ANALYSIS OF SPACE FRAME-STRAP FOOTING-SOIL SYSTEM TO INVESTIGATE COLUMN FORCES UNDER SEISMIC LOADING

Vivek Garg[1] and M. S. Hora[2]
[1]Department of Civil Engineering, Maulana Azad National Institute of Technology, Bhopal, India
[2]Department of Applied Mechanics, Maulana Azad National Institute of Technology, Bhopal, India
E-Mail: vivek_garg5@yahoo.co.in

ABSTRACT

Previous studies emphasis to consider the effect of soil-structure interaction in the design process of low-rise buildings resting on shallow foundations for safe seismic design. Also, there may be a situation where column(s) of a building are located near adjoining property line. In this situation, an eccentric footing is generally provided. This causes angular rotation in such individual footings due to moment developed by eccentric loading. The strap beams may be provided under such circumstances in order to control the rotation within permissible values. In the present work, the seismic interaction analysis of a three-bay three-storey RCC space frame-footing-strap beam-soil system is carried out to investigate the interaction behavior using the finite element method. The frame, foundation and supporting soil mass are considered to be linear elastic and to act as a single compatible structural unit for more realistic analysis. The seismic analyses of space frame-isolated footing-soil and space frame-strap footing-soil systems are carried out to evaluate the forces in the columns. The emphasis is made on the necessity of interaction analysis using strap beams.

Keywords: soil-structure interaction, seismic loading, strap footing, space frame, isolated footing, finite element analysis.

1. INTRODUCTION

In the conventional method of design interaction between soil, foundation and structure is ignored to simplify the structural analysis. A structural designer usually neglects the influence of the settlements of supporting soil media on the structural behavior of the super-structure. Previous studies have revealed that interaction effects are quite significant under seismic excitation, particularly for the structures resting on highly compressible soils. The flexibility of soil mass causes the differential settlement and rotation of footings under the application of load. These displacements along with stiffness of the frame cause redistribution of forces/stresses in the frame members. A more rational solution of a soil-structure interaction problem can be achieved by appropriate analysis. Strap footing is one of the types of combined footing which may be provided when one or more columns exist on the common property line. It comprises of two or more footings of individual columns, connected by a beam called strap beam. The strap beam must be sufficiently rigid to control the rotation of eccentric footing. This type of footing is found more suitable when there are heavy loads on adjoining footings and no overlapping exists between their areas.

Several studies have been made on the effect of soil-structure interaction problems from time to time in attempt to obtain more realistic analysis. Investigators have quantified the effect of interaction behaviour and established that there is redistribution of forces in the frame members.

Aljanabi *et al*. (1990) studied the interaction behaviour of plane frames with an elastic foundation of the Winkler's type, having normal and shear moduli of sub-grade reactions. An exact stiffness matrix for a beam element on an elastic foundation having only a normal modulus of sub-grade reaction was modified to include the shear modulus of sub-grade reaction of the foundation as well as the axial force in the beam. The results indicated that bending moments might be considerably affected according to the type of frame and loading.

Noorzaei *et al*. (1994) evaluated the soil-structure interaction effect in framed structures with proper physical modeling of the structure foundation and the soil mass. Hyperbolic stress strain model has been used to consider the soil non-linearity. The interactive behaviour of a five storey two bay plane frame has been studied in detail and the results are compared with those obtained from a conventional and a linear interactive analysis.

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 obtained from the computational scheme were validated from experimental study. A small scale two-storey two-bay frame made of perspex was analyzed. The frame was placed on a kaolin bed with adequate arrangement of drainage. The proposed computational scheme could be used to predict increase in axial force and moments in structural members due to the effect of soil-structure interaction.

Roy and Dutta (2001) studied the effect of the differential settlement on design force quantities for frame members of building frames with isolated footings. They presented various representative case studies for frames resting on sandy soil and clayey soil by idealizing the soil medium below the footing as linear and nonlinear respectively.

Bhattacharya *et al*. (2006) examined the effect of soil flexibility on base shear and uncoupled torsional-to-lateral natural period ratio. The results of the study conclude that the effect of soil-structure interaction may cause considerable increase in seismic base shear of low-rise building frames, particularly those with isolated footings.

Hora (2006) investigated the computational methodology adopted for nonlinear soil-structure interaction analysis of infilled frame-foundation-soil system. The unbounded domain of the soil mass has been discretized with coupled finite-infinite elements to achieve computational economy. The nonlinear behaviour of the soil mass was modelled using hyperbolic model. The incremental-iterative nonlinear solution algorithm was adopted for carrying out the nonlinear elastic interaction analysis. The interaction analysis showed that the nonlinearity of soil mass plays an important role in redistribution of forces in the superstructure.

Nataralan and Vidivelli (2009) studied the influence of column spacing on the behavior of a space frame-raft-soil system under static load. The analyses were carried out for linear and nonlinear conditions, in which soil was treated as a homogeneous and isotropic continuum. Settlement was greater in the nonlinear analysis and the settlements were higher for higher column spacing. Contact pressure distribution was more uniform in the nonlinear case and its magnitude was less than that of linear soil, particularly in the end panels of the raft.

Chore *et al*. (2010) examined the effect of soil-structure interaction on a space frame resting on a pile group embedded in the cohesive soil (clay) with flexible cap. They evaluated the effects of pile spacing, pile configuration, and pile diameter of the pile group on the response of superstructure. The effect of soil structure interaction is found to be quite significant.

Guzman (2010) studied the effect of contact between strap beam and bearing stratum. Results indicate that when a strap footing is used as part of a foundation system, a detail that allow for pressure to be relieved from the strap beam is necessary on construction documents. Without it, a considerable unforeseen load path could be created that may result in the failure of strap beam followed by overstress of the soil under the eccentric footing.

Thangaraj and Ilamparuthi (2010) compared interaction and non-interaction analyses for the space frame-raft foundation-soil system using ANSYS finite element code. The soil was treated as an isotropic, homogenous and elastic half space medium. A detailed parametric study was conducted by varying the soil and raft stiffness for a constant building stiffness. The interaction analysis showed less total and differential settlements than the non-interaction analysis and relative stiffness of soil plays major role in the performance of the raft.

Xiujuan *et al*. (2010) studied the stress and settlement distribution of a tank foundation by using the finite element analysis software (ANSYS) and comparing the result with the result by formula of criterion. The results indicate that finite element method can simulate the settlement of a tank foundation reliably.

Agrawal and Hora (2012) studied the interaction effect of frame, isolated footing and soil media under seismic loading. Various analyses were performed on frame-footing-soil system by considering plane frame, infill frame, homogeneous soil and layered soil mass. The frame was considered to act in linear elastic manner while the soil mass to act as nonlinear elastic manner. They concluded that the shear forces and bending moments in superstructure get significantly altered due to differential settlements of the soil mass.

2. PROBLEM FOR INVESTIGATION

In present problem a 3 bay x 3 bay three-storey RCC space frame founded on strap footing and resting on homogeneous soil mass is analyzed under seismic loading. The problem under consideration is symmetric about one axis in terms of geometry, material properties and loading. Hence, to make the model computationally economical only half of the model is considered for analysis. To investigate the interaction behavior, the interaction analyses are carried out for the following three cases:

Case-1: The conventional non-interaction analysis (NIA) considering the columns fixed at their bases.
Case-2: The linear interaction analysis of space frame-isolated footing-soil system (LIA-ISO) considering the columns supported on individual column footings and resting on soil media.
Case-3: The linear interaction analysis of space frame-strap footing-soil system (LIA-STR) considering the individual footings of Case-2 connected by strap beams.

The frame, foundation and supporting soil mass are considered to be linear elastic and to act as a single compatible structural unit for more realistic analysis. The seismic loads have been calculated by static method as per Bureau of Indian standards code IS 1893 (Part 1): 2002. Data/parameters for the analysis of problem are given in Table-1.

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Table-1. Data/parameters for the analysis of problem.

Description	**Value/type**
Number of storeys	3
Number of bays in X direction	3
Number of bays in Y direction	3
Storey height	3.5 m
Column height below plinth beam	2.0 m
Bay width in X direction	6.0 m
Bay width in Y direction	6.0 m
Size of beam	0.3 m × 0.5 m
Size of column	0.4 m × 0.4 m
Thickness of all slabs	0.15 m
Isolated footing size	2 m x 2 m x 0.5 m
Size of strap beam	0.4 m x 1.1 m
Elastic modulus of concrete	2.5×10^7 kN/m^2
Poisson's ratio of concrete	0.15
Extent of soil mass	200 m x 100 m x 90 m
Modulus of elasticity of soil	1.47×10^4 kN/m^2
Poisson's ratio of soil	0.35
Seismic zone	V
Seismic intensity	Very severe
Zone factor	0.36
Importance factor	1
Building frame system	Ordinary RC moment-resisting frame
Response reduction factor	3
Spectral acceleration coefficient	2.5

Uniformly distributed loads are applied on floor and plinth beams which include self weight and imposed load on building components. The loads applied on peripheral plinth beams are 19 kN/m and 13 kN/m for other plinth beams. The loads applied on first floor and second floor beams are 35 kN/m for peripheral beams and 45 kN/m for other beams. The loads applied on third floor beams are 22 kN/m and 29 kN/m for peripheral and other beams respectively. The estimated seismic loads at different floor levels are given in Table-2.

Table-2. Seismic loads at different floor levels.

Structural component	**Seismic Load** (kN)
First floor	
(i) Outside	32.0
(ii) Inside	47.0
Second floor	
(i) Outside	127.0
(ii) Inside	186.0
Third floor	
(i) Outside	230.0
(ii) Inside	315.0

The superstructure of proposed model is depicted in Figure-1.

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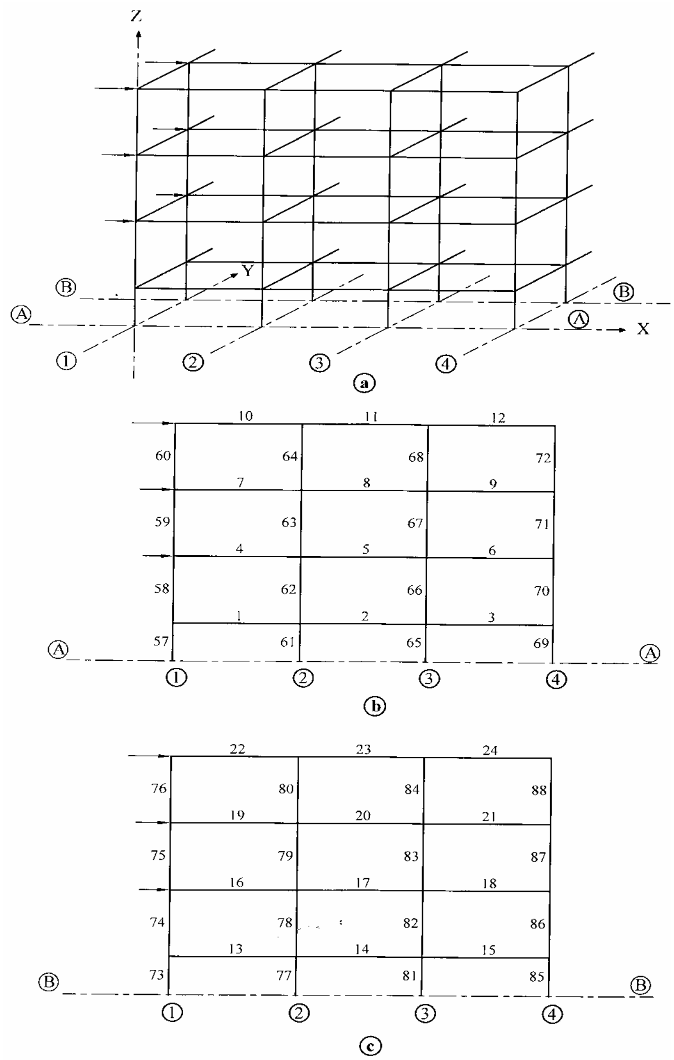

Figure-1 (a, b, c). Symmetric half model of the frame.

The symmetric half model of foundation plan is depicted in Figure-2.

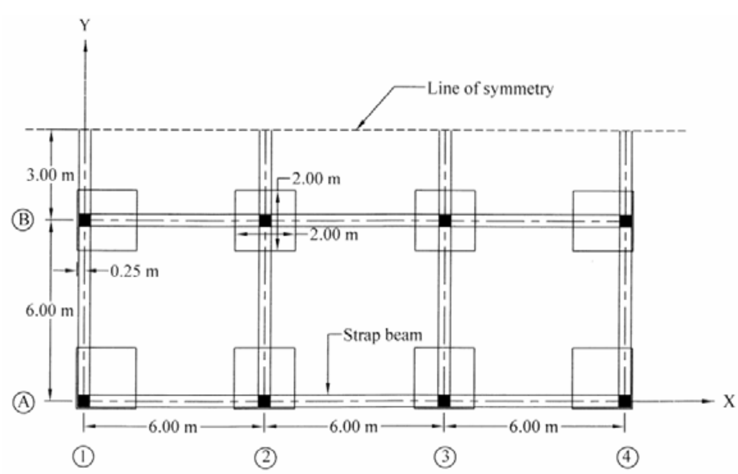

Figure-2. Symmetric half model of foundation plan.

3. FINITE ELEMENT MODELING

The non-interaction and linear interaction analyses of the problem is carried out using ANSYS software (Version 12). The floor beams, plinth beams, strap beams and the columns are discretized with two node beam bending element (BEAM4) with six degrees of freedom per node (Ux, Uy, Uz, Rx, Ry, and Rz). It is assumed that the joints between various members are perfectly rigid. The roof slab is discretized with four node plate bending element (SHELL181) having six degrees of freedom at each node (Ux, Uy, Uz, Rx, Ry and Rz). The footing is discretized with eight node plate bending element (SHELL281) having six degrees of freedom at each node (Ux, Uy, Uz, Rx, Ry and Rz).

The semi-infinite extent of the soil model is considered as 200 m x 100 m x 90 m which is achieved by trial and error performing linear analysis. The extent of soil mass is decided where vertical and horizontal stresses are found to be negligible due to loading on the superstructure. The vertical displacements in soil mass are restrained at the bottom boundary whereas horizontal displacements are restrained at vertical boundaries.

The soil mass is idealized as isotropic, homogeneous, half-space model and discretized with ten-node tetrahedral element (SOLID92) having three degrees of freedom at each node (Ux, Uy and Uz). SOLID 92 have a quadratic displacement behavior and are well suited to model irregular meshes. The interface characteristics between the raft and soil are represented by TARGE170 and CONTA174 elements. The finite element discretization of the problem is shown in Figure-3.

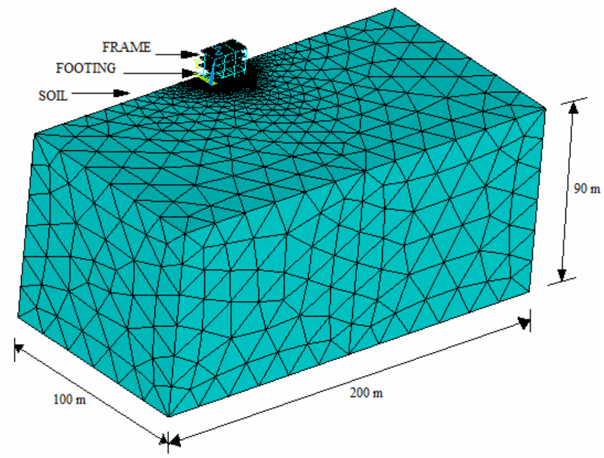

Figure-3. Finite element discretization of frame-footing-soil system (symmetric half model).

The element size for beams, columns, slabs and footings are taken as 0.25 m. The soil mass is discretized with finer meshes in close vicinity of footing where stresses are of higher order.

4. INTERACTION ANALYSIS

The axial force and bending moments in columns are evaluated due to non-interaction analysis and linear interaction analyses and discussed subsequently.

4.1. Axial force Fz in the columns

The axial force in the columns of frame-footing-soil system due to various analyses is depicted in Table-3 and Table-4.

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Table-3. Comparison of axial force Fz (kN) in columns for various analyses (y = 0 m).

Member No.	Co-ordinates			Case-1 NIA	Case-2 LIA-ISO	Case-3 LIA-STR	Comparison of interaction analyses		
	X	Y	Z	1	2	3	2/1	3/1	3/2
57	0.0	0.0	0.0	-360.59	-561.45	-493.33	1.56	1.37	0.88
57	0.0	0.0	2.0	360.59	561.45	493.33	1.56	1.37	0.88
58	0.0	0.0	2.0	-344.79	-508.86	-441.34	1.48	1.28	0.87
58	0.0	0.0	5.5	344.79	508.86	441.34	1.48	1.28	0.87
59	0.0	0.0	5.5	-230.19	-337.75	-292.34	1.47	1.27	0.87
59	0.0	0.0	9.0	230.19	337.75	292.34	1.47	1.27	0.87
60	0.0	0.0	9.0	-93.44	-138.53	-119.32	1.48	1.28	0.86
60	0.0	0.0	12.5	93.44	138.53	119.32	1.48	1.28	0.86
61	6.0	0.0	0.0	-1080.60	-1007.50	-1051.80	0.93	0.97	1.04
61	6.0	0.0	2.0	1080.60	1007.50	1051.80	0.93	0.97	1.04
62	6.0	0.0	2.0	-938.17	-875.71	-918.78	0.93	0.98	1.05
62	6.0	0.0	5.5	938.17	875.71	918.78	0.93	0.98	1.05
63	6.0	0.0	5.5	-578.85	-539.28	-565.81	0.93	0.98	1.05
63	6.0	0.0	9.0	578.85	539.28	565.81	0.93	0.98	1.05
64	6.0	0.0	9.0	-224.19	-205.29	-217.77	0.92	0.97	1.06
64	6.0	0.0	12.5	224.19	205.29	217.77	0.92	0.97	1.06
65	12.0	0.0	0.0	-1001.40	-1117.70	-1074.00	1.12	1.07	0.96
65	12.0	0.0	2.0	1001.40	1117.70	1074.00	1.12	1.07	0.96
66	12.0	0.0	2.0	-874.55	-973.29	-929.80	1.11	1.06	0.96
66	12.0	0.0	5.5	874.55	973.29	929.80	1.11	1.06	0.96
67	12.0	0.0	5.5	-546.57	-610.02	-582.60	1.12	1.07	0.96
67	12.0	0.0	9.0	546.57	610.02	582.60	1.12	1.07	0.96
68	12.0	0.0	9.0	-212.23	-241.17	-228.46	1.14	1.08	0.95
68	12.0	0.0	12.5	212.23	241.17	228.46	1.14	1.08	0.95
69	18.0	0.0	0.0	-848.93	-1025.70	-937.64	1.21	1.10	0.91
69	18.0	0.0	2.0	848.93	1025.70	937.64	1.21	1.10	0.91
70	18.0	0.0	2.0	-711.11	-820.65	-773.57	1.15	1.09	0.94
70	18.0	0.0	5.5	711.11	820.65	773.57	1.15	1.09	0.94
71	18.0	0.0	5.5	-425.32	-495.73	-465.11	1.17	1.09	0.94
71	18.0	0.0	9.0	425.32	495.73	465.11	1.17	1.09	0.94
72	18.0	0.0	9.0	-155.46	-182.99	-171.15	1.18	1.10	0.94
72	18.0	0.0	12.5	155.46	182.99	171.15	1.18	1.10	0.94

Note: Negative sign indicates that axial force acts in downward direction

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Table-4. Comparison of axial force Fz (kN) in columns for various analyses (y = 6 m).

Member No.	Co-ordinates			Case-1 NIA	Case-2 LIA-ISO	Case-3 LIA-STR	Comparison of interaction analyses		
	X	Y	Z	1	2	3	2/1	3/1	3/2
73	0.0	6.0	0.0	-776.70	-807.89	-811.41	1.04	1.04	1.00
73	0.0	6.0	2.0	776.70	807.89	811.41	1.04	1.04	1.00
74	0.0	6.0	2.0	-703.70	-747.09	-732.49	1.06	1.04	0.98
74	0.0	6.0	5.5	703.70	747.09	732.49	1.06	1.04	0.98
75	0.0	6.0	5.5	-454.58	-484.55	-473.18	1.07	1.04	0.98
75	0.0	6.0	9.0	454.58	484.55	473.18	1.07	1.04	0.98
76	0.0	6.0	9.0	-184.19	-197.77	-192.54	1.07	1.05	0.97
76	0.0	6.0	12.5	184.19	197.77	192.54	1.07	1.05	0.97
77	6.0	6.0	0.0	-1734.80	-1398.30	-1520.70	0.81	0.88	1.09
77	6.0	6.0	2.0	1734.80	1398.30	1520.70	0.81	0.88	1.09
78	6.0	6.0	2.0	-1497.00	-1232.30	-1336.10	0.82	0.89	1.08
78	6.0	6.0	5.5	1497.00	1232.30	1336.10	0.82	0.89	1.08
79	6.0	6.0	5.5	-924.86	-753.63	-821.09	0.81	0.89	1.09
79	6.0	6.0	9.0	924.86	753.63	821.09	0.81	0.89	1.09
80	6.0	6.0	9.0	-364.08	-290.56	-319.76	0.80	0.88	1.10
80	6.0	6.0	12.5	364.08	290.56	319.76	0.80	0.88	1.10
81	12.0	6.0	0.0	-1641.40	-1511.60	-1544.90	0.92	0.94	1.02
81	12.0	6.0	2.0	1641.40	1511.60	1544.90	0.92	0.94	1.02
82	12.0	6.0	2.0	-1419.20	-1335.70	-1348.30	0.94	0.95	1.01
82	12.0	6.0	5.5	1419.20	1335.70	1348.30	0.94	0.95	1.01
83	12.0	6.0	5.5	-885.93	-830.19	-841.12	0.94	0.95	1.01
83	12.0	6.0	9.0	885.93	830.19	841.12	0.94	0.95	1.01
84	12.0	6.0	9.0	-350.61	-330.93	-333.49	0.94	0.95	1.01
84	12.0	6.0	12.5	350.61	330.93	333.49	0.94	0.95	1.01
85	18.0	6.0	0.0	-1303.60	-1317.80	-1314.20	1.01	1.01	1.00
85	18.0	6.0	2.0	1303.60	1317.80	1314.20	1.01	1.01	1.00
86	18.0	6.0	2.0	-1107.40	-1102.30	-1115.60	1.00	1.01	1.01
86	18.0	6.0	5.5	1107.40	1102.30	1115.60	1.00	1.01	1.01
87	18.0	6.0	5.5	-669.70	-664.85	-674.75	0.99	1.01	1.01
87	18.0	6.0	9.0	669.70	664.85	674.75	0.99	1.01	1.01
88	18.0	6.0	9.0	-251.79	-248.76	-253.52	0.99	1.01	1.02
88	18.0	6.0	12.5	251.79	248.76	253.52	0.99	1.01	1.02

Note: Negative sign indicates that axial force acts in downward direction

The comparison of axial force due to NIA and LIA reveals that the interaction effect causes redistribution of the forces in column members. The inner columns are relieved of the forces and corresponding increase is found in the corner columns due to interaction effects. This redistribution of axial forces is more significant in case of LIA-ISO in comparison to LIA-STR.

LIA-ISO provides variation of 0.80 to 1.56 times in the axial force compared to NIA. The maximum decrease in ratio of nearly 0.80 times is found in the inner column of third floor (member 80) whereas the maximum

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increase in ratio of nearly 1.56 times is found in the corner column below plinth level (member 57).

The variation of 0.88 to 1.37 times is found in the axial force due to LIA-STR compared to NIA. The maximum decrease in ratio of nearly 0.88 times is found in the inner column below plinth level (member 77) whereas the maximum increase in ratio of nearly 1.37 times is found in the corner column below plinth level (member 57).

LIA-STR provides variation of 0.86 to 1.10 times in the axial force compared to LIA-ISO. The maximum decrease in ratio of nearly 0.86 times is found in the corner columns (members 57 to 60) whereas the maximum increase in ratio of nearly 1.10 times is found in the inner columns (members 77 to 80).

4.2. Bending moment Mx in the columns

The bending moment Mx in the columns of frame-footing-soil system due to various analyses is depicted in Table-5 and Table-6.

Table-5. Comparison of bending moment Mx (kN-m) in columns for various analyses (y = 0 m).

Member No.	Co-ordinates			Case-1 NIA	Case-2 LIA-ISO	Case-3 LIA-STR	Comparison of interaction analyses		
	X	Y	Z	1	2	3	2/1	3/1	3/2
57	0.0	0.0	0.0	7.43	-178.80	44.77	-24.08	6.03	-0.25
57	0.0	0.0	2.0	14.04	58.85	43.16	4.19	3.07	0.73
58	0.0	0.0	2.0	21.64	51.24	42.52	2.37	1.96	0.83
58	0.0	0.0	5.5	32.04	67.45	56.56	2.11	1.77	0.84
59	0.0	0.0	5.5	41.54	84.58	66.38	2.04	1.60	0.78
59	0.0	0.0	9.0	40.22	79.88	63.96	1.99	1.59	0.80
60	0.0	0.0	9.0	41.17	87.40	69.62	2.12	1.69	0.80
60	0.0	0.0	12.5	43.71	100.44	78.43	2.30	1.79	0.78
61	6.0	0.0	0.0	10.78	-331.68	49.12	-30.77	4.56	-0.15
61	6.0	0.0	2.0	20.45	86.15	53.72	4.21	2.63	0.62
62	6.0	0.0	2.0	30.91	53.42	55.67	1.73	1.80	1.04
62	6.0	0.0	5.5	45.45	77.51	73.75	1.71	1.62	0.95
63	6.0	0.0	5.5	57.93	104.02	86.15	1.80	1.49	0.83
63	6.0	0.0	9.0	55.75	97.39	82.81	1.75	1.49	0.85
64	6.0	0.0	9.0	56.05	103.24	88.23	1.84	1.57	0.85
64	6.0	0.0	12.5	58.84	116.54	97.72	1.98	1.66	0.84
65	12.0	0.0	0.0	10.80	-370.69	38.58	-34.31	3.57	-0.10
65	12.0	0.0	2.0	20.63	84.57	50.48	4.10	2.45	0.60
66	12.0	0.0	2.0	30.29	53.48	55.88	1.77	1.84	1.04
66	12.0	0.0	5.5	43.90	78.48	72.85	1.79	1.66	0.93
67	12.0	0.0	5.5	55.79	106.80	84.93	1.91	1.52	0.80
67	12.0	0.0	9.0	53.99	99.88	81.96	1.85	1.52	0.82
68	12.0	0.0	9.0	54.79	106.41	87.98	1.94	1.61	0.83
68	12.0	0.0	12.5	57.70	120.63	97.67	2.09	1.69	0.81
69	18.0	0.0	0.0	7.10	-334.67	6.18	-47.16	0.87	-0.02
69	18.0	0.0	2.0	12.75	84.57	30.72	6.63	2.41	0.36
70	18.0	0.0	2.0	24.18	36.11	45.55	1.49	1.88	1.26
70	18.0	0.0	5.5	38.81	64.66	60.40	1.67	1.56	0.93
71	18.0	0.0	5.5	50.82	93.81	71.22	1.85	1.40	0.76
71	18.0	0.0	9.0	48.09	85.85	67.90	1.79	1.41	0.79
72	18.0	0.0	9.0	47.22	89.41	71.30	1.89	1.51	0.80
72	18.0	0.0	12.5	49.29	101.71	78.68	2.06	1.60	0.77

Note: Negative sign indicates that moment acts in anticlockwise direction about X-axis

Table-6. Comparison of bending moment Mx (kN-m) in columns for various analyses (y = 6 m).

Member No.	Co-ordinates			Case-1 NIA	Case-2 LIA-ISO	Case-3 LIA-STR	Comparison of interaction analyses		
	X	Y	Z	1	2	3	2/1	3/1	3/2
73	0.0	6.0	0.0	0.26	14.76	72.60	56.91	279.89	4.92
73	0.0	6.0	2.0	0.29	44.25	38.98	151.75	133.68	0.88
74	0.0	6.0	2.0	-0.85	24.89	11.47	-29.17	-13.44	0.46
74	0.0	6.0	5.5	-1.70	28.14	16.37	-16.52	-9.61	0.58
75	0.0	6.0	5.5	-1.62	32.68	19.78	-20.17	-12.20	0.61
75	0.0	6.0	9.0	-0.80	32.30	19.60	-40.47	-24.55	0.61
76	0.0	6.0	9.0	-0.57	36.44	22.02	-63.99	-38.67	0.60
76	0.0	6.0	12.5	-1.10	41.33	24.90	-37.67	-22.69	0.60
77	6.0	6.0	0.0	0.38	22.59	88.00	59.27	230.88	3.90
77	6.0	6.0	2.0	0.45	59.95	46.56	133.43	103.63	0.78
78	6.0	6.0	2.0	-1.02	22.96	13.42	-22.46	-13.12	0.58
78	6.0	6.0	5.5	-2.09	29.73	20.10	-14.21	-9.61	0.68
79	6.0	6.0	5.5	-1.91	38.71	25.14	-20.29	-13.17	0.65
79	6.0	6.0	9.0	-0.70	38.27	25.08	-54.62	-35.80	0.66
80	6.0	6.0	9.0	0.06	42.69	28.13	750.54	494.54	0.66
80	6.0	6.0	12.5	-0.31	47.88	31.49	-155.13	-102.04	0.66
81	12.0	6.0	0.0	0.31	23.80	89.77	76.10	287.02	3.77
81	12.0	6.0	2.0	0.35	61.94	46.31	176.01	131.59	0.75
82	12.0	6.0	2.0	-1.01	22.15	12.05	-21.95	-11.94	0.54
82	12.0	6.0	5.5	-2.04	29.05	18.95	-14.27	-9.31	0.65
83	12.0	6.0	5.5	-1.86	38.57	24.26	-20.70	-13.02	0.63
83	12.0	6.0	9.0	-0.70	38.17	24.15	-54.77	-34.65	0.63
84	12.0	6.0	9.0	0.02	42.50	26.98	2571.21	1632.26	0.63
84	12.0	6.0	12.5	-0.36	47.52	30.15	-132.08	-83.82	0.63
85	18.0	6.0	0.0	0.64	16.19	79.54	25.20	123.79	4.91
85	18.0	6.0	2.0	0.88	47.86	38.96	54.53	44.38	0.81
86	18.0	6.0	2.0	-1.05	22.79	6.50	-21.69	-6.18	0.29
86	18.0	6.0	5.5	-2.47	24.85	11.89	-10.08	-4.82	0.48
87	18.0	6.0	5.5	-2.70	29.70	16.23	-11.01	-6.01	0.55
87	18.0	6.0	9.0	-1.56	29.88	16.17	-19.14	-10.36	0.54
88	18.0	6.0	9.0	-1.00	34.28	18.37	-34.30	-18.38	0.54
88	18.0	6.0	12.5	-1.52	38.83	20.83	-25.46	-13.66	0.54

Note: Negative sign indicates that moment acts in anticlockwise direction about X-axis

The comparison of bending moments due to NIA and LIA reveals that the interaction effect causes redistribution of the moments in column members. The significantly higher values of bending moments are found due to LIA. A very high increase in the bending moment of outer columns (member 57, 61, 65 and 69) at the column footing junction is found in LIA-ISO as well as reversal in the sign takes place because of the rotation of eccentrically loaded isolated footings. However, LIA-STR suggests that the use of strap beam controls this moment effectively.

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LIA-STR provides variation of -0.25 to 4.92 times in the bending moment compared to LIA-ISO. The maximum decrease in ratio of nearly 0.25 times with reversal in sign is found in the corner column below plinth level (member 57) whereas the maximum increase in ratio of nearly 4.92 times is found in the side column below plinth level (member 73).

4.3. Bending moment My in the columns

The bending moment My in the columns of frame-footing-soil system due to various analyses is depicted in Table-7 and Table-8.

Table-7. Comparison of bending moment My (kN-m) in columns for various analyses (y = 0 m).

Member No.	Co-ordinates			Case-1 NIA	Case-2 LIA-ISO	Case-3 LIA-STR	Comparison of interaction analyses		
	X	Y	Z	1	2	3	2/1	3/1	3/2
57	0.0	0.0	0.0	154.00	299.54	93.26	1.95	0.61	0.31
57	0.0	0.0	2.0	4.39	48.81	-28.59	11.12	-6.51	-0.59
58	0.0	0.0	2.0	150.23	82.98	127.29	0.55	0.85	1.53
58	0.0	0.0	5.5	116.49	76.42	89.01	0.66	0.76	1.16
59	0.0	0.0	5.5	80.98	27.40	51.23	0.34	0.63	1.87
59	0.0	0.0	9.0	105.91	57.61	78.08	0.54	0.74	1.36
60	0.0	0.0	9.0	21.54	-36.63	-11.59	-1.70	-0.54	0.32
60	0.0	0.0	12.5	57.69	-14.52	16.56	-0.25	0.29	-1.14
61	6.0	0.0	0.0	195.38	98.55	150.31	0.50	0.77	1.53
61	6.0	0.0	2.0	86.77	137.86	68.68	1.59	0.79	0.50
62	6.0	0.0	2.0	246.91	241.23	237.58	0.98	0.96	0.98
62	6.0	0.0	5.5	239.93	242.54	227.89	1.01	0.95	0.94
63	6.0	0.0	5.5	217.99	192.30	202.91	0.88	0.93	1.06
63	6.0	0.0	9.0	230.95	209.07	216.54	0.91	0.94	1.04
64	6.0	0.0	9.0	130.20	107.27	114.79	0.82	0.88	1.07
64	6.0	0.0	12.5	162.28	136.36	144.78	0.84	0.89	1.06
65	12.0	0.0	0.0	196.29	129.11	302.79	0.66	1.54	2.35
65	12.0	0.0	2.0	87.98	229.25	146.93	2.61	1.67	0.64
66	12.0	0.0	2.0	244.87	289.56	255.64	1.18	1.04	0.88
66	12.0	0.0	5.5	235.65	296.00	256.29	1.26	1.09	0.87
67	12.0	0.0	5.5	213.19	254.60	238.67	1.19	1.12	0.94
67	12.0	0.0	9.0	228.15	271.22	252.09	1.19	1.10	0.93
68	12.0	0.0	9.0	128.11	177.94	154.91	1.39	1.21	0.87
68	12.0	0.0	12.5	159.09	216.49	190.23	1.36	1.20	0.88
69	18.0	0.0	0.0	168.60	-212.67	145.39	-1.26	0.86	-0.68
69	18.0	0.0	2.0	31.38	191.68	45.94	6.11	1.46	0.24
70	18.0	0.0	2.0	195.72	170.95	215.19	0.87	1.10	1.26
70	18.0	0.0	5.5	187.41	209.24	206.28	1.12	1.10	0.99
71	18.0	0.0	5.5	172.29	205.15	188.04	1.19	1.09	0.92
71	18.0	0.0	9.0	193.48	223.03	209.43	1.15	1.08	0.94
72	18.0	0.0	9.0	109.02	139.81	128.71	1.28	1.18	0.92
72	18.0	0.0	12.5	149.55	187.16	172.89	1.25	1.16	0.92

Note: Negative sign indicates that moment acts in anticlockwise direction about Y-axis

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Table-8. Comparison of bending moment My (kN-m) in columns for various analyses (y = 6 m).

Member No.	Co-ordinates			Case-1 NIA	Case-2 LIA-ISO	Case-3 LIA-STR	Comparison of interaction analyses		
	X	Y	Z	1	2	3	2/1	3/1	3/2
73	0.0	6.0	0.0	154.19	388.18	80.01	2.52	0.52	0.21
73	0.0	6.0	2.0	-1.14	41.24	-41.99	-36.06	36.72	-1.02
74	0.0	6.0	2.0	144.18	76.27	117.58	0.53	0.82	1.54
74	0.0	6.0	5.5	116.00	74.99	82.80	0.65	0.71	1.10
75	0.0	6.0	5.5	85.10	25.18	50.11	0.30	0.59	1.99
75	0.0	6.0	9.0	107.64	53.83	74.67	0.50	0.69	1.39
76	0.0	6.0	9.0	19.08	-44.35	-19.81	-2.32	-1.04	0.45
76	0.0	6.0	12.5	53.58	-24.24	6.02	-0.45	0.11	-0.25
77	6.0	6.0	0.0	199.73	95.91	141.10	0.48	0.71	1.47
77	6.0	6.0	2.0	89.64	133.65	63.16	1.49	0.70	0.47
78	6.0	6.0	2.0	249.50	246.54	237.31	0.99	0.95	0.96
78	6.0	6.0	5.5	249.44	252.75	232.84	1.01	0.93	0.92
79	6.0	6.0	5.5	234.12	203.17	214.93	0.87	0.92	1.06
79	6.0	6.0	9.0	245.04	218.27	226.52	0.89	0.92	1.04
80	6.0	6.0	9.0	140.00	112.34	120.24	0.80	0.86	1.07
80	6.0	6.0	12.5	169.82	138.96	147.68	0.82	0.87	1.06
81	12.0	6.0	0.0	200.43	139.55	319.21	0.70	1.59	2.29
81	12.0	6.0	2.0	90.47	254.60	156.34	2.81	1.73	0.61
82	12.0	6.0	2.0	247.38	292.45	262.91	1.18	1.06	0.90
82	12.0	6.0	5.5	245.24	312.07	272.06	1.27	1.11	0.87
83	12.0	6.0	5.5	230.02	280.53	264.24	1.22	1.15	0.94
83	12.0	6.0	9.0	243.32	294.83	275.68	1.21	1.13	0.94
84	12.0	6.0	9.0	139.78	197.75	175.32	1.41	1.25	0.89
84	12.0	6.0	12.5	168.83	234.60	209.31	1.39	1.24	0.89
85	18.0	6.0	0.0	175.83	-312.77	168.72	-1.78	0.96	-0.54
85	18.0	6.0	2.0	40.08	211.52	62.75	5.28	1.57	0.30
86	18.0	6.0	2.0	205.16	183.82	229.10	0.90	1.12	1.25
86	18.0	6.0	5.5	205.39	231.69	229.72	1.13	1.12	0.99
87	18.0	6.0	5.5	198.06	235.78	220.75	1.19	1.11	0.94
87	18.0	6.0	9.0	216.77	251.02	239.13	1.16	1.10	0.95
88	18.0	6.0	9.0	129.45	165.47	156.26	1.28	1.21	0.94
88	18.0	6.0	12.5	169.49	213.08	201.19	1.26	1.19	0.94

Note: Negative sign indicates that moment acts in anticlockwise direction about Y-axis

The comparison of bending moments due to NIA and LIA reveals that the interaction effect causes redistribution of the moments in column members. Also, reversal in the sign takes place in some of the column members. A very high increase in the bending moment of outer columns (member 57, 69, 73 and 85) at the column footing junction is found in LIA-ISO. However, LIA-STR suggests that the use of strap beam controls this moment effectively.

LIA-ISO provides variation of -36.06 to 11.12 times in the bending moment compared to NIA. The maximum decrease in ratio of nearly 36.06 times with reversal of sign is found in the side column below plinth level (member 73) whereas the maximum increase in ratio of nearly 11.12 times is found in the corner column below plinth level (member 57).

The variation of -6.51 to 36.72 times is found in the bending moment due to LIA-STR compared to NIA. The maximum decrease in ratio of nearly 6.51 times with reversal of sign is found in the corner column below plinth level (member 57) whereas the maximum increase in ratio of nearly 36.72 times is found in the side column below plinth level (member 73).

LIA-STR provides variation of -1.14 to 2.35 times in the bending moment compared to LIA-ISO. The maximum decrease in ratio of nearly 1.14 times with reversal in sign is found in the corner column of third floor (member 60) whereas the maximum increase in ratio of nearly 2.35 times is found in the side column below plinth level (member 65).

5. CONCLUSIONS

The significant findings from the interaction analysis presented in this paper are summarized as follows:

a) The interaction effect causes significant redistribution of the forces and moments in column members.
b) The interaction effect causes more uniform distribution of axial forces in the columns. The heavily loaded inner columns are relieved of the axial forces and corresponding increase is found in the lighter corner columns.
c) The bending moments of very high magnitude are induced at column bases resting on eccentric footing of space frame-isolated footing-soil interaction system. However, use of strap beams control these moments very effectively.
d) The use of strap beam causes decrease in the bending moments in most of the columns.

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