Earthquakes and Structures, *Vol. 8, No. 5 (2015) 1255-1276*
DOI: http://dx.doi.org/10.12989/eas.2015.8.5.1255

Analysis of settlements of space frame-shear wall-soil system under seismic forces

D.K. Jain* and M.S. Hora[a]

Department of Civil Engineering, Maulana Azad National Institute of Technology, Bhopal, India

(Received May 18, 2014, Revised August 3, 2014, Accepted November 6, 2014)

Abstract. The importance of considering 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 total and differential settlements in the footings due to deformations in the 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 causes significant total and differential settlements in the footings. Maximum total settlement in footings occurs under vertical loads and inner footings settle more than outer footings creating a saucer shaped settlement profile of the footings. Each combination of seismic loads causes maximum differential settlement in one or more footings. Presence of shear wall decreases pulling/pushing effect of seismic forces on footings resulting in more stability to the structures.

Keywords: soil-structure interaction; ANSYS; space frame; shear wall; linear analysis; differential settlement; isolated column footing; seismic force

1. 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, deformations take place in soil, which are transferred to the structure due to soil-structure interaction, causing total and differential settlements in foundations. 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

*Corresponding author, Ph. D. Student, E-mail: dkjain63@gmail.com
[a]Professor, E-mail: hora1961@gmail.com

http://www.techno-press.org/journals/eas&subpage=7 ISSN: 2092-7614 (Print), 2092-7622 (Online)

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 linear interaction analysis (LIA), for the space frame with and without shear wall, are evaluated to investigate the total settlements and differential settlements in the footings. The interaction effect causes significant total and differential settlements in the footings. Maximum total settlement in footings occurs under vertical loads. Inner footings settle more than outer footings creating a saucer shaped settlement profile of the footings under the influence of vertical loads. Each combination of seismic loads causes maximum differential settlement in one or more footings which reflects the importance of considering various load combinations.

2. 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 have been drawn. 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. 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. Mandal *et al.* (1998) presented a computational iterative scheme for studying the effect of soil-structure interaction on axial force and column moments. Wang *et al.* (2000) incorporated Ritz method for settlement analysis of rectangular thick rafts resting on homogeneous, elastic half-space. Stavridis (2002) presented a simplified analysis approach for layered soil-structure analysis in which an arbitrary structure was considered for analysis. Hayashi and Takahashi (2004) studied soil-structure interaction effect on the earthquake response of buildings by carrying out a simulation analysis on a 2-D finite element model. 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. Hora (2006) proposed a computational methodology for nonlinear interaction analysis of infilled frame-foundation-soil system. Yahyai *et al*. (2008) analyzed the effect of soil -structure interaction between two adjacent 32 storey buildings under seismic loading. A 2-D analysis was carried out using ANSYS software. 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. Thangaraj and Illamparuthi (2010) compared interaction and non-interaction analyses for the space frame-raft foundation-soil system using ANSYS software. 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. Shakib and Atefatdoost (2011) examined the effect of soil structure interaction on torsional response of asymmetrical wall type systems. 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. Renzi *et al*. (2013) evolved a simplified empirical method for assessing seismic soil-structure interaction effects on ordinary shear-type buildings.

Usually in design offices full 3-D analysis of structures is carried out for all important RC framed buildings. Likewise a full 3-D soil-structure-interaction analysis is needed to capture the effect of interaction on 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 evaluated on settlement of footings of a 6-storey RC framed building with and without shear wall.

3. 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. Such types of

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×500 mm
Column sizes: (i) Foundation to 3rd storey (ii) 4th storey to 6th storey	 500 mm×500 mm 400 mm×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×3 m×0.5 m
Footing size below shear wall	3 m×9 m×0.5 m
Semi-infinite extent of soil mass	100 m×100 m×25 m

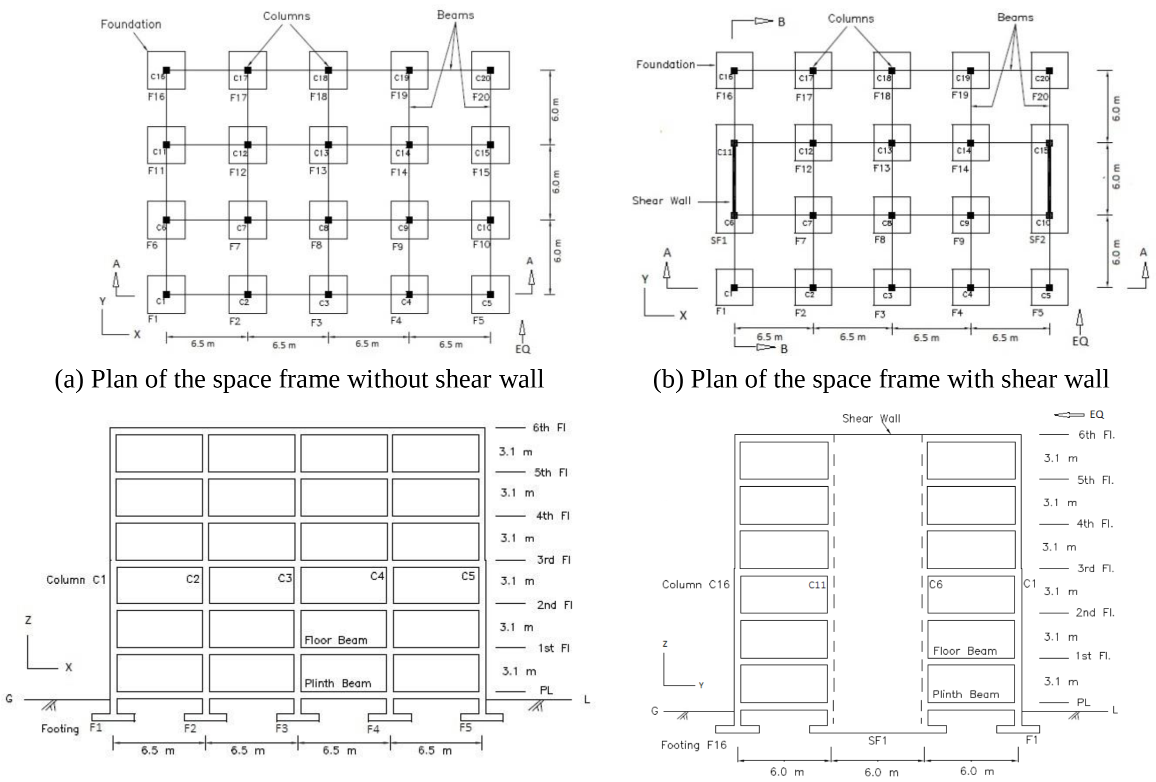
buildings are very common in urban areas. The space frame, shear walls and soil mass are considered as a single compatible structural unit for the interaction analysis. The interaction analyses are carried out with and without shear walls. The complete details of the problem under investigation are shown in Figs. 1(a)-(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.

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

The minimum thickness of shear wall is prescribed as 150 mm under para 9.1.2 of IS 13920: 1993. The thickness of 200 mm is considered appropriate for the building keeping in view its size and height, after comparing with other buildings available in the literature.

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

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. It is assumed that there are no solid interior walls in the building and the weight of light partitions are included in the slab weight/loads. The details of various loads considered are given in Table 3. These are in addition to the self-weight of the structure.



(a) Plan of the space frame without shear wall (b) Plan of the space frame with shear wall

(c) Sectional elevation at section A-A (d) Sectional elevation at section B-B

Fig. 1 Details of space frame with and without shear wall

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

Table 3 Dead load and live load on the space frame

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

Table 4 Parameters for lateral seismic load calculations on the space frame

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)$^{0.75}$=0.728 (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 Fig. 2 of IS 1893 (Part 1): 2002, for the natural period T_a of 0.728 sec)	1.868

Table 5 Lateral seismic loads at various floor levels

Floor level	Intensity of seismic load (KN)	
	Space frame without shear wall	Space frame with shear wall
6	1181.5	1185.4
5	899.6	906.6
4	610.6	615.4
3	382.4	385.4
2	205.4	206.9
1	80.6	81.2
0	3.9	4.1

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. The calculated values of design lateral seismic loads are shown in Table 5.

4. 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 seismic 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 $\times g$

g=Acceleration due to gravity

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:

$T_a=0.075h^{0.75}$

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 is $V_B=A_hW$

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

$A_h=(Z/2)\times(I/R)\times(S_a/g)$

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 [Fig. 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 stiffnesses (clause 7.7.2.1 of IS 1893 (Part 1): 2002).

4.1 Calculations for the space frame without shear wall

Following loads are considered for the space frame without shear wall:

1. Weight of slabs	=26×18×0.2×25	= 2340 KN
2. Weight of beams projecting below slabs	=0.3×0.3×181.6×25	= 409 KN
3. Weight of plinth beams	=0.3×0.5×178.5×25	= 669 KN
4. Weight of columns from 4th to 6th storey	=0.4×0.4×3.1×20×25	= 248 KN
5. Weight of columns from plinth to 3rd storey	=0.5×0.5×3.1×20×25	= 388 KN
6. Weight of columns from footing to plinth level	=0.5×0.5×2.1×20×25	= 263 KN
7. Weight of floor finish	=25.54×17.54×1	= 448 KN
8. Weight of water proofing on roof	=25.54×17.54×2.5	= 1120 KN
9. Weight of brick wall on outer periphery	=0.23×2.6×82.4×19	= 936 KN
10. Weight of parapet wall on roof	=0.23×1×87.08×19	= 381 KN
11. Live load on floor (50%)	=25.54×17.54×2	= 896 KN
12. Live load on roof (25%)	=25.54×17.54×0.375	= 168 KN

Based on these loads, the seismic weight calculation on various floors is provided in Table 6 and design seismic load intensity is provided in Table 7.

Design seismic base shear, $V_B=A_h\times W$

$A_h=(Z/2)\times(I/R)\times(Sa/g)=(0.36/2)\times(1.5/5)\times1.868=0.1009$

Base shear $V_B=0.1009\times33339=3364$ KN

Table 6 Seismic weight calculation for the space frame without shear wall

Floor level	Lumped seismic weight at the floor level in KN						
	Slab	Floor finish/ water proofing	Beam	Column	Periphery wall	Live load	Total seismic weight (W_i)
6	2340	1120	409	124	849	168	5010
5	2340	448	409	248	936	896	5277
4	2340	448	409	248	936	896	5277
3	2340	448	409	318	936	896	5347
2	2340	448	409	388	936	896	5417
1	2340	448	409	388	936	896	5417
0	0	0	669	457	468	0	1594
Total (W)							33339

Table 7 Vertical distribution of base shear at different floor levels for the space frame without shear wall

Floor level	W_i (KN)	h_i (m)	$W_i \times (h_i)^2$	$Q_i = [W_i \times (h_i)^2 / \Sigma\{W_i \times (h_i)^2\}] \times V_B$ (KN)
6	5010	20.7	2146734.9	1181.5
5	5277	17.6	1634603.5	899.6
4	5277	14.5	1109489.2	610.6
3	5347	11.4	694896.1	382.4
2	5417	8.3	373177.1	205.4
1	5417	5.2	146475.6	80.6
0	1594	2.1	7029.5	3.9
	Total		6112406.1	3364.0

Table 8 Seismic weight calculation for the space frame with shear wall

Floor Level	Lumped seismic weight at the floor level in KN							
	Slab	Floor finish/ water proofing	Beam	Column	Shear Wall	Periphery wall	Live load	Total seismic weight (W_i)
6	2340	1120	384	124	87	786	168	5009
5	2340	448	384	248	174	809	896	5299
4	2340	448	384	248	174	809	896	5299
3	2340	448	384	318	174	809	896	5369
2	2340	448	384	388	174	809	896	5439
1	2340	448	384	388	174	809	896	5439
0	0	0	628	457	203	405	0	1693
			Total (W)					33547

Table 9 Vertical distribution of base shear to different floor levels for the space frame with shear wall

Floor level	W_i (KN)	h_i (m)	$W_i \times (h_i)^2$	$Q_i = [W_i \times (h_i)^2 / \Sigma\{W_i \times (h_i)^2\}] \times V_B$ (KN)
6	5009	20.7	2146306.4	1185.4
5	5299	17.6	1641418.2	906.6
4	5299	14.5	1114114.7	615.4
3	5369	11.4	697755.2	385.4
2	5439	8.3	374692.7	206.9
1	5439	5.2	147070.5	81.2
0	1693	2.1	7466.1	4.1
	Total		6128824.0	3385.0

4.2 Calculations for the space frame with shear wall

Following loads are considered for the space frame with shear wall:

1. Weight of slabs $=26\times18\times0.2\times25$ = 2340 KN
2. Weight of beams projecting below slabs $=0.3\times0.3\times170.6\times25$ = 384 KN
3. Weight of plinth beams $=0.3\times0.5\times167.5\times25$ = 628 KN

4. Weight of columns from 4th to 6th storey	=0.4×0.4×3.1×20×25	= 248 KN
5. Weight of columns from plinth to 3rd storey	=0.5×0.5×3.1×20×25	= 388 KN
6. Weight of columns from footing to plinth level	=0.5×0.5×2.1×20×25	= 263 KN
7. Weight of floor finish	=25.54×17.54×1	= 448 KN
8. Weight of water proofing on roof	=25.54×17.54×2.5	= 1120 KN
9. Weight of shear wall	=5.6×3.1×0.2×2×25	= 174 KN
10. Weight of shear wall below plinth level	=5.5×2.1×0.2×2×25	= 116 KN
11. Weight of brick wall on outer periphery	=0.23×2.6×71.2×19	= 809 KN
12. Weight of parapet wall on roof	=0.23×1×87.08×19	= 381 KN
13. Live load on floor (50%)	=25.54×17.54×2	= 896 KN
14. Live load on roof (25%)	=25.54×17.54×0.375	= 168 KN

Based on these loads, the seismic weight calculation for various floors is provided in Table 8 and design seismic load intensity is provided in Table 9.

Base shear V_B=0.1009×33547=3385 KN

5. Finite element modelling

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 modelled 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 with tension, compression, torsion and bending capabilities.

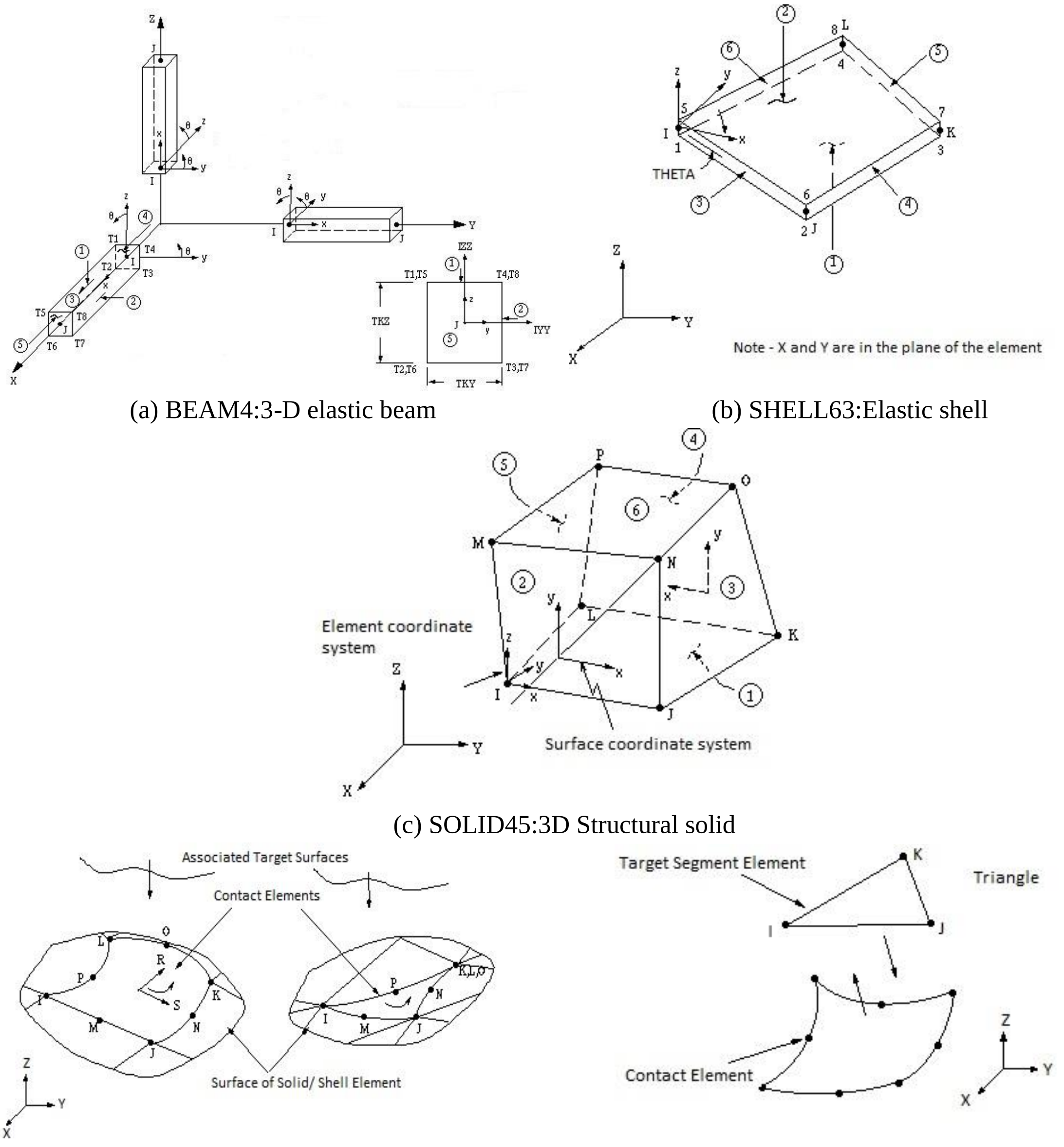
Slabs and shear walls are modelled using four node Shell63 (Elastic Shell) element of ANSYS. The element has both bending as well as membrane capabilities. Both in-plane and normal loads are permitted. The element has six degrees of freedom at each node: translations in the nodal *x*, *y* and *z* directions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

The footings and soil mass are modelled 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.

Surface to surface contact is established between foundation bottom area and soil using ANSYS surface to surface contact elements CONTA174 and TARGE170.

CONTA174 is used to represent contact and sliding between 3-D "target" surfaces (TARGE170) and a deformable surface, defined by this element. This element has three degrees of freedom at each node: translations in the nodal *x*, *y* and *z* directions. This element is located on the surfaces of 3-D solid or shell elements. It has the same geometric characteristics as the solid or shell element face with which it is connected. Contact occurs when the element surface penetrates one of the target segment elements (TARGE170) on a specified target surface. Coulomb and shear stress friction is allowed. The element is defined by eight nodes. It can degenerate to a six node element depending on the shape of the underlying solid or shell elements. If the underlying solid or shell elements do not have mid-side nodes it can be used by dropping the mid-side nodes.

TARGE170 is used to represent various 3-D "target" surfaces for the associated contact elements (CONTA174). The contact elements themselves overlay the solid elements describing the boundary of a deformable body and are potentially in contact with the target surface, defined by TARGE170. This target surface is discretized by a set of target segment elements (TARGE170)



(a) BEAM4:3-D elastic beam (b) SHELL63:Elastic shell

(c) SOLID45:3D Structural solid

(d) CONTA174: Contact surface element (e) TARGE170:Target surface element

Fig. 2 Elements used in the finite element analysis and is paired with its associated contact surface via a shared real constant set. Any translational or rotational displacement can be imposed on the target segment element. Forces and moments can also be imposed on target elements. All these elements are shown in Figs. 2(a)-(e).

To create a contact pair, ANSYS requires assigning the same real constant number to both the target and contact elements. 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 footings. Coefficient of friction between concrete and soil is taken as 0.5.

5.1 Extent of soil mass

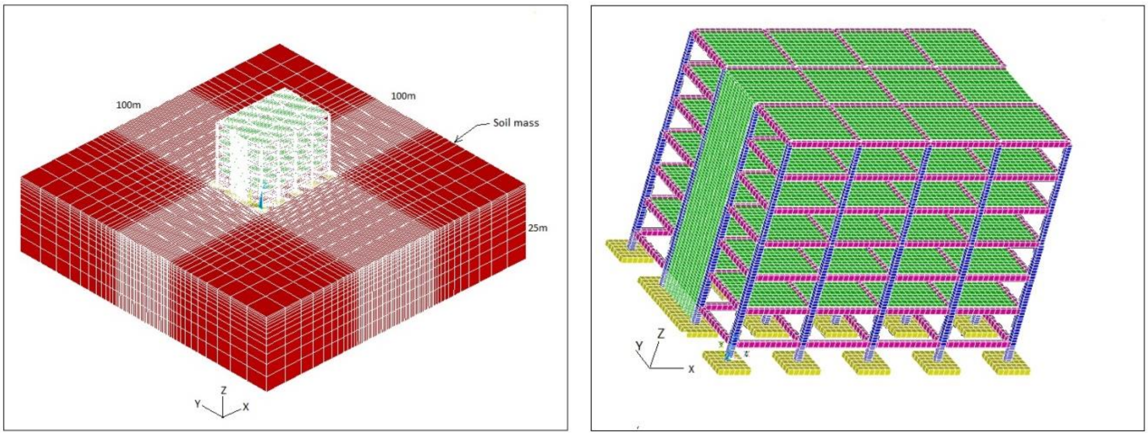
The soil mass is considered to be made up of homogeneous linear elastic isotropic material. Usually bed rock is encountered in most of the sites at varying depth from ground level. It is assumed that bed rock is encountered 25 m below top of soil in the present case. Various horizontal stretches of soil 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 25 m from building line under worst combination of vertical loads (about 30 m in case of worst combination with lateral loads), whereas, stresses in soil reduces to less than 5% of peak value beyond about 15 m from building line (about 17 m 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 100 m×100 m in this study making soil participating volume of 100 m×100 m×25 m which is sufficient to capture the dominant effect of soil-structure-interaction of the problem under consideration.

5.2 Meshing and mesh optimization

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

The optimum mesh refinement is achieved 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 displacements 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 12×13 divisions for slabs. For the columns 12 mesh divisions are found suitable. The foundation mesh size is kept as 500 mm.

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 displacements 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



(a)Space frame-shear wall-soil system (b) Space frame-shear wall system

Fig. 3 Finite element discretization

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. 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 Fig. 3(a)-(b).

5.3 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).

6. 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.

In non-interaction analyses column bottoms are assumed to be fixed and hence there are no settlements of foundations. Under interaction analysis deformations are allowed in soil, which result in consequential settlement in foundations. The following interaction analyses are carried out for the structural system;

Case 1: The linear interaction analysis of the space frame-soil System without shear wall considering the columns supported on isolated footings resting on deformable soil.

Case 2: The linear interaction analysis of the space frame-shear wall-soil system, considering the columns supported on isolated footings resting on deformable soil.

The purpose of this study is to compare the effect of inclusion of shear walls in the space frame in the structurally weaker direction (i.e., Y-direction) from the point of view of seismic forces.

Table 10 Load combinations

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

Hence, the analyses are carried out for the seismic forces assumed to act in the Y-direction only.

For each of the above analyses, the combinations (Table 10) 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.

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.

7. Results and discussion

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

- Settlement of the footings (U_z)
- Differential settlement of the footings

The results are discussed to highlight the effect of shear wall. The results are tabulated for settlement and differential settlements at the centres of the footings.

7.1 Settlement of foundations

Table 11 shows the comparison of settlement (U_z) of footings for space frame-soil system under various load cases. It is found that the maximum settlement for each footing occurs under vertical loads i.e., load case LC1. The least settlement is found in the corner footings while maximum settlement is found in the middle footings resulting in a saucer shaped deflection profile.

The maximum settlement of 127.28 mm is found in the central footings F8 and F13 and minimum settlement of 84.31 mm is found in the corner footings (F1, F5, F16 and F 20). Under all combinations of seismic loads, value of settlement varies from 24.71 mm to 105.12 mm. The minimum settlement of 24.71 mm occurs in corner footings F1 and F5 while maximum settlement of 105.12 mm is found in the footing F13, for +ve seismic loads.

The comparison of settlement (U_z) of footings under various load cases for space frame-shear wall-soil system is provided in Table 12. It is found that in this case also maximum settlement under each footing occurs under load case LC1. The corner footings settle less compared to the middle footings causing a saucer like profile. The maximum settlement of 126.90 mm occurs under central footings F8 and F13 and minimum settlement of 83.82 mm is found in the corner

Table 11 Comparison of settlements (U_z) of footings for space frame-soil system under various load cases

Footing Designation	Coordinates (m)			Vertical settlement of footing for various load cases (mm)						
	X	*Y*	*Z*	LC1*	LC2	LC3	LC4	LC5	LC6	LC7
F1	0.0	0.0	0.0	84.31	54.81	79.72	50.56	81.61	24.71	57.03
F2	6.5	0.0	0.0	104.40	69.65	97.04	62.83	96.98	31.52	66.95
F3	13.0	0.0	0.0	110.32	74.08	102.07	66.45	101.35	33.57	69.76
F4	19.5	0.0	0.0	104.40	69.65	97.04	62.83	96.98	31.52	66.95
F5	26.0	0.0	0.0	84.31	54.81	79.72	50.56	81.61	24.71	57.03
F6	0.0	6.0	0.0	99.67	76.64	82.49	72.97	80.26	43.37	51.02
F7	6.5	6.0	0.0	120.85	93.16	99.86	85.71	94.06	50.84	59.54
F8	13.0	6.0	0.0	127.28	98.18	105.12	89.65	98.31	53.16	62.18
F9	19.5	6.0	0.0	120.85	93.16	99.86	85.71	94.06	50.84	59.54
F10	26.0	6.0	0.0	99.67	76.64	82.49	72.97	80.26	43.37	51.02
F11	0.0	12.0	0.0	99.67	82.49	76.64	80.26	72.97	51.02	43.37
F12	6.5	12.0	0.0	120.85	99.86	93.16	94.06	85.71	59.54	50.84
F13	13.0	12.0	0.0	127.28	105.12	98.18	98.31	89.65	62.18	53.16
F14	19.5	12.0	0.0	120.85	99.86	93.16	94.06	85.71	59.54	50.84
F15	26.0	12.0	0.0	99.67	82.49	76.64	80.26	72.97	51.02	43.37
F16	0.0	18.0	0.0	84.31	79.72	54.81	81.61	50.56	57.03	24.71
F17	6.5	18.0	0.0	104.40	97.04	69.65	96.98	62.83	66.95	31.52
F18	13.0	18.0	0.0	110.32	102.07	74.08	101.35	66.45	69.76	33.57
F19	19.5	18.0	0.0	104.40	97.04	69.65	96.98	62.83	66.95	31.52
F20	26.0	18.0	0.0	84.31	79.72	54.81	81.61	50.56	57.03	24.71

*Maximum values

footings (F1, F5, F16 & F20). Under all combinations of seismic loads value of settlement varies from 24.29 mm to 104.13 mm. The minimum settlement of 24.29 mm occurs in corner footings F1 and F5 while maximum settlement of 104.13 mm is found in the footing F13, for +ve seismic loads.

For both the interaction systems (i.e., space frame with and without shear wall), it is found that seismic load causes uplifting (tension) and compression on the same footings when reversal in the direction of load takes place. It is characterised by lesser and greater settlement values, respectively, for the same footings.

Table 13 shows comparison of settlements (U_z) of the footings between space frame-shear wall-soil system and space frame-soil system under various load cases. It is found that due to presence of shear wall there is insignificant decrease of nearly 2% in the settlements of the footings under interaction effect due to vertical loads.

Under various combinations of seismic loads, the maximum decrease of nearly 22% and maximum increase of nearly 15% occurs in shear wall footing SF1 (under column C6 and C12) and SF2 (under column C10 and C15) when direction of seismic forces is reversed. On the contrary, the maximum increase of nearly 13% and the maximum decrease of nearly 7% is found in the footing F3 and F18 when direction of seismic load is reversed. The insignificant decrease of less than 3% is found in the corner footings and the footings located diagonally adjacent to the corner footings under seismic loads.

The presence of shear wall reduces the effect of uplifting (tension) and compression caused due to seismic loads, in the footings F2, F3, F4, F8, F13, F17, F18 and F19 causing increase or decrease in the settlement values. The effect is nullified by the shear wall footings, providing stability to the structure.

Fig. 4 shows settlement profile of the front row footings (F1, F2, F3, F4 and F5) under various load cases for space frame-shear wall-soil system. Fig. 5 shows settlement profile of the middle row footings parallel to seismic loads (F3, F8, F13 and F18) under various load cases for space frame-shear wall-soil system. It can be seen from these figures that the inner footings settle more than the outer footings, under the influence of vertical loads. Under the influence of seismic loads, the footings farther from the seismic loads settle more and the nearer footings settle less showing the compression or uplift in the footings.

Table 12 Comparison of settlements (U_z) of the footings for space frame-shear wall-soil system under various load cases

Footing Designation	Coordinates (m)			Vertical settlement of footing for various load cases (mm)						
	X	*Y*	*Z*	LC1*	LC2	LC3	LC4	LC5	LC6	LC7
F1	0.0	0.0	0.0	83.82	54.25	79.37	50.02	81.34	24.29	56.87
F2	6.5	0.0	0.0	104.11	71.89	94.16	65.80	93.56	34.63	63.55
F3	13.0	0.0	0.0	110.29	77.52	98.40	70.85	96.87	38.08	65.21
F4	19.5	0.0	0.0	104.11	71.89	94.16	65.80	93.56	34.63	63.55
F5	26.0	0.0	0.0	83.82	54.25	79.37	50.02	81.34	24.29	56.87
SF1 (below Column C6)	0.0	6.0	0.0	97.94	68.29	87.87	63.06	87.51	33.75	58.70
F7	6.5	6.0	0.0	119.27	91.21	99.05	83.86	93.64	49.40	59.53
F8	13.0	6.0	0.0	126.90	98.32	104.13	90.05	97.30	53.70	61.27
F9	19.5	6.0	0.0	119.27	91.21	99.05	83.86	93.64	49.40	59.53
SF2 (below Column C10)	26.0	6.0	0.0	97.94	68.29	87.87	63.06	87.51	33.75	58.70
SF1 (below Column C11)	0.0	12.0	0.0	97.94	87.87	68.29	87.51	63.06	58.70	33.75
F12	6.5	12.0	0.0	119.27	99.05	91.21	93.64	83.86	59.53	49.40
F13	13.0	12.0	0.0	126.90	104.13	98.32	97.30	90.05	61.27	53.70
F14	19.5	12.0	0.0	119.27	99.05	91.21	93.64	83.86	59.53	49.40
SF2 (below Column C15)	26.0	12.0	0.0	97.94	87.87	68.29	87.51	63.06	58.70	33.75
F16	0.0	18.0	0.0	83.82	79.37	54.25	81.34	50.02	56.87	24.29
F17	6.5	18.0	0.0	104.11	94.16	71.89	93.56	65.80	63.55	34.63
F18	13.0	18.0	0.0	110.29	98.40	77.52	96.87	70.85	65.21	38.08
F19	19.5	18.0	0.0	104.11	94.16	71.89	93.56	65.80	63.55	34.63
F20	26.0	18.0	0.0	83.82	79.37	54.25	81.34	50.02	56.87	24.29

*Maximum values

Table 13 Comparison of settlements (U_z) of the footings between space frame-shear wall-soil system and space frame-soil system under various load cases

Footing Designation	% change in vertical settlement of footing for various load cases (mm)						
	LC1	LC2	LC3	LC4	LC5	LC6	LC7
F1	-0.58	-1.03	-0.44	-1.06	-0.34	-1.72	-0.29
F2	-0.28	3.22	-2.96	4.72	-3.53	9.86	-5.08
F3	-0.03	4.65	-3.59	6.62	-4.42	13.44	-6.51
F4	-0.28	3.22	-2.96	4.72	-3.53	9.86	-5.08
F5	-0.58	-1.03	-0.44	-1.06	-0.34	-1.72	-0.29
F6 (SF1: below column C6)	-1.74	-10.89	6.53	-13.57	9.03	-22.18	15.06
F7	-1.31	-2.10	-0.81	-2.16	-0.45	-2.84	-0.02
F8	-0.30	0.14	-0.94	0.45	-1.02	1.02	-1.45
F9	-1.31	-2.10	-0.81	-2.16	-0.45	-2.84	-0.02
F10 (SF2: below column C10)	-1.74	-10.89	6.53	-13.57	9.03	-22.18	15.06
F11 (SF1:below column C11)	-1.74	6.53	-10.89	9.03	-13.57	15.06	-22.18
F12	-1.31	-0.81	-2.10	-0.45	-2.16	-0.02	-2.84
F13	-0.30	-0.94	0.14	-1.02	0.45	-1.45	1.02
F14	-1.31	-0.81	-2.10	-0.45	-2.16	-0.02	-2.84
F15 (SF2: below column C15)	-1.74	6.53	-10.89	9.03	-13.57	15.06	-22.18
F16	-0.58	-0.44	-1.03	-0.34	-1.06	-0.29	-1.72
F17	-0.28	-2.96	3.22	-3.53	4.72	-5.08	9.86
F18	-0.03	-3.59	4.65	-4.42	6.62	-6.51	13.44
F19	-0.28	-2.96	3.22	-3.53	4.72	-5.08	9.86
F20	-0.58	-0.44	-1.03	-0.34	-1.06	-0.29	-1.72

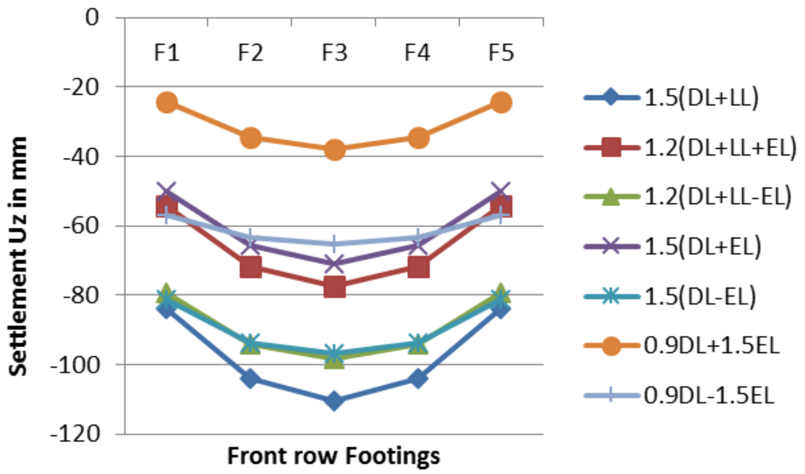


Fig. 4 Settlement profile of the footings (F1, F2, F3, F4 and F5) under various load cases for space frame-shear wall-soil system

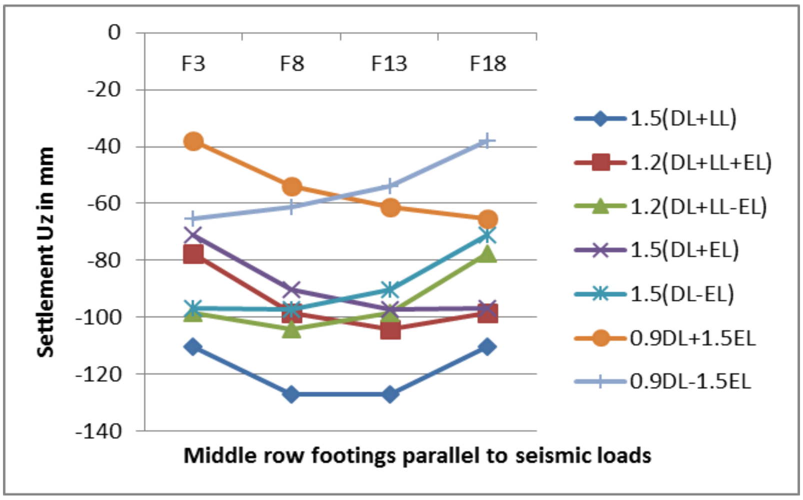
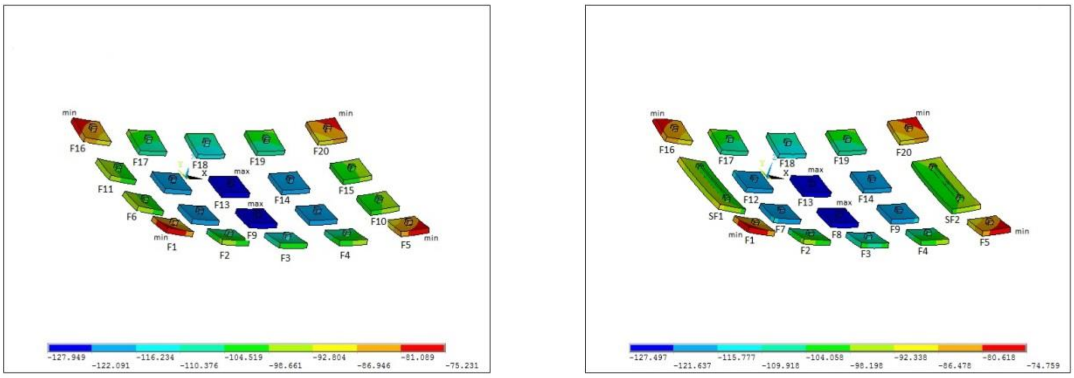
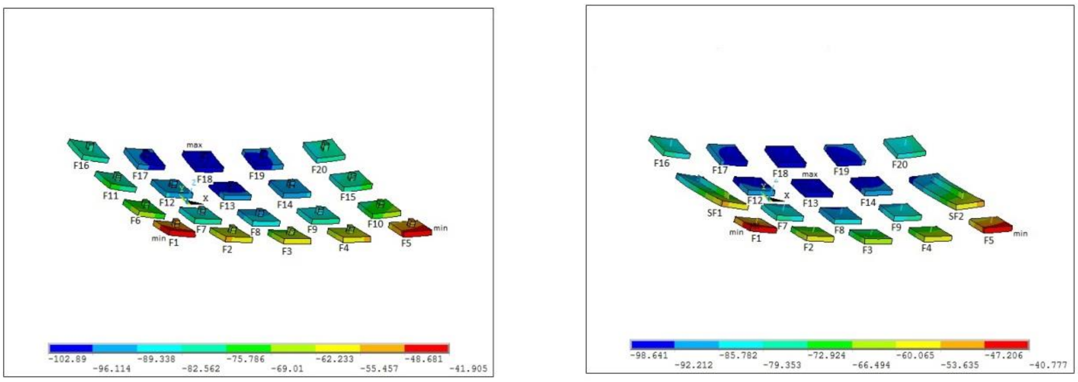


Fig. 5 Settlement profile of the middle footings (F3, F8, F13 and F18) under various load cases for space frame-shear wall-soil system



(a) Footings of space frame-soil system (b) Footings of space frame-shear wall-soil system

Fig. 6 Settlement profiles (magnified) of footings under vertical load case LC1



(a) Footings of space frame-soil system (b) Footings of space frame-shear wall-soil system

Fig. 7 Settlement profiles (magnified) of footings under seismic load case LC4

Figs. 6(a) and 6(b) shows settlement profile of footings of ‘space frame-soil system’ and ‘space frame-shear wall-soil system’ respectively for load case LC1 under interaction effect. The settlement profile resembles like shape of a saucer with the minimum settlement in corner footings and the maximum settlements in the central footings.

Figs. 7(a) and 7(b) shows settlement profile of footings of ‘space frame-soil system’ and ‘space frame-shear wall-soil system’ respectively for seismic load case LC4 under interaction effect. The seismic load is applied in Y-direction from front. The settlement profiles show that the minimum settlement is found in front row corner footings (F1 and F5). Maximum settlement is found in the extreme row middle footing (F18) in case of ‘space frame-soil system’ and in 3rd row middle footing (F13) in case of ‘space frame-shear wall-soil system’ under interaction effect.

7.2 Differential settlement of footings

Table 14 shows the comparison of differential settlement of footings under various load cases for space frame-soil system. For each load case, the footing, in which the settlement is the least, is taken as benchmark and differential settlements are calculated with respect to this benchmark. The

Table 14 Comparison of differential settlements of the footings for space frame-soil system under various load cases

Footing Desig-nation	Coordinates (m)			Differential settlement of footings (mm)						
	X	*Y*	*Z*	LC1	LC2	LC3	LC4	LC5	LC6	LC7
F1	0.0	0.0	0.0	0.00*	0.00*	24.91	0.00*	31.05	0.00*	32.32#
F2	6.5	0.0	0.0	20.09	14.84	42.23	12.27	46.42#	6.81	42.24
F3	13.0	0.0	0.0	26.01	19.27	47.26	15.89	50.79#	8.86	45.05
F4	19.5	0.0	0.0	20.09	14.84	42.23	12.27	46.42#	6.81	42.24
F5	26.0	0.0	0.0	0.00	0.00	24.91	0.00	31.05	0.00	32.32#
F6	0.0	6.0	0.0	15.36	21.83	27.68	22.41	29.70#	18.66	26.31
F7	6.5	6.0	0.0	36.54	38.35	45.05#	35.15	43.50	26.13	34.83
F8	13.0	6.0	0.0	42.97	43.37	50.31#	39.09	47.75	28.45	37.47
F9	19.5	6.0	0.0	36.54	38.35	45.05#	35.15	43.50	26.13	34.83
F10	26.0	6.0	0.0	15.36	21.83	27.68	22.41	29.70#	18.66	26.31
F11	0.0	12.0	0.0	15.36	27.68	21.83	29.70#	22.41	26.31	18.66
F12	6.5	12.0	0.0	36.54	45.05#	38.35	43.50	35.15	34.83	26.13
F13	13.0	12.0	0.0	42.97	50.31#	43.37	47.75	39.09	37.47	28.45
F14	19.5	12.0	0.0	36.54	45.05#	38.35	43.50	35.15	34.83	26.13
F15	26.0	12.0	0.0	15.36	27.68	21.83	29.70#	22.41	26.31	18.66
F16	0.0	18.0	0.0	0.00	24.91	0.00	31.05	0.00	32.32#	0.00
F17	6.5	18.0	0.0	20.09	42.23	14.84	46.42#	12.27	42.24	6.81
F18	13.0	18.0	0.0	26.01	47.26	19.27	50.79#	15.89	45.05	8.86
F19	19.5	18.0	0.0	20.09	42.23	14.84	46.42#	12.27	42.24	6.81
F20	26.0	18.0	0.0	0.00	24.91	0.00*	31.05	0.00*	32.32#	0.00*

*Benchmark for calculation of differential settlements # Maximum value for the footing maximum total settlements are found in all the footings under vertical loads (LC1), whereas, maximum differential settlements are found in the footings under various seismic load combinations. It is interesting to note that each combination of seismic load results in maximum differential settlement in at least one of the footings. Thus, it justifies considering all seismic load combinations. The maximum differential settlement of 50.79 mm occurs under footings F3 and F18 for load cases LC5 and LC4 respectively.

The comparison of differential settlement of footings of space frame-shear wall-soil system under various load cases is provided in Table 15. For each load case, the benchmark for calculation of differential settlement is selected below the footing where the settlement is the least. In this case also the maximum total settlements are found in all the footings under vertical loads (LC1), whereas, maximum differential settlements are found in the footings under various seismic load combinations and each combination of seismic load results in maximum differential

Table 15 Comparison of differential settlements of footings for space frame-shear wall-soil system under various load cases

Footing Designation	Coordinates (m)			Differential settlements (mm)						
	X	*Y*	*Z*	LC1	LC2	LC3	LC4	LC5	LC6	LC7
F1	0.0	0.0	0.0	0.00*	0.00*	25.12	0.00*	31.32	0.00*	32.58#
F2	6.5	0.0	0.0	20.29	17.64	39.91	15.78	43.54#	10.34	39.26
F3	13.0	0.0	0.0	26.47	23.27	44.15	20.83	46.85#	13.79	40.92
F4	19.5	0.0	0.0	20.29	17.64	39.91	15.78	43.54#	10.34	39.26
F5	26.0	0.0	0.0	0.00	0.00	25.12	0.00	31.32	0.00	32.58#
SF1 (below column C6)	0.0	6.0	0.0	14.12	14.04	33.62	13.04	37.49#	9.46	34.41
F7	6.5	6.0	0.0	35.45	36.96	44.80#	33.84	43.62	25.11	35.24
F8	13.0	6.0	0.0	43.08	44.07	49.88#	40.03	47.28	29.41	36.98
F9	19.5	6.0	0.0	35.45	36.96	44.80#	33.84	43.62	25.11	35.24
SF2 (below column C10)	26.0	6.0	0.0	14.12	14.04	33.62	13.04	37.49#	9.46	34.41
SF1 (below Column C11)	0.0	12.0	0.0	14.12	33.62	14.04	37.49#	13.04	34.41	9.46
F12	6.5	12.0	0.0	35.45	44.80#	36.96	43.62	33.84	35.24	25.11
F13	13.0	12.0	0.0	43.08	49.88#	44.07	47.28	40.03	36.98	29.41
F14	19.5	12.0	0.0	35.45	44.80#	36.96	43.62	33.84	35.24	25.11
SF2 (below Column C15)	26.0	12.0	0.0	14.12	33.62	14.04	37.49#	13.04	34.41	9.46
F16	0.0	18.0	0.0	0.00	25.12	0.00	31.32	0.00	32.58#	0.00
F17	6.5	18.0	0.0	20.29	39.91	17.64	43.54#	15.78	39.26	10.34
F18	13.0	18.0	0.0	26.47	44.15	23.27	46.85#	20.83	40.92	13.79
F19	19.5	18.0	0.0	20.29	39.91	17.64	43.54#	15.78	39.26	10.34
F20	26.0	18.0	0.0	0.00	25.12	0.00*	31.32	0.00*	32.58#	0.00*

*Benchmark for calculation of differential settlements; # Maximum value for the footing settlement in at least one of the footings. The maximum differential settlement of 49.88 mm is found in footings F8 and F13 under load cases LC3 and LC2 respectively.

Table 16 shows comparison of differential settlements of the footings between space frame-shear wall-soil system and space frame-soil system under various load cases. The insignificant change in the differential settlements is found under load case LC1 due to presence of shear wall. The maximum decrease of nearly 8% is found under shear wall footings SF1 and SF2, whereas, maximum increase of nearly 2% is found in footings F3 and F18. Under various combinations of seismic loads, the presence of shear wall causes significant decrease/increase in differential settlement in various footings. The maximum decrease of nearly 50% and maximum increase of nearly 31% occurs in shear wall footing SF1 (below column C6 and C11) and SF2 (below column C10 and C15) when direction of seismic forces is reversed. On the contrary, the maximum increase of nearly 56% and maximum decrease of nearly 9% is found in the footing F3 and F18 when direction of seismic forces is reversed. Insignificant difference in absolute maximum differential settlement is found due to presence of shear wall.

Table 16 Comparison of differential settlements of the footings between space frame-shear wall-soil system and space frame-soil system under various load cases

Footing Designation	% change in differential settlement						
	LC1	LC2	LC3	LC4	LC5	LC6	LC7
F1	0.00	0.00	0.86	0.00	0.86	0.00	0.80
F2	1.00	18.88	-5.48	28.58	-6.21	51.79	-7.06
F3	1.77	20.78	-6.58	31.10	-7.75	55.66	-9.15
F4	1.00	18.88	-5.48	28.58	-6.21	51.79	-7.06
F5	0.00	0.00	0.86	0.00	0.86	0.00	0.80
F6 (SF1: below column C6)	-8.08	-35.68	21.47	-41.79	26.22	-49.30	30.81
F7	-2.98	-3.63	-0.55	-3.73	0.27	-3.92	1.18
F8	0.26	1.60	-0.85	2.40	-0.97	3.39	-1.29
F9	-2.98	-3.63	-0.55	-3.73	0.27	-3.92	1.18
F10 (SF2: below column C10)	-8.08	-35.68	21.47	-41.79	26.22	-49.30	30.81
F11 (SF1: below column C11)	-8.08	21.47	-35.68	26.22	-41.79	30.81	-49.30
F12	-2.98	-0.55	-3.63	0.27	-3.73	1.18	-3.92
F13	0.26	-0.85	1.60	-0.97	2.40	-1.29	3.39
F14	-2.98	-0.55	-3.63	0.27	-3.73	1.18	-3.92
F15 (SF2: below column C15)	-8.08	21.47	-35.68	26.22	-41.79	30.81	-49.30
F16	0.00	0.86	0.00	0.86	0.00	0.80	0.00
F17	1.00	-5.48	18.88	-6.21	28.58	-7.06	51.79
F18	1.77	-6.58	20.78	-7.75	31.10	-9.15	55.66
F19	1.00	-5.48	18.88	-6.21	28.58	-7.06	51.79
F20	0.00	0.86	0.00	0.86	0.00	0.80	0.00

8. Conclusions

The important research findings are summarized below:

• The interaction effect causes differential settlement of footings. For frame without shear wall as well as for frame with shear wall, the maximum total settlement is found under vertical loads. Settlement in inner footings is more than that in outer footings, whereas, the corner footings settle the least. The deflection profile obtained resembles like a saucer.

• The seismic force causes compression/uplift in the footings and reversal in the nature of forces is found when direction of seismic force is reversed. Presence of shear wall reduces this effect, thus providing more stability to the structure.

• The interaction analysis of space frame-shear wall-soil system suggests that the presence of shear wall causes insignificant decrease in the settlements (less than 2%) of the footings under vertical loads.

The insignificant decrease of less than 3% is found in the settlement due to the presence of shear walls, for the corner footings and the footings located diagonally adjacent to the corner footings under seismic loads. The maximum decrease of nearly 22% and the maximum increase of nearly 15% is found in shear wall footings when direction of seismic forces is reversed. On the contrary, the maximum increase of nearly 13% and the maximum decrease of nearly 7% is found in the footing F3 and F18 respectively when direction of seismic load is reversed.

• The maximum total settlements are found in all the footings under vertical loads (LC1), whereas, maximum differential settlements are found in the footings under various seismic load combinations. It is interesting to note that each combination of seismic loads results in maximum differential settlement in at least one of the footings. Thus, it justifies considering all seismic load combinations.

• The presence of shear wall causes significant decrease/increase in the differential settlement in many footings under seismic loads. The absolute maximum differential settlement is found in the central footings. The insignificant difference in absolute maximum differential settlement is found due to presence of shear wall.

• The proposed methodology can be effectively used to evaluate the settlements and forces in the foundations and superstructure for multi-story space frame-shear wall-soil system for better and efficient building design.

References

Agrawal, R. and Hora, M.S. (2010), "Effect of differential settlements on nonlinear interaction behaviour of plane frame-soil system", *J. Eng. Appl. Sci.*, ARPN, **5**(7), 75-87.

ANSYS Inc. (2009), *ANSYS Structural Analysis Guide*, ANSYS Inc., Southpointe, 275 Technology Drive, Canonsburg, PA 15317.

Arlekar, J.N., Jain, S. and Murthy, C.V.R. (1997), "Seismic response of R.C. frame buildings with soft first storeys", *Proceedings of the CBRI Golden Jubilee Year Conference on Natural Hazards in Urban Habitat,* New Delhi, India.

Bishop, A.W. and Henkel, D.J. (1962), *The Measurement of Soil Properties in the Tri-axial Test,* Edward Arnold Ltd., London, UK.

Code IS 456 (2000), *Indian Standard, plain and reinforced concrete-code of practice (Fourth Revision)*, Bureau of Indian Standards, New Delhi, India.

Code IS 875 (Part 2) (1987), *Indian Standard code of practice for design loads (other than earthquake) for* *buildings and structures, part 2, imposed loads (Second Revision)*, Bureau of Indian Standards, New Delhi, India.

Code IS 1893 (Part 1) (2002), *Criteria for earthquake resistant design of structures (Part 1: General Provisions And Buildings) (Fifth Revision)*, Bureau of Indian Standards, New Delhi, India.

Edgers, L., Sanayei, M. and Alonge, J.L. (2005), "Modeling the effects of soil-structure interaction on a tall building bearing on a mat foundation", *Civ. Eng. Practice*, ASCE, 51-68.

Garg, V. and Hora, M.S. (2012), "Interaction effect of space frame-strap footing-soil system on forces in superstructure", *ARPN J. Eng. Appl. Sci.*, **7**(11), 1402-1415.

Hayashi, Y. and Takahashi, I. (2004), "Soil-structure interaction effects on building response in recent earthquakes", *Proceedings of the Third UJNR Workshop on Soil-Structure Interaction*, Monto Park, California, USA.

Hora, M. (2006), "Nonlinear interaction analysis of infilled building frame-soil system", *J. Struct. Eng*., **33**(4), 309-318.

Mandal, A., Moitra, D. and Dutta, S.C. (1998), "Soil-structure interaction on building frame: a small scale model study", *Int. J. Struct.*, **18**(2), 92-108.

Natarajan, K. and Vidivelli, B. (2009), "Effect of column spacing on the behaviour of frame-raft and soil systems", *J. Appl. Sci*., **9**(20), 3629-3640.

Noorzaei, J., Viladkar, M.N. and Godbole, P.N. (1995), "Elasto-plastic analysis for soil-structure interaction in framed structures", *Comput. Struct*., **55**(5), 797-807.

Pankaj, A. and Manish, S. (2006), *Earthquake Resistant Design of Structures*, PHI Learning Pvt. Ltd, Delhi, India.

Renzi, S., Madiai, C. and Vannucchi, G. (2013), "A simplified empirical method for assessing seismic soil-structure interaction effects on ordinary shear-type buildings", *Soil Dyn. Earthq. Eng*., **55**(2013), 100-107.

Shah, H.J. and Jain, S.K. (2008), *Final Report :: A - Earthquake Codes, IITK-GSDMA Project on Building Codes: Design example of a six storey building*, Document No. :: IITK-GSDMA-EQ26-V3.0, National Information Centre of Earthquake Engineering, IIT Kanpur, India.

Shakib, H. and Atefatdoost, G.R. (2011), "Effect of soil-structure interaction on torsional response of asymmetrical wall type systems", *Procedia Eng.*, Elsevier, **14**, 1729-1736.

SP-22 (1982), *Explanatory Handbook on Codes for Earthquake Engineering (IS: 1893-1975 and IS: 4326-1976)*, Bureau of Indian Standards, New Delhi, India.

Stavridis, L.T. (2002), "Simplified analysis of layered soil-structure interaction", *J. Struct. Eng. Div*., ASCE, **128**(2), 224-230.

Thangaraj, D. and Ilamparuthi, K. (2010), "Parametric study on the performance of raft foundation with interaction of frame", *Electron J. Geotech. Eng*., **15**, 861-878.

Wang, C.M., Chow, Y.K. and How, Y.C. (2001), "Analysis of rectangular thick rafts on an elastic half-space", *Comput. Geotech*, **28**(3), 161-184.

Yahyai, M., Mirtaheri, M., Mahoutian, M. and Daryan, A. (2008), "Soil structure interaction between two adjacent buildings under earthquake load", *Am. J. Eng. Appl. Sci*., **1**(2), 121-125.

CC