^2
Poisson's ratio of soil	0.35

The building is considered to be an institutional building. The live loads are considered as per IS 875 (Part 2):1987. The live loads of 4 KN/ m^2 on floors and 1.5 KN/ m^2 on roof are considered. The brick masonry wall on outer periphery of the building and parapet wall on roof are also considered. The details of various loads considered are given in Table-3. These are in addition to the self-weight of the structure.

Table-3. Dead load and live load on structure.

Description	Value
Dead load of floor finish	1 KN/m^2
Dead load of finishing and water proofing on roof	2.5 KN/m^2
Live load on floors	4 KN/m^2
Live load on roof	1.5 KN/m^2
Brick walls (only on plinth/floor periphery)	11.362 KN/m
Parapet wall on roof periphery	4.37 KN/m

For seismic load calculations, equivalent static lateral force method is used as per IS 1893 (Part 1): 2002. The parameters used for seismic load calculations are given in Table-4.

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Table-4. Parameters for Lateral Seismic Load calculations on the structure.

Parameter	Value
Earthquake zone	V
Zone factor 'Z' (Table 2 of IS 1893 (Part 1): 2002)	0.36
Importance factor 'I' (Table 6 of IS 1893 (Part 1): 2002)	1.5
Response reduction factor 'R' (Table-7 of IS 1893 (Part 1): 2002) (Ductile shear wall with SMRF)	5.0
Approximate fundamental natural period of vibration (T_a) $T_a = 0.075\ h^{0.75} = 0.075\ (20.7)^{0.75} = 0.7278452$ (as per clause 7.6.1 of IS 1893 (Part 1): 2002)	0.728 sec
Average response acceleration coefficient (S_a/g) $S_a/g = 1.36/\ T_a$ (for soil for 5% damping, as given in Figure-2 of IS 1893 (Part 1): 2002, for the natural period T_a of 0.7278452 sec)	1.8685

SEISMIC LOAD CALCULATIONS

The equivalent static lateral force method [IS 1893 (Part 1): 2002] is adopted for evaluation of seismic forces:

(i) Calculation of lumped masses to various floor levels

The earthquake loads are calculated for full dead load plus the percentage of imposed load as given Table-8 of IS 1893 (Part 1): 2002. Accordingly 50% of live load on floors and 25% of live load on roof is considered.

The lumped mass of each floor is worked out by adding mass of slab, mass of reduced live load on slabs, mass of beams in longitudinal as well as transverse directions at that floor, mass of column for half column height above and below floor, mass of wall for half height above and below beams (wall is considered only on outer periphery), mass of parapet wall on outer periphery beams on roof.

Seismic weight of floor = lumped masses of floors x g
g = gravitational acceleration
W = Seismic weight of building (sum of seismic weights of all floors)

(ii) Determination of fundamental natural period of the shear wall-space frame

The approximate fundamental natural period of vibration (T_a) of the space frame-shear wall structure is estimated as per the empirical expression given in the clause 7.6.1 of IS 1893 (Part 1): 2002:

$T_a = 0.075\ h^{0.75}$

Where h = height of building, in m.

(iii) Determination of design base shear

The design base shear is calculated as per clause 7.5.3 of IS 1893 (Part 1): 2002:

The design seismic base shear, $V_B = A_h\ W$

A_h = Design horizontal acceleration spectrum coefficient, as per clause 6.4.2 of IS 1893 (Part 1): 2002.
W = Seismic weight of the building
$A_h = (Z/2)x(I/R)x(S_a/g)$
Z = Zone factor [Table 2 of IS 1893 (Part 1): 2002].
I = Importance factor [Table 6 of IS 1893 (Part 1): 2002].
R = Response reduction factor, depending on the perceived seismic damage performance of the building [Table 7 of IS 1893 (Part 1): 2002].
S_a/g = Average response acceleration coefficient for soil for 5% damping [Figure-2 of IS 1893 (Part 1): 2002] for the natural period as worked out above.

(iv) Determination of vertical distribution of base shear to different floor levels

The design seismic base shear, V_B is distributed to different floor levels along the height of the building as per the clause 7.7.1 of IS 1893 (Part 1): 2002;

$$Q_i = V_B \frac{W_i h_i^2}{\sum_{j=1}^{n} W_j h_j^2}$$

Where
Q_i = Design lateral force at floor 'i'
W_i = Seismic weight of floor 'i'
h_i = Height of floor i measured from base, and
n = Number of storeys in the building is the number of levels at which masses are located

(v) Distribution of design lateral force at floor level to different frames of the structure

The design lateral force at floor level is distributed amongst the frames in the direction considered for seismic load (i.e. Y-direction in present analysis) in proportion to their stiffness [clause 7.7.2.1 of IS 1893 (Part 1): 2002].

FINITE ELEMENT MODELING

The finite element modelling and analysis of the problem is achieved using ANSYS software which has wide variety of elements and material models suited for the problem under consideration.

ANSYS requires creation of model geometry, selection of appropriate element types, defining real constant sets in terms of cross sectional details for various elements, defining material properties, assigning these element types, real constants and material properties to various components of the interaction system and finite element mesh discretization in its pre-processing module. Boundary conditions, analysis type and loads are defined in its solution module.

The beams and columns are modeled in ANSYS using its advanced line element Beam4 (3D Elastic Beam) having two nodes with 6 degrees of freedom at each node: translations in the nodal x, y and z directions and rotations about the nodal x, y and z axes. It is a uniaxial element

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with tension, compression, torsion and bending capabilities.

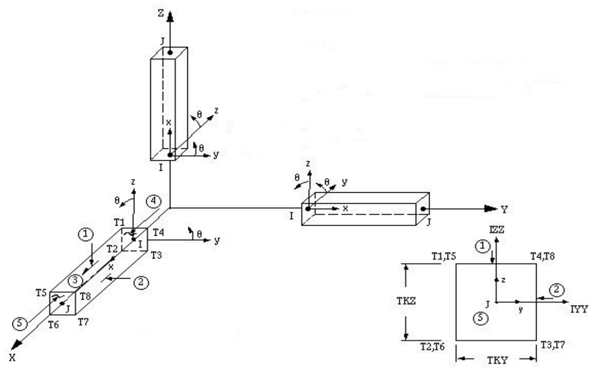

Figure-2(a). BEAM4:3-D elastic beam.

Slabs and shear walls are modelled using four node Shell63 (Elastic Shell) element of ANSYS. The element has both bending as well as membrane capabilities. Both in-plane and normal loads are permitted. The element has six degrees of freedom at each node: translations in the nodal x, y and z directions and rotations about the nodal x, y and z axes.

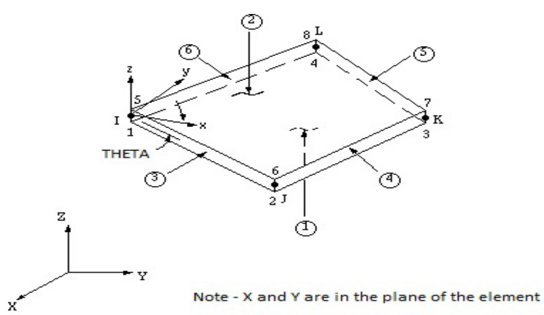

Figure-2(b). SHELL63: Elastic shell element

The footings and soil mass are modeled in ANSYS using its SOLID45 (3D Structural Solid) element. The element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. Adopting same element type for foundation and soil mass enables better contact modeling between foundation and soil mass.

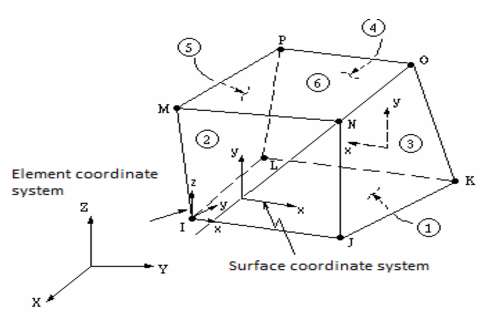

Figure-2(c). SOLID45:3D structural solid.

Surface to surface contact is established between foundation bottom area and soil using ANSYS surface to surface contact elements CONTA174 and TARGE170. To create a contact pair, ANSYS requires assigning the same real constant number to both the target and contact elements. The contact problems are highly nonlinear and require significant computer resources to solve. Except contact, the whole analysis of the structure and soil mass is considered linear elastic in the present problem. Contact can be established in ANSYS using contact wizard and picking contact and target surfaces. Under contact basic properties, behavior of contact surface is chosen as 'standard', which allows sliding as well as lifting of foundations. Coefficient of friction between concrete and soil is taken as 0.5.

Extent of soil mass

The soil mass is considered to be made up of homogeneous linear elastic isotropic material. Usually bed rock is encountered in most of the sites at varying depth from ground level. It is assumed that bed rock is encountered 25m below top of soil in the present case. Various horizontal stretches of soil volumes were considered for analysis to decide the appropriate extent of soil mass. From the results, it is observed that soil displacements reduces to less than 5% of peak value beyond about 25m from building line under worst combination of vertical loads (about 30m in case of worst combination with lateral loads), whereas, stresses in soil reduces to less than 5% of peak value beyond about 15m from building line (about 17m in case of worst combination with lateral loads). The values of displacements and stresses in soil reduce further to negligible values as we move further 10 to 15 m away from the building line. Therefore, horizontal extent of soil mass is considered as 100m x 100m in this study making soil participating volume of 100m x 100m x 25m which is sufficient to capture the dominant effect of soil-structure-interaction of the problem under consideration.

Meshing and mesh optimization

The finite element discretization of various structural components and soil mass is achieved through mesh tool of ANSYS.

The extensive mesh refinement is achieved out both for superstructure as well as for soil mass. Several trial analyses were conducted on the structure with varying mesh divisions to observe the effect of increasing number of mesh division on maximum displacement and maximum stresses. It is observed that results do not change considerably beyond 10 divisions. 8 to 12 divisions are found appropriate to capture reasonably accurate results for the purpose. The finer meshing consumes considerable execution time especially when we carry out interaction analysis. Finally, the mesh size of 500 mm is adopted for beams, slabs and shear wall resulting in 12 divisions for beams and shear wall and 12x13 divisions for slabs. For the columns 12 mesh divisions are found suitable. The foundation mesh size is kept as 500 mm.

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For soil mass also, the extensive mesh refinement study is carried out by conducting several trial analyses with varying mesh divisions to observe the effect of increasing number of mesh division on maximum displacement and maximum stresses on soil. It is found that keeping equal mesh size throughout the soil mass results in a very inefficient model. It consumes enormous amount of processing time even for results which are far from converged results. Therefore, graded meshing is adopted. The finer mesh is adopted for soil just below and around the building where deformations and stresses are of higher order and increasing mesh size is adopted for soil mass away from it. The mesh sizes of 1500, 750 and 500 were tried below and around the building and it is observed that mesh size of 500 mm, though consumes more processing time, maps the foundation and soil most efficiently and gives better converged results. The graded meshing is adopted beyond building area in increasing order of size and by several trial and error mesh size giving optimized converged results with least processing time is achieved as depicted in Figures 3 and 4.

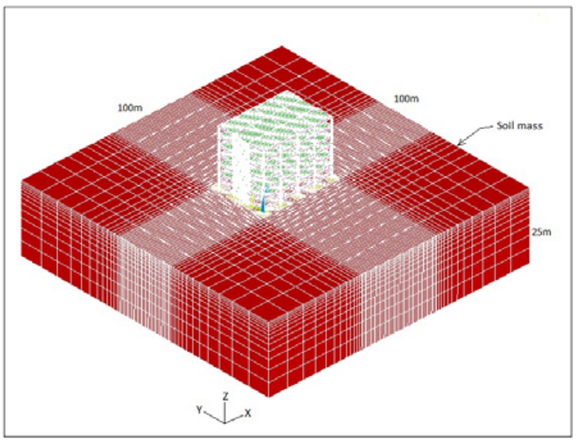

Figure-3. Finite element discretization of space frame-shear wall-soil system.

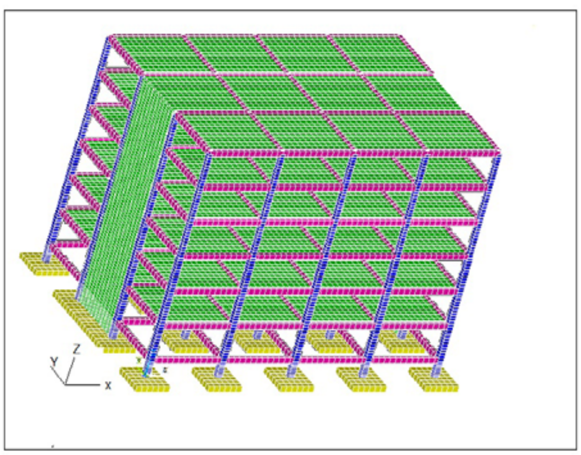

Figure-4. Finite element discretization of space frame-shear wall structural system.

Boundary conditions

The vertical displacement (U_z) is restrained on soil bottom as bed rock is assumed to be encountered at this location. The side boundaries of soil are considered to be restrained laterally (i.e. horizontal displacement (U_x) is restrained on boundaries perpendicular to X-direction and horizontal displacement (U_y) is restrained on boundaries perpendicular to Y-direction). Trial analyses were carried out by keeping side boundaries free and it was found that the results generally do not vary beyond 10% (from those when side boundaries were laterally restrained).

LINEAR INTERACTION ANALYSIS

The linear interaction analyses of the space frame-soil system and space frame-shear wall-soil system are carried out assuming the structure, shear wall and soil to act as a single compatible structural unit and to behave in linear elastic manner. The non-interaction analyses (with and without shear wall) are also carried out for comparison of the results with the interaction analyses.

The following analyses are carried out for the structural system;

Case-1: The conventional i.e. non-interaction analysis of the space frame without shear wall (NIA-SW) considering columns fixed at their bases.

Case-2: The linear interaction analysis of the space frame-soil System without shear wall (LIA-SW) considering the columns supported on isolated footings resting on deformable soil.

Case-3: The conventional i.e. non-interaction analysis of the space frame-shear wall (NIA+SW) considering columns fixed at their bases.

Case-4: The linear interaction analysis of the space frame-shear wall-soil system (LIA+SW), considering the columns supported on isolated footings resting on deformable soil.

For each of the these analyses, the following combinations of dead load (DL), live load (LL) and seismic load (EL) are considered as per Clause 6.3.1.2 of IS 1893 (Part 1): 2002

Load case no.	Designation	Load combination
1	LC1	1.5(DL+LL)
2	LC2	1.2(DL+LL+EL
3	LC3	1.2(DL+LL-EL)
4	LC4	1.5(DL+EL)
5	LC5	1.5(DL-EL)
6	LC6	0.9DL+1.5EL
7	LC7	0.9DL-1.5EL

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Seismic load (EL) is applied in Y-direction. Positive sign of seismic load shows that it is applied from front and negative sign shows that it is applied from back i.e. from opposite direction.

RESULTS AND DISCUSSIONS

The results of the interaction and non- interaction analyses are compared to investigate the following;

- Axial force on the footings (F_z)
- Bending moment on the footings about X-axis (M_x)
- Bending moment on the footings about Y-axis (M_y)

The results are discussed to highlight the effect of shear wall. The results are tabulated taking advantage of symmetry and only quarter portion of the problem is considered. Thus, axial forces and bending moments are tabulated for the footings F1, F2, F3, F6, F7, F8 and SF1 owing to the symmetry.

Due to interaction effect, differential settlements take place in the footings, which results in redistribution of axial forces and moments in the footings. Figures 5(a) to 5(d) show the settlements in the footings for LIA-SW and LIA+SW systems, under vertical and seismic loads.

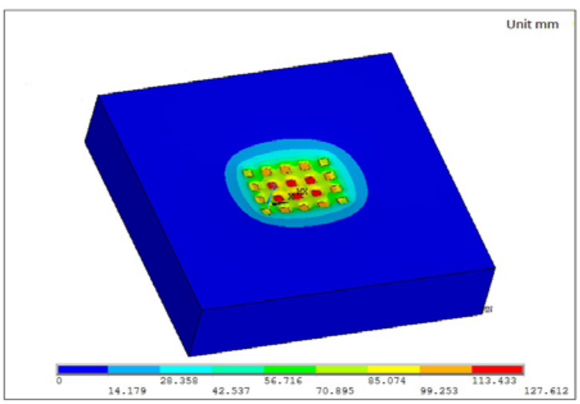

Figure-5(a). Settlements in the footings of LIA-SW system under vertical loads (load case LC1).

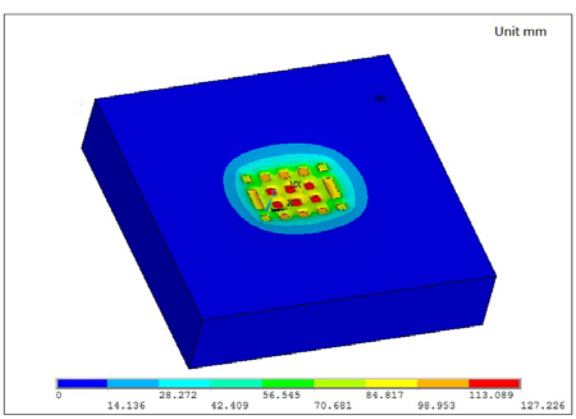

Figure-5(b). Settlements in the footings of LIA+SW system under vertical loads (load case LC1).

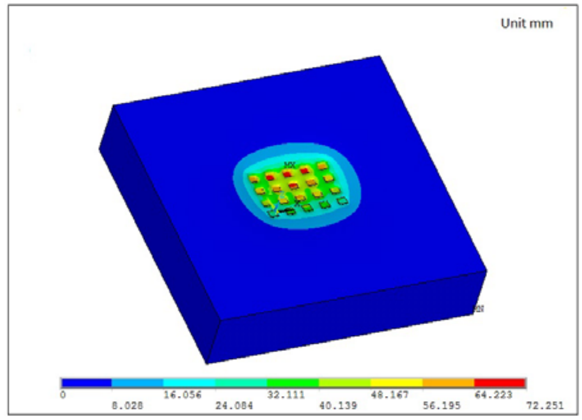

Figure-5(c). Settlements in the footings of LIA-SW system under seismic load case LC6.

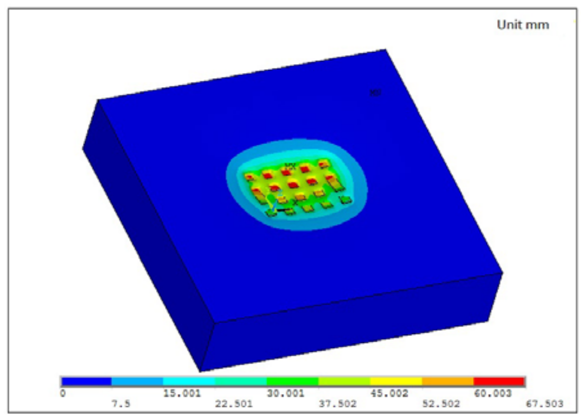

Figure-5(d). Settlements in the footings of LIA+SW system under seismic load case LC6.

Axial force in foundations

Table-5 shows comparison of axial force (F_z) in the footings for NIA-SW and LIA-SW systems. It is found that vertical loads (load case LC1), causes decrease in axial forces in inner footings and increase of axial forces in outer footings due to interaction effect. The variation of nearly +48.5 to -24% is found in the footings. As inner footings settle more they transfer their load to the outer footings. The maximum increase of nearly 48.5% is found in the corner footing F1 and the maximum decrease of nearly 24% is found in the inner footing F7. Under all combinations of seismic loads, the interaction effect causes decrease in axial forces in the inner footings and increase is found in the corner footings. The maximum increase of nearly two times in the corner footing F1 whereas the maximum decrease of nearly 30% is fund in the inner footing F7. The outer footings adjacent to corner footings i.e. F2 and F6 show increase in axial force in some seismic load cases and decrease in axial force in the remaining load cases. The maximum increase of nearly 39% is found in the footing F2 and the maximum decrease of nearly 10% is found in the footing F6.

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Table-5. Comparison of axial forces in the footings for NIA-SW and LIA-SW systems under various load cases.

S. No.	Footing	Coordinates (m)			Analysis type	Axial force in footings (KN)						
		X	Y	Z		LC1	LC2	LC3	LC4	LC5	LC6	LC7
1	F1	0.0	0.0	0.0	NIA-SW	1839.20	878.89	2062.40	804.75	2284.10	186.62	1666.00
					LIA-SW	2729.90	1602.20	2764.50	1432.30	2885.70	572.80	2021.40
					% diff.	48.43	82.30	34.04	77.98	26.34	206.93	21.33
2	F2	6.5	0.0	0.0	NIA-SW	2904.30	1633.00	3013.00	1418.30	3143.30	505.72	2230.80
					LIA-SW	3123.70	1915.70	3082.20	1654.70	3113.00	701.91	2155.90
					% diff.	7.55	17.31	2.30	16.67	-0.96	38.79	-3.36
3	F3	13.0	0.0	0.0	NIA-SW	2856.40	1598.40	2971.60	1385.40	3101.80	487.89	2204.30
					LIA-SW	3246.30	2009.60	3185.00	1724.60	3194.00	741.18	2206.10
					% diff.	13.65	25.73	7.18	24.48	2.97	51.92	0.08
4	F6	0.0	6.0	0.0	NIA-SW	2835.40	2324.30	2214.50	2285.60	2148.30	1399.30	1262.00
					LIA-SW	2962.80	2289.90	2451.30	2167.50	2368.70	1255.80	1465.60
					% diff.	4.49	-1.48	10.69	-5.17	10.26	-10.26	16.13
5	F7	6.5	6.0	0.0	NIA-SW	4215.40	3445.00	3300.10	3015.60	2834.40	1845.70	1664.50
					LIA-SW	3201.90	2485.30	2637.90	2208.00	2398.10	1282.80	1482.10
					% diff.	-24.04	-27.86	-20.07	-26.78	-15.39	-30.50	-10.96
6	F8	13.0	6.0	0.0	NIA-SW	4139.10	3384.10	3238.50	2950.90	2768.80	1806.90	1624.90
					LIA-SW	3301.30	2563.20	2719.10	2253.40	2447.60	1308.90	1512.30
					% diff.	-20.24	-24.26	-16.04	-23.64	-11.60	-27.56	-6.93

Table-6 provides the comparison of axial force (F_z) in the footings for NIA+SW and LIA+SW systems. The vertical loads (load case LC1) causes decrease in axial forces in the inner footings and increase in the outer footings due to interaction effect. The maximum increase of nearly 83% is found in shear wall footing SF1. The maximum decrease of nearly 25% occurs in the inner footing F7. Under all combinations of seismic loads interaction effect causes decrease in axial force in the inner footings and increase or decrease in the outer footings under different load combinations. The variation of nearly +69 to -28% is found in the footings. The maximum increase of nearly 69% occurs in the corner footing F1wherease the maximum decrease of nearly 28% occurs in the footing F2. The behaviour of shear wall footing is quite different under seismic loads. The non interaction analysis causes tension (lifting) in shear wall footing SF1 (below column C6) and excessive compression when direction of seismic forces is reversed. The interaction effect relieves the magnitudes of forces as well as reversal in the nature of forces. The tension is converted into compression and its magnitude decreases significantly from 48 to 70% under various combinations of seismic loads.

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Table-6. Comparison of axial forces in the footings for NIA+SW and LIA+SW systems under various load cases.

S. No.	Footing	Coordinates (m)			Analysis type	Axial forces in footings (KN)						
		X	Y	Z		LC1	LC2	LC3	LC4	LC5	LC6	LC7
1	F1	0.0	0.0	0.0	NIA+SW	1779.40	1209.80	1634.40	1231.40	1762.20	632.02	1162.80
					LIA+SW	2668.40	1570.80	2693.50	1407.70	2811.40	562.42	1965.70
					% diff.	49.96	29.84	64.80	14.32	59.54	-11.01	69.05
2	F2	6.5	0.0	0.0	NIA+SW	2907.70	2186.10	2465.20	2108.90	2457.90	1195.30	1544.20
					LIA+SW	3089.40	2030.10	2911.30	1808.20	2909.40	858.35	1965.70
					% diff.	6.25	-7.14	18.10	-14.26	18.37	-28.19	27.30
3	F3	13.0	0.0	0.0	NIA+SW	2865.90	2166.90	2418.50	2093.60	2408.10	1193.20	1507.70
					LIA+SW	3232.60	2179.70	2991.50	1942.40	2956.90	956.28	1977.30
					% diff.	12.80	0.59	23.69	-7.22	22.79	-19.86	31.15
4	SF1(below column C6)	0.0	6.0	0.0	NIA+SW	944.91	1503.50 (T)	3015.00	2086.50 (T)	3561.50	2381.60 (T)	3266.40
					LIA+SW	1731.10	1193.70	1573.30	1083.00	1562.40	575.48	990.33
					% diff.	83.20	*	-47.82	*	-56.13	*	-69.68
5	F7	6.5	6.0	0.0	NIA+SW	4049.90	3183.40	3296.50	2734.00	2875.30	1612.20	1753.50
					LIA+SW	3050.90	2327.50	2556.50	2053.00	2338.90	1171.30	1461.80
					% diff.	-24.67	-26.89	-22.45	-24.91	-18.66	-27.35	-16.64
6	F8	13.0	6.0	0.0	NIA+SW	4168.60	3357.40	3312.50	2910.20	2854.00	1757.40	1701.20
					LIA+SW	3269.30	2554.30	2679.70	2252.50	2408.80	1315.20	1479.50
					% diff.	-21.57	-23.92	-19.10	-22.60	-15.60	-25.16	-13.03

* Reversal of sign; (T) indicates axial tension (uplift)

Table-7 shows change in axial forces in the footings under various load cases due to presence of shear wall in the space frame. Under load case LC1, the presence of shear wall results in significant decrease of nearly 67% in axial force in footing SF1 (below column C6) in case of non-interaction analysis and nearly 42% in case of interaction analysis. The insignificant change is found in all other footings. Under all combinations of seismic loads, presence of shear wall causes significant increase in axial forces in footings F1, F2 and F3 and significant decrease of axial forces on the same footings when direction of seismic forces is reversed. The maximum increase of nearly 2.5 times is found in the footing F1 and the maximum decrease of nearly 32% is

Table-7. Change in axial forces in the footings under various load cases due to presence of shear wall in the space frame.

Footing designation	Analysis type	Cases compared	% change in axial forces						
			LC1	LC2	LC3	LC4	LC5	LC6	LC7
F1	Non-interaction	3 and 1	-3.25	37.65	-20.75	53.02	-22.85	238.67	-30.20
	Interaction	4 and 2	-2.25	-1.96	-2.57	-1.72	-2.57	-1.81	-2.76
F2	Non-interaction	3 and 1	0.12	33.87	-18.18	48.69	-21.81	136.36	-30.78
	Interaction	4 and 2	-1.10	5.97	-5.54	9.28	-6.54	22.29	-8.82
F3	Non-interaction	3 and 1	0.33	35.57	-18.61	51.12	-22.36	144.56	-31.60
	Interaction	4 and 2	-0.42	8.46	-6.08	12.63	-7.42	29.02	-10.37
F6 (SF1: below column C6)	Non-interaction	3 and 1	-66.67	*	36.15	*	65.78	*	158.83
	Interaction	4 and 2	-41.57	-47.87	-35.82	-50.03	-34.04	-54.17	-32.43
F7	Non-interaction	3 and 1	-3.93	-7.59	-0.11	-9.34	1.44	-12.65	5.35
	Interaction	4 and 2	-4.72	-6.35	-3.09	-7.02	-2.47	-8.69	-1.37
F8	Non-interaction	3 and 1	0.71	-0.79	2.29	-1.38	3.08	-2.74	4.70
	Interaction	4 and 2	-0.97	-0.35	-1.45	-0.04	-1.59	0.48	-2.17

*reversal of force (compression to tension)

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found in the footing F3. The interaction effect nullifies this effect. The presence of shear wall causes more uniform distribution of axial force under shear wall footings. The axial force decreases by 32 to 55%, under all combinations of seismic loads.

Bending moment M_x in foundations

Table-8 shows the comparison of bending moment (M_x) in the footings for NIA-SW and LIA-SW systems. The interaction effect causes increase in the values of M_x in all footings significantly for load case LC1. The maximum increase of nearly 24 times is found in the footing F3 and the minimum increase of nearly 2.5 times is found in the footing F7. For most of the seismic load combinations, the interaction effect causes increase in the values of M_x in the footings but decrease is found in some of the cases. The effect is more pronounced in the outer footings than in the inner footings. The maximum increase of nearly 93% and the maximum decrease of nearly 15% is found in the footing F3 under various seismic load combinations.

Table-8. Comparison of bending moment (M_x) in the footings for NIA-SW and LIA-SW systems under various load cases.

S. No.	Footing designation	Coordinates (m)			Analysis type	Bending moment M_x (KN-m)						
		X	Y	Z		LC1	LC2	LC3	LC4	LC5	LC6	LC7
1	F1	0.0	0.0	0.0	NIA-SW	15.74	-322.91	347.39	-405.12	432.76	-410.82	427.05
					LIA-SW	146.16	-378.54	624.90	-502.53	753.19	-520.89	719.79
					% diff.	828.35	17.23	79.88	24.04	74.04	26.79	68.55
2	F2	6.5	0.0	0.0	NIA-SW	10.39	-341.01	357.64	-429.34	443.97	-432.26	441.05
					LIA-SW	228.80	-308.43	678.52	-434.72	797.61	-488.40	737.91
					% diff.	2102.54	-9.55	89.72	1.25	79.65	12.99	67.31
3	F3	13.0	0.0	0.0	NIA-SW	10.09	-341.54	357.69	-429.95	444.09	-432.78	441.26
					LIA-SW	249.20	-289.88	690.46	-417.89	805.77	-480.25	740.33
					% diff.	2369.53	-15.13	93.03	-2.80	81.44	10.97	67.78
4	F6	0.0	6.0	0.0	NIA-SW	2.00	-372.12	375.01	-466.81	467.11	-466.95	466.97
					LIA-SW	13.01	-404.41	423.35	-508.52	527.90	-522.88	533.43
					% diff.	550.36	8.68	12.89	8.94	13.01	11.98	14.23
5	F7	6.5	6.0	0.0	NIA-SW	7.48	-382.73	394.70	-481.70	490.09	-483.38	488.42
					LIA-SW	25.22	-372.45	409.80	-470.13	505.60	-491.20	509.58
					% diff.	237.26	-2.69	3.83	-2.40	3.16	1.62	4.33
6	F8	13.0	6.0	0.0	NIA-SW	7.41	-383.12	394.97	-482.18	490.44	-483.83	488.79
					LIA-SW	28.91	-363.54	406.61	-460.15	500.22	-483.14	504.05
					% diff.	290.24	-5.11	2.95	-4.57	1.99	-0.14	3.12

The comparison of bending moment (M_x) in the footings for NIA+SW and LIA+SW systems is provided Table-9. The highly significant increase is found in the bending moments in all footings due to the interaction effect. The increase of nearly 3 times is found in the footing F8 and 24 times in the footing F3 for load case LC1. Due to all combinations of seismic loads (LC2 to LC7), the significant increase of nearly 6 times is found in the footing F8 and nearly 12 times in the footing F2/F3.

Table-9. Comparison of bending moment (M_x) in the footings for NIA+SW and LIA+SW systems under various load cases.

S. No.	Footing designation	Coordinates (m)			Analysis type	Bending moment M_x (KN-m)						
		X	Y	Z		LC1	LC2	LC3	LC4	LC5	LC6	LC7
1	F1	0.0	0.0	0.0	NIA+SW	20.85	-39.44	72.26	-51.54	88.08	-58.98	80.64
					LIA+SW	150.12	-337.26	597.84	-449.40	719.10	-444.48	674.65
					% diff.	620.03	755.19	727.35	771.93	716.41	653.57	736.63
2	F2	6.5	0.0	0.0	NIA+SW	10.02	-30.61	46.65	-41.23	55.35	-44.05	52.53
					LIA+SW	230.01	-242.94	608.21	-354.92	708.49	-422.67	648.49
					% diff.	2196.20	693.56	1203.83	760.91	1179.99	859.55	1134.56
3	F3	13.0	0.0	0.0	NIA+SW	10.10	-30.57	46.74	-41.24	55.40	-44.07	52.57
					LIA+SW	248.16	-224.68	616.37	-338.16	712.56	-415.71	647.27
					% diff.	2356.79	634.87	1218.83	719.94	1186.30	843.25	1131.35
4	SF1 (below column C6)	0.0	6.0	0.0	NIA+SW	16.72	-97.37	124.05	-127.41	149.37	-131.82	144.96
					LIA+SW	101.41	-1297.00	1457.90	-1646.50	1793.90	-1711.80	1795.30
					% diff.	506.48	1232.01	1075.25	1192.28	1100.98	1198.59	1138.48
5	F7	6.5	6.0	0.0	NIA+SW	7.39	-37.09	48.92	-49.66	57.86	-51.30	56.22
					LIA+SW	33.01	-307.75	358.45	-390.41	439.80	-415.07	444.99
					% diff.	346.54	729.65	632.70	686.10	660.16	709.07	691.54
6	F8	13.0	6.0	0.0	NIA+SW	7.43	-37.12	49.01	-49.69	57.97	-51.34	56.32
					LIA+SW	29.18	-307.21	350.90	-389.55	430.37	-414.26	435.72
					% diff.	292.48	727.61	616.03	684.02	642.38	706.85	673.72

Table-10 shows change in bending moments M_x in the footings under various load cases due to presence of shear wall in the space frame. Under load case LC1, the presence of shear wall causes significant increase of nearly 7.5 times in the bending moments M_x in shear wall footing SF1 (below column C6) for non-interaction analysis and nearly 7 times in case of interaction analysis. The significant increase of nearly 30% is found in the footings F1 and F7 in case of non-interaction and interaction analysis respectively. The insignificant increase is found in the remaining footings. Due to all combinations of seismic loads, the non-interaction analysis suggests that the presence of shear wall causes significant decrease of nearly 65 to 90% in the values of bending moments in the footings. However, the interaction effect causes substantial reversal effect (restoration) in the bending moments except in the shear wall footings further increase of nearly 2.5 times is found. The significant decrease of nearly 5% to 22% is found in other footings in the interaction analysis.

Table-10. Change in bending moments (M_x) in the footings under various load cases due to presence of shear wall in the space frame.

Footing designation	Analysis type	Cases compared	% change in bending moment (M_x)						
			LC1	LC2	LC3	LC4	LC5	LC6	LC7
F1	Non-interaction	3 and 1	32.43	-87.79	-79.20	-87.28	-79.65	-85.64	-81.12
	Interaction	4 and 2	2.71	-10.91	-4.33	-10.57	-4.53	-14.67	-6.27
F2	Non-interaction	3 and 1	-3.57	-91.02	-86.96	-90.40	-87.53	-89.81	-88.09
	Interaction	4 and 2	0.53	-21.23	-10.36	-18.36	-11.17	-13.46	-12.12
F3	Non-interaction	3 and 1	0.10	-91.05	-86.93	-90.41	-87.53	-89.82	-88.09
	Interaction	4 and 2	-0.42	-22.49	-10.73	-19.08	-11.57	-13.44	-12.57
F6 (SF: below column C6)	Non-interaction	3 and 1	735.67	-73.83	-66.92	-72.71	-68.02	-71.77	-68.96
	Interaction	4 and 2	679.30	220.71	244.37	223.78	239.82	227.38	236.56
F7	Non-interaction	3 and 1	-1.15	-90.31	-87.61	-89.69	-88.19	-89.39	-88.49
	Interaction	4 and 2	30.89	-17.37	-12.53	-16.96	-13.01	-15.50	-12.68
F8	Non-interaction	3 and 1	0.34	-90.31	-87.59	-89.70	-88.18	-89.39	-88.48
	Interaction	4 and 2	0.92	-15.49	-13.70	-15.34	-13.96	-14.26	-13.56

Thus, it is noticed that the interaction effect causes significant change in the value of M_x in the footings. The results obtained from non-interaction analysis may be highly misleading in deformable soils as moments in the footings do not actually get reduced to that extent as that in case of non-interaction analysis. Therefore, the shear wall footings designed on the basis of non-interaction analysis may be more vulnerable.

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Bending moment M_y in foundations

Table-11 shows comparison of bending moment (M_y) in the footings of NIA-SW and LIA-SW systems. The interaction effect causes significant increase in values of M_y in the footings. The increase in the range of 0.01 to 15 times is found in the footings. The maximum increase of nearly 15 times is found in footing F6 (under load case LC5) and the minimum increase of nearly 1% in the footing F2 (under load case LC7). The reversal in the sign is found in some of the footings for certain load cases.

Table-11. Comparison of bending moment (M_y) in the footings for NIA-SW and LIA-SW systems under various load cases.

S. No.	Footing designation	Coordinates (m)			Analysis type	Bending moment M_y (KN-m)						
		X	Y	Z		LC1	LC2	LC3	LC4	LC5	LC6	LC7
1	F1	0.0	0.0	0.0	NIA-SW	-18.91	-14.15	-16.17	-15.46	-17.98	-8.79	-11.31
					LIA-SW	-131.12	-85.40	-111.39	-75.66	-107.62	-26.38	-60.20
					% diff.	593.35	503.41	588.91	389.46	498.65	20 0.18	432.45
2	F2	6.5	0.0	0.0	NIA-SW	-2.65	-1.13	-3.20	1.06	-1.51	1.13	-1.45
					LIA-SW	-17.03	-13.22	-10.10	-12.65	-8.38	-3.88	-1.46
					% diff.	543.07	1066.02	215.96	1093.40 (*)	454.07	243.63 (*)	1.00
3	F3	13.0	0.0	0.0	NIA-SW	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					LIA-SW	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					% diff.	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	F6	0.0	6.0	0.0	NIA-SW	-14.25	-11.56	-11.21	-9.99	-9.55	-6.07	-5.64
					LIA-SW	-200.87	-150.41	-158.60	-140.56	-150.70	-71.90	-81.26
					% diff.	1309.71	1201.69	1314.93	1307.39	1477.35	1084.45	1341.57
5	F7	6.5	6.0	0.0	NIA-SW	-10.89	-8.87	-8.54	-6.28	-5.86	-3.85	-3.43
					LIA-SW	-29.30	-22.35	-21.02	-20.17	-18.51	-9.59	-8.00
					% diff.	169.00	151.90	146.30	221.00	215.79	148.93	133.50
6	F8	13.0	6.0	0.0	NIA-SW	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					LIA-SW	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					% diff.	0.00	0.00	0.00	0.00	0.00	0.00	0.00

*reversal of sign

The comparison of bending moment M_y in the footings of NIA+SW and LIA+SW systems is shown in Table-12. The footings F3 and F8 are not subjected to moment M_y, as they exist on the line of symmetry. The interaction effect causes significant increase in values of M_y in all footings except F7 in which increase/decrease is found under different load cases. The maximum increase of nearly 22 times occurs in the shear wall footing SF1 (under load case LC7) whereas, the maximum decrease of nearly 85% occurs in the footing F7 (under load case LC4). The reversal in the sign is also found in some of the footings.

Table-12. Comparison of bending moment (M_y) in the footings for NIA+SW and LIA+SW systems under various load cases.

S. No.	Footing designation	Coordinates (m)			Analysis type	Bending moment M_y (KN-m)						
		X	Y	Z		LC1	LC2	LC3	LC4	LC5	LC6	LC7
1	F1	0.0	0.0	0.0	NIA+SW	-18.87	-15.07	-15.17	-16.62	-16.74	-9.96	-10.08
					LIA+SW	-126.61	-81.11	-107.60	-71.29	-103.95	-22.50	-58.35
					% diff.	571.10	438.09	609.29	328.95	520.93	125.86	478.66
2	F2	6.5	0.0	0.0	NIA+SW	-2.58	-2.08	-2.13	-0.14	-0.21	-0.09	-0.16
					LIA+SW	-14.00	-13.24	-5.31	-13.21	-3.21	-3.75	1.53
					% diff.	443.44	538.23	148.74	9437.97	1412.76	4050.73	665 (*)
3	F3	13.0	0.0	0.0	NIA+SW	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					LIA+SW	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					% diff.	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	SF1 (below column C6)	0.0	6.0	0.0	NIA+SW	-15.71	-14.36	-10.74	-13.10	-8.58	-8.76	-4.23
					LIA+SW	-215.64	-152.96	-174.89	-139.22	-167.09	-59.26	-96.23
					% diff.	1272.63	965.18	1528.10	962.67	1847.73	576.70	2172.61
5	F7	6.5	6.0	0.0	NIA+SW	-11.35	-10.70	-7.44	-8.69	-4.60	-6.02	-1.94
					LIA+SW	-10.38	-3.97	-9.87	-1.23	-9.17	6.43	-6.77
					% diff.	-8.52	-62.92	32.68	-85.80	99.08	1.26(*)	248.64
6	F8	13.0	6.0	0.0	NIA+SW	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					LIA+SW	0.00	0.00	0.00	0.00	0.00	0.00	0.00
					% diff.	0.00	0.00	0.00	0.00	0.00	0.00	0.00

*reversal of sign

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Table-13 shows change in bending moments M_y in the footings under various loads due to presence of shear wall in the space frame. In non-interaction analysis maximum increase of nearly 83% and maximum decrease of nearly 92% is found in the footing F2 under different load cases. The interaction analysis causes significant decrease in the footing F7 and increase/decrease in other footings under different load combinations. The maximum decrease of nearly 94% is found in in the footing F7 and the maximum increase of nearly of 18% is found in the shear wall footing SF1.

Table-13. Change in bending moments (M_y) in the footings under various load cases due to presence of shear wall in the space frame.

Footing designation	Analysis type	Cases compared	**% change in bending moment** (M_y)						
			LC1	**LC2**	**LC3**		**LC5**	**LC6**	**LC7**
F1	Non-interaction	3 and 1	-0.24	6.50	-6.18	7.51	-6.88	13.37	-10.82
	Interaction	4 and 2	-3.44	-5.03	-3.40	-5.78	-3.41	-14.70	-3.08
F2	Non-interaction	3 and 1	-2.70	83.05	-33.20	-86.79 (*)	-85.97	-92.01 (*)	-88.66
	Interaction	4 and 2	-17.78	0.20	-47.41	4.48	-61.69	-3.33	4.70 (*)
F3	Non-interaction	3 and 1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Interaction	4 and 2	0.00	0.00	0.00	0.00	0.00	0.00	0.00
F6 (SF1: below column C6)	Non-interaction	3 and 1	10.25	24.28	-4.17	31.18	-10.21	44.25	-24.89
	Interaction	4 and 2	7.35	1.70	10.27	-0.95	10.88	-17.59	18.41
F7	Non-interaction	3 and 1	4.18	20.61	-12.88	38.20	-21.46	56.42	-43.36
	Interaction	4 and 2	-64.57	-82.25	-53.07	-93.89	-50.49	-32.87 (*)	-15.43
F8	Non-interaction	3 and 1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Interaction	4 and 2	0.00	0.00	0.00	0.00	0.00	0.00	0.00

CONCLUSIONS

The important research findings emerged from the study, are summarized as follows:

a) Non interaction analysis causes tension (uplift) in the footings located below shear wall and on the side where seismic loads are applied. The compression is found in the footings located on the opposite side of loads. The interaction causes significant reversal effect in the nature and magnitude of forces (tension to compression).
b) The differential settlement of footings causes significant redistribution of forces and moments in the footings of space frame-soil and space frame-shear wall-soil systems.
c) The seismic forces cause compression/tensions in the footings and reversal in the nature of forces is found when direction of seismic forces is reversed. Interaction effect reduces this effect and provides more stability to the structure. Shear walls further add to the stability of the structure.
d) The interaction effect causes significant increase in axial force in the outer footings and significant decrease in the inner footings under vertical load.
e) Under seismic loads, the interaction effect causes significant increase in axial force in the corner footings and significant decrease in the central footings for most of the load cases. The maximum increase is found in the corner footings in frame without shear wall (under shear wall footings in frame with shear wall) and the maximum decrease is found under footings located diagonally adjacent to the corner footings.
f) The interaction effect significantly increases the value of bending moments (M_x) in all footings of space frame-soil system in most of the load cases. The space frame-shear wall-soil system experiences manifold increase in the value of bending moments in all footings for all load cases.
g) The interaction analysis suggests that due to the presence of shear wall, bending moments (M_x) in the footings do not actually get reduced to that significant extent as found in case of non-interaction analysis. Therefore, the footings designed on the basis of non-interaction analysis may be more vulnerable.
h) The interaction effect causes highly significant increase in values of bending moments M_y in the footings of space frame-soil system as well as for space frame-shear wall-soil system. The highly increased values may require revision of design.
i) The proposed methodology can be effectively used to evaluate the settlements and forces in the superstructure and foundation for multi-story space frame-shear wall-soil system for better and efficient building design.

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