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Evaluation of the influence of interface elements for structure – isolated footing – soil interaction analysis

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Abstract. In this study, two extreme cases of compatibility of the horizontal displacements between the foundation and soil are considered, for which the pressure and settlements of the isolated footings and member end actions in structural elements are obtained using the three dimensional models and numerical experiments. The first case considered is complete slip between foundation and soil, termed as the *un-coupled analysis*. In the second case of analysis, termed as the *coupled analysis*, complete welding is assumed of joints between the foundation and soil elements. The model and the corresponding computer program developed simulate these two extreme states of compatibility giving insight into the variation of horizontal displacements and horizontal stresses and their intricacies, for evaluation of the influence of using the interface elements in soil-structure interaction analysis of three dimensional multiscale structures supported by isolated footings.

Keywords: isolated footing, interface element, link element, mat foundation, settlement, soil-structure interaction.

1. Introduction

Conventional design of buildings often implies the assumption of fixity at the base of foundation neglecting the flexibility of the foundation, compressibility of the soil mass and consequently the effect of foundation settlement on redistribution of bending moments and shear force on the building. The term soil structure interaction (SSI) has been largely used for mechanics of interaction between the soil and structure or the part of the structure underneath. From the term SSI itself, it is easy to understand that this is an issue that cannot be ignored in geotechnical and structural engineering. Previously, numerous studies have been made on the effect of SSI under static loadings. Initially, these studies have been conducted with simplified models. However, it was demonstrated that the force quantities of the structure should be revised to reflect the effect of SSI. In the studies by Grasshoff (1957), Sommer (1965), Lee, Harrison (1970) and Seetharamulu, Kumar (1973), the combined footing has been modeled as a beam on the Winkler medium. Brown (1975)

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used the elastic half space approach for the physical representation of subsoil. Jain, Trikha, Jain (1977) proposed an efficient iterative procedure for analyzing space frames and found significant reduction in the differential settlements and additional moments if the effects of SSI are included. Haddadin (1971) proposed the substructure approach for considering the relative stiffness between the soil and the foundation and that between the foundation and superstructure. The same approach was adopted by Lee and Brown (1972). It was found that the stiffness of the structure has a profound influence on the distribution of the loads and moments to the raft.

A limited number of studies have been conducted on the soil–structure interaction effect with the buildings modeled as three dimensional space frames. King and Chandrashekharan (1974a,b), King (1977), King and Yao (1983) and Sankaran and Srinivasaraghavan (1979, 1983), Roy and Dutta (2001) and Kumar, Walia and Saran (2005) were among the researchers who have made use of the finite element method to consider the super structure – raft / combined footing soil as a single model of analysis. The studies conducted by Viladkar, Godbole and Noorzaei (1991, 1993, 1994) indicated that a two-dimensional plane frame analysis might substantially overestimate or underestimate the actual interaction effect for a space frame.

From the aforementioned studies, it is obvious that the consideration of the SSI effect significantly alters the design force quantities of the building. Sekhar Chandra Dutta, Rana Roy (2002), found that these studies may be quantitatively approximate, but clearly point out the need to study the soil–structure interaction in order to estimate the realistic force quantities in the structural members, accounting for their three dimensional behavior. Zolghadr, Izzuddin and Zdravkovic investigated the modelling of coupled soil-structure interaction problems by domain decomposition techniques. Chore, Ingle and Sawant (2009) presented interaction analysis for building frames resting on pile foundation based on a more rational approach and realistic assumption. Subsequently, Chore, Ingle and Sawant (2010) studied the effect of SSI on a single storey, two bay space frames resting on a pile group.

The mechanical properties of the soil-structure interface have attracted great attention and many experiments have been conducted in order to gain insights into the complex phenomena occurring in the interface. Analysis and design of any structure founded on or in the soil warrants a coupling of some level between the soil and structure. In the SSI analysis of a structure, studies have been carried out by introducing the link/interface elements between two substructures of different materials. Basically two kinds of interface constitutive equations are used to model these mechanisms in numerical simulations based on the following assumptions (Boulon and Nova 1990):

1. The soil interface is considered as a thin continuum layer.
2. The continuum equations are degenerated in such a way that interface zone is replaced by a bi-dimensional constitutive relation (Boulon 1989).

However, the literature reveals that the usage of such elements is limited to only very simple cases like single footings, single piles, groups of piles with pile cap, and plane frames sitting on combined footings. Liu, Song, Ling (2006) quoted that the serviceability of soil-structure systems, such as shallow foundations, tunnels, and retaining walls, depends largely on the behavior of the soil-structure interfaces. RajashekharSwamy, Krishnamoorthy, Prabhakara and Bhavikatti. (2011) conducted an interaction analysis on three dimensional frames resting on mat foundation to study the usage of interface elements between the mat foundation and soil. They concluded that the interface element between mat foundation and soil has no effect on the member end actions of the building, but can affect the displacements, differential displacements and stresses in soils.

The above review of literature reveals a number of works on the interactive analysis of either isolated footings or combined footings or group of piles and a case of multiscale structure on raft foundation. To the knowledge of the authors, the case of a SSI of any multi scale structure with the implementation of an interface element between the soil and isolated footings in a multiscale structure has not been thoroughly studied. Therefore it is imperative to study the effectiveness of using the interface elements in a multiscale structure.

In this study, two extreme cases of compatibility of the horizontal displacements between the foundation and soil are considered, for which the pressure and settlements of the isolated footings and member end actions in structural elements are obtained using the three dimensional models and numerical experiments. The first case refers to the complete slip/frictionless interface between the foundation and soil, termed as the un-coupled analysis. The second case of analysis, termed as the coupled analysis, is based on the assumption of complete welding/bonding of joints between the foundation and soil elements. It is natural to expect that the magnitudes of the stress and displacement resultants of the soil structure system incorporating the interface elements shall lie between the results obtained from the analyses of the above two extreme cases. Therefore, the studies of the two extreme cases will provide some guidelines for evaluating the influence of using the interface elements between the foundation and soil in the SSI of structures subjected to static loads.

2. Problem definition

The structure under consideration is shown in Fig. 1(a) and the geometrical details are given in Table 1. As the soil is semi infinite, the size of the soil mass considered is $153 \times 20 \times 95$ m as shown in Fig. 1(a). This size is arrived after ascertaining negligibly small stresses at the boundaries. For this three dimensional structure, the SSI analysis is carried out for both the uncoupled and coupled cases of interface between the foundation and soil.

Table 1 Details of the structure modeled

Sl no	Structure	Component	Details
1	Frame	No. of storey	5
		No. of bays	5×3
		Storey height	3.5 m
		Bay width	5 m
		Beam size	0.3×0.6 m
		Column size	0.4×0.4 m
		Footing size	$2.0 \times 2.0 \times 0.4$ m
2	soil	Soil mass	$153.0 \times 95.0 \times 20.0$ m
3	Elastic modulus of soil		1.33×10^7 N/m^2
4	Poisson's ratio of soil		0.45
5	Bulk modulus of concrete		6.1×10^6 N/m^2
6	Elastic modulus of concrete		1.4×10^{10} N/m^2

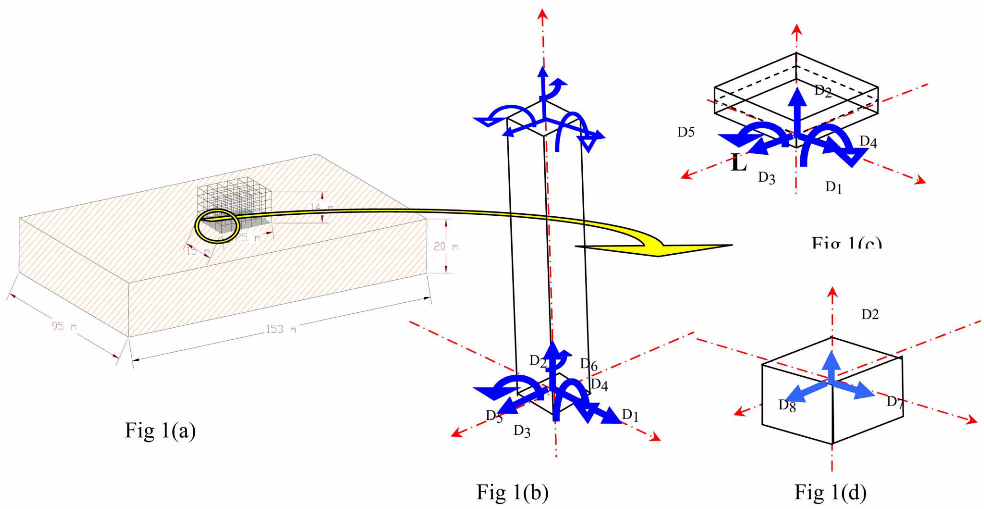

Fig. 1 Details of the model and elements used

3. Numerical formulation

Since the numerical methods are more versatile than analytical methods for dealing problems with irregularities in geometry and materials, the finite element method is adopted to study the complex behavior of the SSI system.

3.1 Finite element formulation

Finite element formulation in the SSI analysis of the frame - isolated footings -soil system is shown in Fig. 2, the various components of the system are modeled as follows:

1. Soil mass is modeled using as eight-nodded brick elements with three translational degrees of freedom per node viz., D_7, D_2, and D_8. Refer to Fig. 1(d).
2. Mat Foundation is modeled using plate elements with five degrees of freedom per node i.e. three translational degrees of freedom (i.e. D_1, D_2, and D_3) and two rotational degrees of freedom (i.e. D_4 and D_5). Refer to Fig. 1 (c).
3. Columns and beams are modeled as one dimensional beam elements with six degrees of freedom per node (three translational and three rotational degrees of freedom). Refer to Fig. 1(b).

The soil is modeled with $33 \times 21 \times 7$ layers in the longitudinal, transverse and vertical directions respectively resulting in a total of 4851 brick elements. Each footing is modeled by four plate elements. The number of plate elements used is 96. The number of beam elements in the longitudinal direction (X-direction) is 80, in transverse (Z-direction) it is 72 and in vertical (y-direction) is 96. Member numbers are shown in Fig. 3.

3.2 Details of analysis

The linear elastic stiffness matrices for all types of elements are generated and included in a

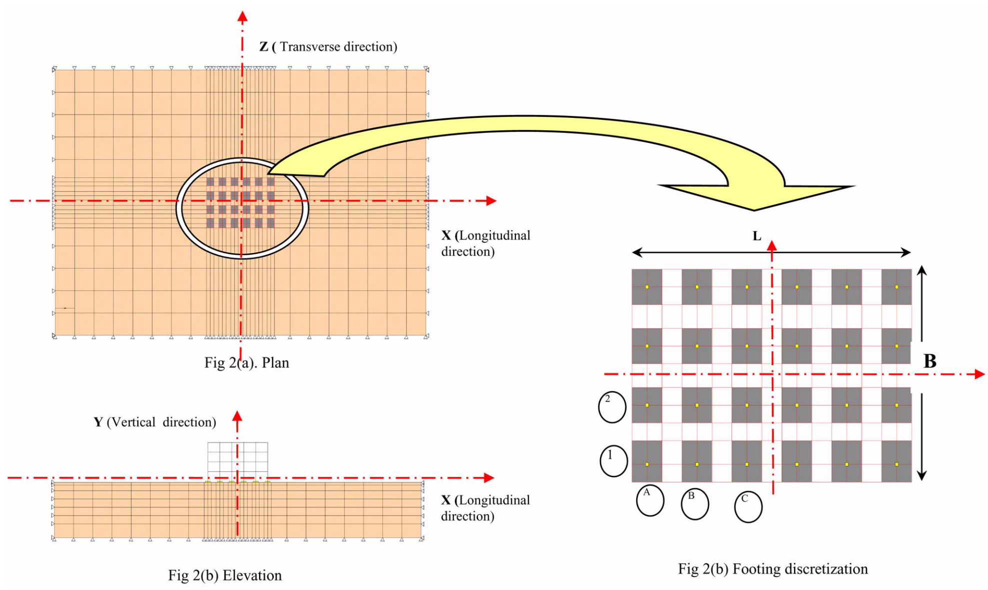

Fig. 2 Details of FEM model for frame – isolated footings – soil interaction analysis

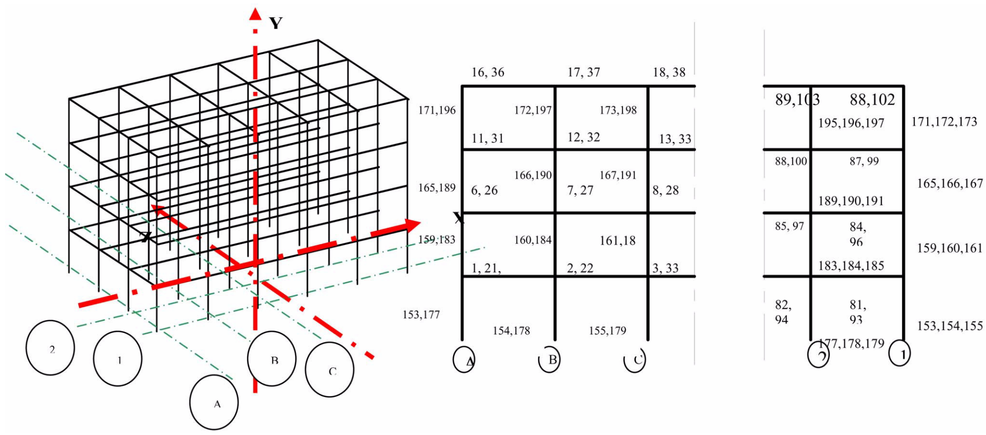

Fig. 3 Member numbers for quarter frame

general-purpose FORTRAN program for simulating the multiscale structure. The assembly of stiffness matrix is carried out and stored in skyline form. With the load vector made available, the displacements were solved from the system equation using the Gauss elimination method. The program is validated for each of the element by comparing the results of standard structures, such as cantilever plate and three dimensional frames, with results available elsewhere.

3.3 Degrees of freedom in coupled and uncoupled analysis

In the coupled analysis, the translational degrees of freedom D_1 and D_3 of the plate elements are bonded with D_6 and D_7 of the soil elements, i.e. $D_1 = D_7$ and $D_3 = D_8$. This ensures no slippage between soil and foundation. Refer to Fig. 1(c) and Fig. 1(d).

In the uncoupled analysis, the translational degrees of freedom D_1 and D_3 of the plate elements are not bonded with D_7 and D_8 of the soil elements. Thus, compatibility is disrupted in the horizontal directions and complete slip between the foundation and soil is allowed.

4. Results and discussion

The structure is primarily analyzed with fixed base. These results are taken as the reference for comparing the structural responses obtained for the uncoupled and coupled cases. The stresses and displacements obtained are plotted against X/L in the longitudinal direction and B/Z in the transverse direction. Refer Fig. 2(c).

4.1 Effect of SSI on displacements of soil

The effects of uncoupled and coupled analyses on the displacements have been shown in Fig. 4 and Fig. 5 respectively, for different Y/D values.

For the uncoupled analysis, the maximum horizontal displacement in the longitudinal direction occurs at $X/L = 0.58$ at a depth of 6.0m from the foundation, whereas in the transverse direction it occurs at $Z/B = 1.03$ at the same depth. The absolute maximum vertical displacement is 29.58 mm with a maximum differential settlement of 10.84 mm.

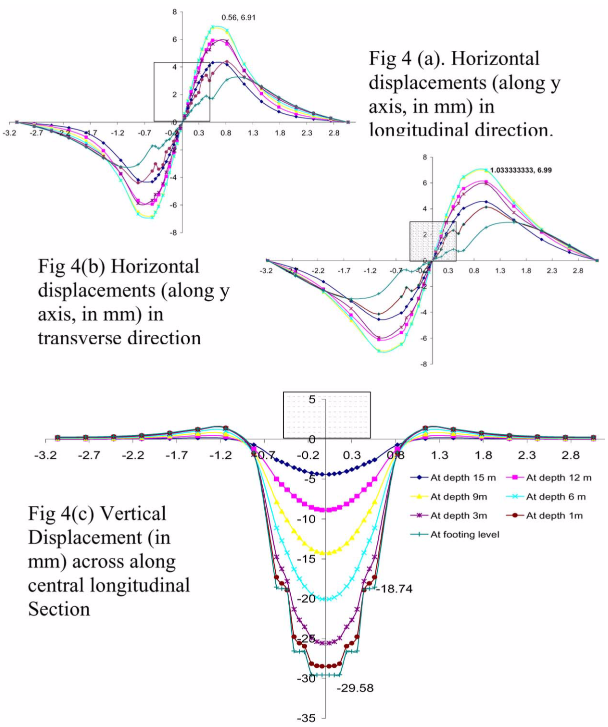

Fig 4 (a). Horizontal displacements (along y axis, in mm) in longitudinal direction.

Fig 4(b) Horizontal displacements (along y axis, in mm) in transverse direction

Fig 4(c) Vertical Displacement (in mm) across along central longitudinal Section

Fig. 4 Displacements in soil for uncoupled analysis

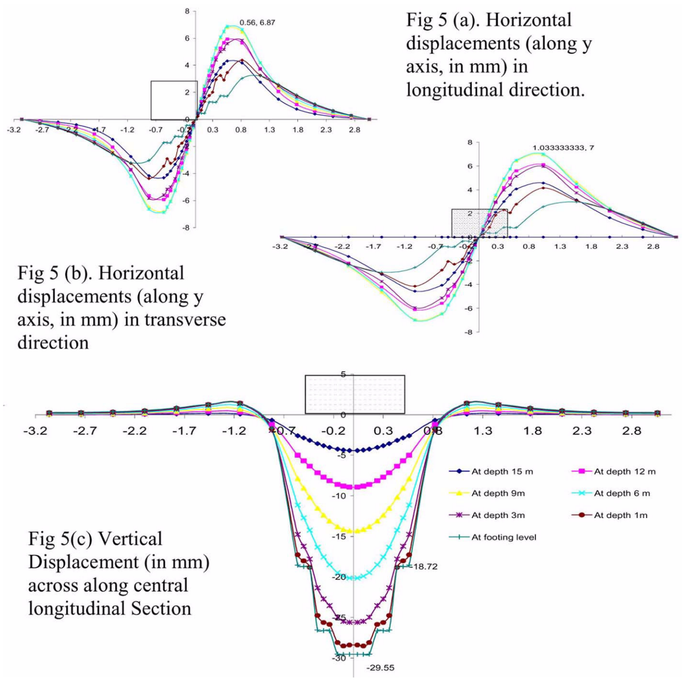

Fig. 5 Displacements in soil for coupled analysis

For the coupled analysis, the maximum horizontal displacement in the longitudinal direction occurs at $X/L = 0.58$ at a depth of 6.0 m from the foundation, whereas in the transverse direction it occurs at $Z/B = 1.03$ at the same depth. The absolute maximum vertical displacement is 29.55 mm with a maximum differential settlement of 10.83 mm.

The maximum displacement from the coupled analysis is 0.9989 times the max displacement from the uncoupled analysis. Meanwhile, the maximum differential settlement from the coupled analysis is 0.999 times the maximum differential settlement from the uncoupled analysis. This clearly shows that the coupling has no effect on the maximum settlement of the structure, as well as on the differential settlement.

4.2 Effect of SSI on stresses in soil

The effects of the uncoupled and coupled analyses on the stresses of the soil are shown in Fig. 6 and Fig. 7. The maximum stresses occur at $X/L = \pm\, 0.33$ and $Z/B = \pm\, 0.33$ for both cases.

In the uncoupled analysis, the maximum longitudinal stress is 3.545 times the longitudinal stress at the centre of the soil and the maximum stress in the transverse direction is 3.828 times the transverse stress at the centre of the soil. The maximum vertical stress is 3.494 times the vertical stress at the centre of the soil. Refer to Fig. 6 (a), (c) and (e).

In the coupled analysis, the maximum longitudinal stress is 7.5 times the longitudinal stress at the centre of the soil and the maximum stress in the transverse direction is 4.369 times the transverse stress at the centre. The maximum vertical stress is 4.608 times the vertical stress at the centre of the soil. Refer to Fig. 6 (b), (d) and (f).

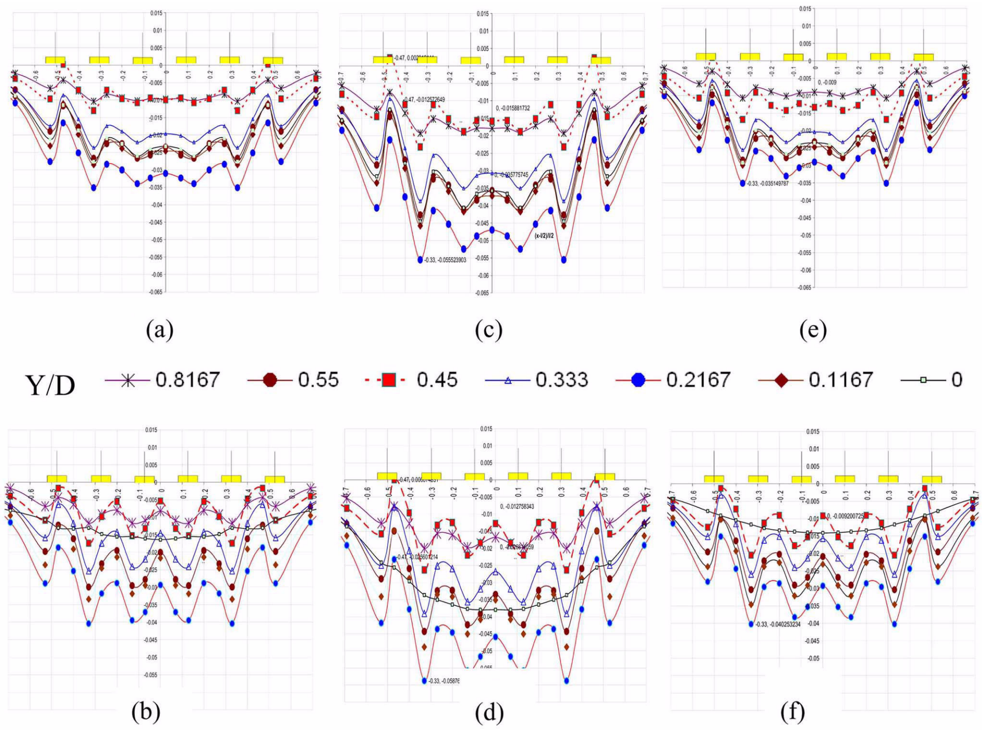

Fig. 6 Longitudinal stress (a & b), vertical stress (c & d), and transverse stress (e & f) below footings uncoupled and coupled analysis for different values of y/d

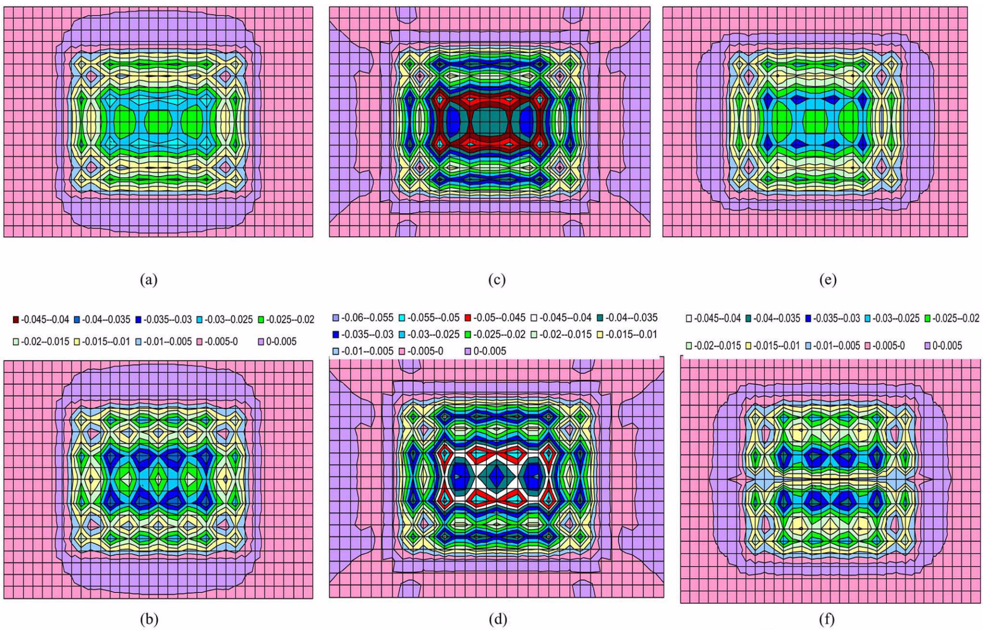

Fig. 7 Longitudinal stress (a & b), vertical stress (c & d) and tranverse stress (e & f) contours below footings in uncoupled and coupled analysis

The minimum longitudinal stress obtained from the coupled analysis is 0.5393 times the minimum longitudinal stress obtained from the uncoupled analysis. The maximum longitudinal stress obtained from the coupled analysis is 1.1493 times the maximum longitudinal stress obtained from the uncoupled analysis.

The minimum transverse stress obtained from the coupled analysis is 1.02 times the minimum transverse stress obtained from the uncoupled analysis. The maximum transverse stress obtained from the coupled analysis is 1.1451 times the maximum transverse stress obtained from the uncoupled analysis.

The minimum vertical stress obtained from the coupled analysis is 0.803 times the minimum vertical stress obtained from the uncoupled analysis. The maximum vertical stress obtained from the coupled analysis is 1.0589 times the maximum vertical stress obtained from the uncoupled analysis.

In general it is observed that the results obtained from the coupled analysis show higher differential stresses, especially for the horizontal directions. Fig. 7 shows the stress contours at the footing level.

4.3 Effect of SSI on end actions of structural members

Let F_x. F_y and F_z represent the axial force, shear force in the *y*-direction and shear force in the *z*-direction in the local coordinates, respectively, and M_x, M_y and M_z represent the moments about the

Table 2(a) Translational forces at the nodes of beams in *X*-direction

Member No	Nodes	Non-interactive analysis		Uncoupled analysis		Coupled analysis		Member No	Nodes	Non-interactive analysis		Uncoupled analysis		Coupled analysis	
		Fx_1	Fy_1	Fx_2	Fy_2	Fx_3	Fy_3			Fx_1	Fy_1	Fx_2	Fy_2	Fx_3	Fy_3
1	1	-6.71	72.47	-30.2	89.73	-32.2	89.19	21	1	-6.71	72.47	-31.2	94.31	-33.5	93.61
	2	6.71	82.53	30.27	65.27	32.2	65.81		2	6.71	82.53	31.2	60.69	33.5	61.39
2	1	-6.54	77.92	-48.9	79.57	-51.4	79.55	22	1	-6.54	77.92	-51.3	80.38	-54.6	80.27
	2	6.54	77.08	48.91	75.43	51.4	75.45		2	6.54	77.08	51.34	74.62	54.6	74.73
3	1	-6.38	77.5	-54.2	77.5	-56.7	77.5	23	1	-6.38	77.5	-57.0	77.5	-60.4	77.5
6	1	-0.02	74.96	3.05	99.31	3.37	99.4	26	1	-0.02	74.96	3.24	103.8	3.6	103.9
	2	0.02	80.04	-3.05	55.69	-3.37	55.6		2	0.02	80.04	-3.24	51.14	-3.6	51.05
7	1	-1.28	77.2	2.19	82.03	2.45	82.02	27	1	-1.28	77.2	2.56	83.1	2.89	83.08
	2	1.28	77.8	-2.19	72.97	-2.45	72.98		2	1.28	77.8	-2.56	71.9	-2.89	71.92
8	1	-1.12	77.5	2.21	77.5	2.45	77.5	28	1	-1.12	77.5	2.56	77.5	2.86	77.5
11	1	-4.27	76.48	-6.78	100.4	-6.82	100.5	31	1	-4.27	76.48	-7.15	104.8	-7.18	104.9
	2	4.27	78.52	6.78	54.55	6.82	54.5		2	4.27	78.52	7.15	50.11	7.18	50.06
12	1	-3.34	76.65	-6.66	81.87	-6.68	81.88	32	1	-3.34	76.65	-7.15	82.96	-7.16	82.96
	2	3.34	78.35	6.66	73.13	6.68	73.12		2	3.34	78.35	7.15	72.04	7.16	72.04
13	1	-3.22	77.5	-6.66	77.5	-6.67	77.5	33	1	-3.22	77.5	-7.15	77.5	-7.17	77.5
16	1	18.74	71.58	38.16	86.75	38.2	86.78	36	1	18.74	71.58	41.66	89.53	41.7	89.56
	2	-18.7	83.42	-38.1	68.25	-38.2	68.22		2	-18.7	83.42	-41.6	65.47	-41.7	65.44
17	1	18.53	77.44	57.25	79.38	57.3	79.38	37	1	18.53	77.44	64.3	79.83	64.4	79.83
	2	-18.5	77.56	-57.2	75.62	-57.3	75.62		2	-18.5	77.56	-64.3	75.17	-64.4	75.17
18	1	18.22	77.5	61.52	77.5	61.6	77.5	38	1	18.22	77.5	69.47	77.5	69.5	77.5

Table 2(b) Normalized translational forces at the nodes of beams in X-direction

Member No	Nodes	Uncoupled vs Non-interactive		Coupled vs Non-nteractive		Coupled vs Uncoupled		Member No	Nodes	Uncoupled vs Non-interactive		Coupled vs Non-nteractive		Coupled vs Uncoupled	
		Fx_2/Fx_1	Fy_2/Fy_1	Fx_3/Fx_1	Fy_3/Fy_1	Fx_3/Fx_2	Fy_3/Fy_2			Fx_2/Fx_1	Fy_2/Fy_1	Fx_3/Fx_1	Fy_3/Fy_1	Fx_3/Fx_2	Fy_3/Fy_2
1	1	4.51	1.24	4.81	1.23	1.07	0.99	21	1	4.65	1.30	5.00	1.29	1.08	0.99
	2	4.51	0.79	4.81	0.80	1.07	1.01		2	4.65	0.74	5.00	0.74	1.08	1.01
2	1	7.48	1.02	7.87	1.02	1.05	1.0	22	1	7.85	1.03	8.36	1.03	1.06	1.0
	2	7.48	0.98	7.87	0.98	1.05	1.0		2	7.85	0.97	8.36	0.97	1.06	1.0
3	1	8.50	1.00	8.89	1.00	1.05	1.0	23	1	8.94	1.00	9.48	1.00	1.06	1.0
6	1	-152.5	1.32	-168.5	1.33	1.10	1.0	26	1	-162	1.39	-180	1.39	1.11	1.0
	2	-152.5	0.70	-168.5	0.69	1.10	1.0		2	-162	0.64	-180	0.64	1.11	1.0
7	1	-1.71	1.06	-1.91	1.06	1.12	1.0	27	1	-2.0	1.08	-2.26	1.08	1.13	1.0
	2	-1.71	0.94	-1.91	0.94	1.12	1.0		2	-2.0	0.92	-2.26	0.92	1.13	1.0
8	1	-1.97	1.00	-2.19	1.00	1.11	1.0	28	1	-2.29	1.00	-2.55	1.00	1.12	1.0
11	1	1.59	1.31	1.60	1.31	1.01	1.0	31	1	1.67	1.37	1.68	1.37	1.00	1.0
	2	1.59	0.69	1.60	0.69	1.01	1.0		2	1.67	0.64	1.68	0.64	1.00	1.0
12	1	1.99	1.07	2.00	1.07	1.00	1.0	32	1	2.14	1.08	2.14	1.08	1.00	1.0
	2	1.99	0.93	2.00	0.93	1.00	1.0		2	2.14	0.92	2.14	0.92	1.00	1.0
13	1	2.07	1.00	2.07	1.00	1.00	1.0	33	1	2.22	1.00	2.23	1.00	1.00	1.0
16	1	2.04	1.21	2.04	1.21	1.00	1.0	36	1	2.22	1.25	2.23	1.25	1.00	1.0
	2	2.04	0.82	2.04	0.82	1.00	1.0		2	2.22	0.78	2.23	0.78	1.00	1.0
17	2	3.09	1.03	3.09	1.03	1.00	1.0	37	1	3.47	1.03	3.47	1.03	1.00	1.0
	2	3.09	0.97	3.09	0.97	1.00	1.0		2	3.47	0.97	3.47	0.97	1.00	1.0
18	1	3.38	1.00	3.38	1.00	1.00	1.0	38	1	3.81	1.00	3.82	1.00	1.00	1.0

local x-, y-, and z-axes, respectively. The second subscripts 1, 2 and 3 represent the non-interactive case, uncoupled case and coupled case, respectively.

4.3.1 On X-beams (Longitudinal direction)

Absolute values of member end actions are given in Table 2(a) and 3(a). Table 2(b) and 3(b) indicates normalized values with respect to non-interactive analysis. In Table 2(b), the axial forces on the beams of the structure obtained from the uncoupled analysis are, 1.59 to 8.94 times the axial forces obtained from the non-interactive analysis. The axial forces on the beams of the structure obtained from the coupled analysis are 2.55 to 9.48 times the forces obtained from the non-interactive analysis. The minimum and maximum axial forces obtained from the coupled analysis are 1.001 times the minimum and maximum axial forces obtained from the uncoupled analysis.

The shear forces on the beams of the structure in the longitudinal direction obtained from both the uncoupled and coupled analyses are 0.64 to 1.39 times the shear forces obtained from the non-interactive analysis. The minimum and maximum shear forces are the same for both analyses.

From Table 3(b), it can be observed that the end moments on the beams in the longitudinal direction obtained from both the uncoupled and coupled analysis are −.16 to 2.46 times the end moments from the non-interactive analysis.

Table 3(a) Moments at the nodes of beams in *X*-direction

Member numbers	Nodes	Non-interactive analysis	Uncoupled analysis	Coupled analysis	Member numbers	Nodes	Non-interactive analysis	Uncoupled analysis	Coupled analysis
		M_{z1}	Mz_2	Mz_2			M_{z1}	Mz_2	Mz_2
1	1	43.33	82.12	83.93	21	1	43.33	93.33	95.57
	2	-68.5	-23.7	-22.8		2	-68.5	-12.8	-11.5
2	1	66.28	61.39	61.45	22	1	66.28	61.47	61.81
	2	-64.2	-51.1	-51.1		2	-64.2	-47.6	-47.4
3	1	64.43	58.82	58.83	23	1	64.43	57.8	57.83
6	1	50.51	112.6	112.3	26	1	50.51	124.1	123.8
	2	-63.2	-3.06	-3.23		2	-63.2	8.2	8.04
7	1	63.65	68	68.07	27	1	63.65	69.22	69.3
	2	-65.1	-45.4	-45.4		2	-65.1	-41.3	-41.3
8	1	64.72	60.03	60.04	28	1	64.72	59.06	59.07
11	1	54.91	115.9	115.8	31	1	54.91	127.2	127.1
	2	-60	-0.87	-1.01		2	-60	10.01	9.89
12	1	61.68	67.31	67.3	32	1	61.68	68.65	68.65
	2	-65.9	-45.4	-45.5		2	-65.9	-41.3	-41.4
13	1	64.9	60.02	60.02	33	1	64.9	59.05	59.05
16	1	35.93	72.48	72.39	36	1	35.93	79.19	79.12
	2	-65.5	-26.1	-26.2		2	-65.5	-18.9	-19
17	2	64.69	60.25	60.27	37	1	64.69	59.68	59.71
	2	-65	-50.9	-50.9		2	-65	-48	-48.1
18	1	64.56	58.68	58.69	38	1	64.56	57.51	57.52

Table 3(b) Normalized moments at the nodes of beams in *X*-direction

Member numbers	Nodes	Uncoupled vs Non-interactive	Coupled vs Non-interac-tive	Coupled vs Uncoupled	Member numbers	Nodes	Uncoupled vs Non-interactive	Coupled vs Non-inter-active	Coupled vs Uncoupled
		M_{z1}	Mz_2	Mz_2			M_{z1}	Mz_2	Mz_2
1	1	1.90	1.94	1.022	21	1	2.15	2.21	1.024
	2	0.35	0.33	0.963		2	0.19	0.17	0.900
2	1	0.93	0.93	1.001	22	1	0.93	0.93	1.006
	2	0.80	0.80	1.000		2	0.74	0.74	0.996
3	1	0.91	0.91	1.000	23	1	0.90	0.90	1.001
6	1	2.23	2.22	0.997	26	1	2.46	2.45	0.998
	2	0.05	0.05	1.056		2	-0.13	-0.13	0.980
7	1	1.07	1.07	1.001	27	1	1.09	1.09	1.001
	2	0.70	0.70	1.000		2	0.63	0.63	1.000
8	1	0.93	0.93	1.000	28	1	0.91	0.91	1.000
11	1	2.11	2.11	0.999	31	1	2.32	2.31	0.999
	2	0.01	0.02	1.161		2	-0.17	-0.16	0.988
12	1	1.09	1.09	1.000	32	1	1.11	1.11	1.000
	2	0.69	0.69	1.001		2	0.63	0.63	1.000
13	1	0.92	0.92	1.000	33	1	0.91	0.91	1.000
16	1	2.02	2.01	0.999	36	1	2.20	2.20	0.999
	2	0.40	0.40	1.003		2	0.29	0.29	1.004
17	2	0.93	0.93	1.000	37	1	0.92	0.92	1.001
	2	0.78	0.78	1.000		2	0.74	0.74	1.000
18	1	0.91	0.91	1.000	38	1	0.89	0.89	1.000

Table 4(a) Translational forces at the nodes of beams in *Z*-direction

Member No	Nodes	Non-interactive analysis		Uncoupled analysis		Coupled analysis		Member No	Nodes	Non-interactive analysis		Uncoupled analysis		Coupled analysis	
		Fx_1	Fy_1	Fx_2	Fy_2	Fx_3	Fy_3			Fx_1	Fy_1	Fx_2	Fy_2	Fx_3	Fy_3
81	1	-6.88	72.52	-24.24	91.08	-27.1	90.3	99	1	-4.57	76.45	-8.05	103.98	-8.11	104.03
	2	6.88	82.48	24.24	63.92	27.1	64.7		2	4.57	78.55	8.05	51.02	8.11	50.97
82	1	-6.94	77.5	-34.02	77.5	-37.9	77.5	100	1	-3.94	77.5	-8.67	77.5	-8.72	77.5
84	1	0.17	74.93	3.07	97.79	3.57	97.93	102	1	18.94	71.71	40.73	89.97	40.79	90.01
	2	-0.17	80.07	-3.07	57.21	-3.57	57.07		2	-18.94	83.29	-40.73	65.03	-40.79	64.99
85	1	-1.16	77.5	2.54	77.5	3.05	77.5	103	1	19.18	77.5	57.44	77.5	57.52	77.5
87	1	-4.57	76.45	-7.51	99.08	-7.57	99.15	105	1	-6.88	72.52	-26.14	98.09	-29.36	97.12
	2	4.57	78.55	7.51	55.92	7.57	55.85		2	6.88	82.48	26.14	56.91	29.36	57.88
88	1	-3.94	77.5	-7.94	77.5	-7.98	77.5	106	1	-6.94	77.5	-37.79	77.5	-42.51	77.5
90	1	18.94	71.71	36.94	86.75	37	86.79	108	1	0.17	74.93	3.45	104.95	3.99	105.08
	2	-18.94	83.29	-36.94	68.25	-37	68.21		2	-0.17	80.07	-3.45	50.05	-3.99	49.92
91	1	19.18	77.5	50.77	77.5	50.87	77.5	109	1	-1.16	77.5	3.22	77.5	3.84	77.5
93	1	-6.88	72.52	-25.51	96.02	-28.62	95.11	111	1	-4.57	76.45	-8.33	106.18	-8.39	106.23
	2	6.88	82.48	25.51	58.98	28.62	59.89		2	4.57	78.55	8.33	48.82	8.39	48.77
94	1	-6.94	77.5	-36.55	77.5	-41.01	77.5	112	1	-3.94	77.5	-9.07	77.5	-9.12	77.5
96	1	0.17	74.93	3.37	102.77	3.9	102.91	114	1	18.94	71.71	42.5	91.45	42.54	91.48
	2	-0.17	80.07	-3.37	52.23	-3.9	52.09		2	-18.94	83.29	-42.5	63.55	-42.54	63.52
97	1	-1.16	77.5	3.08	77.5	3.67	77.5	115	1	19.18	77.5	60.53	77.5	60.61	77.5

Table 4(b) Normalized translational forces at the nodes of beams in *Z*-direction

Member No	Nodes	Non-interactive analysis		Uncoupled analysis		Coupled analysis		Member No	Nodes	Non-interactive analysis		Uncoupled analysis		Coupled analysis	
		Fx_2/Fx_1	Fy_2/Fy_1	Fx_3/Fx_1	Fy_3/Fy_1	Fx_3/Fx_2	Fy_3/Fy_2			Fx_2/Fx_1	Fy_2/Fy_1	Fx_3/Fx_1	Fy_3/Fy_1	Fx_3/Fx_2	Fy_3/Fy_2
81	1	3.52	1.26	3.94	1.25	1.12	0.99	99	1	1.76	1.36	1.77	1.36	1.01	1.00
	2	3.52	0.77	3.94	0.78	1.12	1.01		2	1.76	0.65	1.77	0.65	1.01	1.00
82	1	4.90	1.00	5.46	1.00	1.11	1.00	100	1	2.20	1.00	2.21	1.00	1.01	1.00
84	1	18.1	1.31	21.0	1.31	1.16	1.00	102	1	2.15	1.25	2.15	1.26	1.00	1.00
	2	18.1	0.71	21.0	0.71	1.16	1.00		2	2.15	0.78	2.15	0.78	1.00	1.00
85	1	-2.19	1.00	-2.6	1.00	1.20	1.00	103	1	2.99	1.00	3.00	1.00	1.00	1.00
87	1	1.64	1.30	1.66	1.30	1.01	1.00	105	1	3.80	1.35	4.27	1.34	1.12	0.99
	2	1.64	0.71	1.66	0.71	1.01	1.00		2	3.80	0.69	4.27	0.70	1.12	1.02
88	1	2.02	1.00	2.03	1.00	1.01	1.00	106	1	5.45	1.00	6.13	1.00	1.12	1.00
90	1	1.95	1.21	1.95	1.21	1.00	1.00	108	1	20.2	1.40	23.4	1.40	1.16	1.00
	2	1.95	0.82	1.95	0.82	1.00	1.00		2	20.2	0.63	23.4	0.62	1.16	1.00
91	1	2.65	1.00	2.65	1.00	1.00	1.00	109	1	-2.8	1.00	-3.3	1.00	1.19	1.00
93	1	3.71	1.32	4.16	1.31	1.12	0.99	111	1	1.82	1.39	1.84	1.39	1.01	1.00
	2	3.71	0.72	4.16	0.73	1.12	1.02		2	1.82	0.62	1.84	0.62	1.01	1.00
94	1	5.27	1.00	5.91	1.00	1.12	1.00	112	1	2.30	1.00	2.31	1.00	1.01	1.00
96	1	19.8	1.37	22.9	1.37	1.16	1.00	114	1	2.24	1.28	2.25	1.28	1.00	1.00
	2	19.8	0.65	22.9	0.65	1.16	1.00		2	2.24	0.76	2.25	0.76	1.00	1.00
97	1	-2.66	1.00	-3.2	1.00	1.19	1.00	115	1	3.16	1.00	3.16	1.00	1.00	1.00

Table 5(a) Moments at the nodes of beams in *Z*-direction

Member numbers	Nodes	Non-interactive analysis	Uncoupled analysis	Coupled analysis	Member numbers	Nodes	Non-interactive analysis	Uncoupled analysis	Coupled analysis
		M_{z1}	Mz_2	Mz_2			M_{z1}	Mz_2	Mz_2
81	1	43.37	83.17	85.73	99	1	55.04	122.4	122.3
	2	-68.3	-19.2	-17.8		2	-60.3	10.23	10.09
82	1	65.82	49.97	50.11	100	1	63.09	46.89	46.92
84	1	50.5	106.8	106.3	102	1	36.29	77.37	77.28
	2	-63.4	-4.6	-4.86		2	-65.3	-14.8	-14.9
85	1	64.23	50.42	50.49	103	1	65.14	44.71	44.76
87	1	55.04	110.5	110.3	105	1	43.37	99.69	102.7
	2	-60.3	-2.24	-2.41		2	-68.3	-1.61	0.22
88	1	63.09	49.76	49.79	106	1	65.82	44.88	45.17
90	1	36.29	70.14	70.04	108	1	50.5	124.1	123.7
	2	-65.3	-23.7	-23.8		2	-63.4	13.81	13.55
91	1	65.14	48.29	48.34	109	1	64.23	46.13	46.18
93	1	43.37	94.83	97.71	111	1	55.04	127.8	127.7
	2	-68.3	-6.78	-5.11		2	-60.3	15.85	15.72
94	1	65.82	46.39	46.63	112	1	63.09	45.6	45.62
96	1	50.5	118.8	118.4	114	1	36.29	80.66	80.58
	2	-63.4	8.21	7.95		2	-65.3	-10.8	-10.9
97	1	64.23	47.44	47.5	115	1	65.14	43.07	43.11

Table 5(b) Normalized moments at the nodes of beams in *Z*-direction

Member numbers	Nodes	Uncoupled vs Non-interactive	Coupled vs Non-interactive	Coupled vs Uncoupled	Member numbers	Nodes	Uncoupled vs Non-interactive	Coupled vs Non-interactive	Coupled vs Uncoupled
		M_{z1}	Mz_2	Mz_2			M_{z1}	Mz_2	Mz_2
81	1	1.92	1.98	1.031	99	1	2.22	2.22	0.999
	2	0.28	0.26	0.930		2	-0.17	-0.17	0.986
82	1	0.76	0.76	1.003	100	1	0.74	0.74	1.001
84	1	2.11	2.11	0.996	102	1	2.13	2.13	0.999
	2	0.07	0.08	1.057		2	0.23	0.23	1.007
85	1	0.78	0.79	1.001	103	1	0.69	0.69	1.001
87	1	2.01	2.00	0.999	105	1	2.30	2.37	1.030
	2	0.04	0.04	1.076		2	0.02	0.00	-0.14
88	1	0.79	0.79	1.001	106	1	0.68	0.69	1.006
90	1	1.93	1.93	0.999	108	1	2.46	2.45	0.997
	2	0.36	0.36	1.005		2	-0.22	-0.21	0.981
91	1	0.74	0.74	1.001	109	1	0.72	0.72	1.001
93	1	2.19	2.25	1.030	111	1	2.32	2.32	0.999
	2	0.10	0.07	0.754		2	-0.26	-0.26	0.992
94	1	0.70	0.71	1.005	112	1	0.72	0.72	1.000
96	1	2.35	2.34	0.996	114	1	2.22	2.22	0.999
	2	-0.13	-0.13	0.968		2	0.16	0.17	1.008
97	1	0.74	0.74	1.001	115	1	0.66	0.66	1.001

Table 6 (a) Translational forces at the nodes of columns

Member No	Non-interactive analysis			Uncoupled analysis			Coupled analysis				Non-interactive analysis			Uncoupled analysis			Coupled analysis		
	Fx_1	Fy_1	Fz_1	Fx_2	Fy_2	Fz_2	Fx_3	Fy_3	Fz_3		Fx_1	Fy_1	Fz_1	Fx_2	Fy_2	Fz_2	Fx_3	Fy_3	Fz_3
153	-591.1	-7.74	7.66	-750.9	-4.14	8.24	-750	-2.47	5.87	177	-929.9	-7.74	-0.51	-947.9	-6.57	3.08	-947.9	-4.58	2.13
154	-929.3	0.36	7.66	-959.4	0.31	10.57	-959	0.85	7.97	178	1268.1	0.36	-0.51	1090.9	-1.85	4.76	1092	-0.88	3.51
155	-916.4	-0.12	7.66	1007.8	1.02	11.48	1007	1.02	8.78	179	1255.2	-0.12	-0.51	1133.1	0.54	5.43	1134	0.64	4.03
159	-446.1	-14.45	14.54	-570.1	-34.4	32.47	-570.6	-34.73	32.96	183	-697.4	-14.45	-0.45	-712.2	-37.78	12.85	-712.1	-38.15	12.92
160	-696.3	0.53	14.54	-718.5	-18.32	36.08	-718.5	-18.31	36.6	184	-947.7	0.53	-0.45	-813.4	-22	15.81	-813	-22.02	15.9
161	-689.3	0.03	14.54	-756.8	-4.28	37.63	-757	-4.27	38.15	185	-940.6	0.03	-0.45	-846.5	-5.16	17.07	-846.4	-5.15	17.19
165	-296.2	-14.47	14.36	-373	-31.35	29.4	-373.2	-31.36	29.39	189	-464.9	-14.47	0.87	-473.6	-34.55	13.39	-473.6	-34.55	13.44
166	-464.2	-0.73	14.36	-478	-19.18	32.7	-478	-19.23	32.69	190	-632.9	-0.73	0.87	-549.4	-22.68	16.09	-549.3	-22.73	16.14
167	-459.1	0.19	14.36	-501.4	-4.26	34.18	-501.5	-4.27	34.16	191	-627.8	0.19	0.87	-569.6	-5.17	17.3	-569.5	-5.17	17.34
171	-143.3	-18.74	18.94	-173.5	-38.13	36.91	-173.6	-38.17	36.96	195	-232.4	-18.74	0.24	-235.3	-41.7	13.81	-235.3	-41.74	13.84
172	-232.6	0.2	18.94	-237.6	-19.05	40.75	-237.6	-19.09	40.81	196	-321.7	0.2	0.24	-287.8	-22.68	16.72	-287.8	-22.71	16.75
173	-226.8	0.31	18.94	-244.6	-4.26	42.51	-244.6	-4.26	42.55	197	-315.9	0.31	0.24	-293.7	-5.17	18.05	-293.7	-5.18	18.07

Table 6(b) Normalized translational forces at the nodes of columns

Member no	Non-interactive analysis			Uncoupled analysis			Coupled analysis			Member no	Non-interactive analysis			Uncoupled analysis			Coupled analysis		
	Fx_2/Fx_1	Fx_2/Fx_1	Fx_2/Fx_1	Fx_2/Fx_1	Fx_2/Fx_1	Fx_2/Fx_1	Fx_2/Fx_1	Fx_2/Fx_1	Fx_2/Fx_1		Fx_2/Fx_1	Fx_2/Fx_1	Fx_2/Fx_1	Fx_2/Fx_1	Fx_2/Fx_1	Fx_2/Fx_1	Fx_2/Fx_1	Fx_2/Fx_1	Fx_2/Fx_1
153	1.27	0.53	1.08	1.27	0.32	0.77	1.0	0.6	0.7	177	1.02	0.85	-6.04	1.02	0.59	-4.18	1.0	0.7	0.7
154	1.03	0.86	1.38	1.03	2.36	1.04	1.0	2.7	0.8	178	0.86	-5.14	-9.33	0.86	-2.44	-6.88	1.0	0.5	0.7
155	-1.1	-8.50	1.50	1.01	-8.50	1.15	1.0	1.0	0.8	179	0.90	-4.50	-10.6	0.90	-5.33	-7.90	1.0	1.2	0.7
159	1.28	2.38	2.23	1.28	2.40	2.27	1.0	1.0	1.0	183	1.02	2.61	-28.5	1.02	2.64	-28.71	1.0	1.0	1.0
160	1.03	-34.5	2.48	1.03	-34.55	2.52	1.0	1.0	1.0	184	0.86	-41.5	-35.1	0.86	-41.55	-35.33	1.0	1.0	1.0
161	1.10	-142.	2.59	1.10	-142.3	2.62	1.0	1.0	1.0	185	0.90	-172.	-37.9	0.90	-171.6	-38.20	1.0	1.0	1.0
165	1.26	2.17	2.05	1.26	2.17	2.05	1.0	1.0	1.0	189	1.02	2.39	15.3	1.02	2.39	15.45	1.0	1.0	1.0
166	1.03	26.27	2.28	1.03	26.34	2.28	1.0	1.0	1.0	190	0.87	31.07	18.4	0.87	31.14	18.55	1.0	1.0	1.0
167	1.09	-22.4	2.38	1.09	-22.47	2.38	1.0	1.0	1.0	191	0.91	-27.2	19.8	0.91	-27.21	19.93	1.0	1.0	1.0
171	1.21	2.03	1.95	1.21	2.04	1.95	1.0	1.0	1.0	195	1.01	2.23	57.5	1.01	2.23	57.67	1.0	1.0	1.0
172	1.02	-95.2	2.15	1.02	-95.45	2.15	1.0	1.0	1.0	196	0.89	-113	69.6	0.89	-113.5	69.79	1.0	1.0	1.0
173	1.08	-13.7	2.24	1.08	-13.74	2.25	1.0	1.0	1.0	197	0.93	-16.6	75.2	0.93	-16.71	75.29	1.0	1.0	1.0
153	1.27	0.53	1.08	1.27	0.32	0.77	1.0	0.6	0.7	177	1.02	0.85	-6.04	1.02	0.59	-4.18	1.0	0.7	0.7

4.3.2 On Z-beams (Transverse direction)

Absolute values of member end actions are given in Table 4(a) and 5(a). Table 4(b)and 5(b) indicates normalized values with respect to non-interactive analysis. In Table 4(b), the axial forces on the beams of the structure obtained from the uncoupled analysis are −2.78 to 4.45 times the forces from the non-interactive analysis. The axial forces on the beams obtained from the coupled analysis are −3.31 to 6.13 times the forces from the non-interactive analysis. The minimum and maximum axial forces obtained from the coupled analysis are 1.001 times the minimum and maximum axial forces obtained from the uncoupled analysis.

The shear forces on the beams of the structure in the longitudinal direction obtained from both the uncoupled and coupled analysis are 0.64 to 1.39 times the shear forces from the non-interactive analysis. The minimum and maximum shear forces are the same for both analyses.

The end moments on the beams of the structure obtained from both the uncoupled and coupled analysis are -0.26 to 2.46 times the forces from the non-interactive analysis. The minimum and maximum end moments obtained from the coupled analysis are 1.005 and 0.999 times the minimum and maximum end moments from the uncoupled analysis. Refer Table 5(b).

4.3.3 On Columns

Absolute values of member end actions are given in Table 6(a) and 7(a). Table 2(b)and 3(b) indicates normalized values with respect to non-interactive analysis. From Table 6(b), it may be

Table 7(a)Comparison of moments at the nodes of columns

Member No	Nodes	Non-interactive analysis		Non-interactive analysis		Uncoupled analysis		Member No	Nodes	Non-interactive analysis		Non-interactive analysis		Uncoupled analysis	
		My_1	Mz_1	My_2	Mz_2	My_3	Mz_3			My_1	Mz_1	My_2	Mz_2	My_3	Mz_3
153	1	9.03	9.18	-2.4	-9.51	2.07	-6.35	177	1	-0.57	9.18	-0.6	-7.15	1.07	-3.41
153	2	17.77	17.9	22.96	18.15	26.78	20.83	177	2	-1.23	17.9	8.07	23.2	9.69	26.41
154	1	9.03	-0.32	-0.19	-8.08	4.7	-7.13	178	1	-0.57	-0.32	0.8	-6.3	3.03	-4.57
154	2	17.77	-0.92	28.07	5.12	32.28	6.04	178	2	-1.23	-0.92	11.48	9.38	13.63	11.06
155	1	9.03	0.17	0.58	-3.48	5.64	-3.47	179	1	-0.57	0.17	1.26	-3.1	3.76	-2.92
155	2	17.77	0.26	30.17	-0.09	34.54	-0.09	179	2	-1.23	0.26	12.85	0.86	15.23	1.03
159	1	25.6	25.43	60.22	63.98	58.97	63.12	183	1	-1.22	25.43	22.73	70.11	22.59	69.15
159	2	25.27	25.14	55.14	57.57	54.67	57.27	183	2	-0.37	25.14	22.48	63.41	22.39	63.09
160	1	25.6	-1.3	66.75	32.61	65.42	32.62	184	1	-1.22	-1.3	28.12	39.28	27.89	39.22
160	2	25.27	-0.57	61.34	31.47	60.85	31.48	184	2	-0.37	-0.57	27.55	37.8	27.43	37.8
161	1	25.6	0.02	69.52	7.79	68.17	7.82	185	1	-1.22	0.02	30.41	9.34	30.15	9.37
161	2	25.27	-0.14	64.02	7.14	63.53	7.17	185	2	-0.37	-0.14	29.74	8.67	29.61	8.71
165	1	25.22	25.37	51.62	55	51.67	55	189	1	1.22	25.37	23.34	60.66	23.24	60.68
165	2	25.05	25.26	51.25	54.76	51.21	54.71	189	2	1.83	25.26	23.69	60.27	23.61	60.23
166	1	25.22	1.01	57.48	33.47	57.54	33.37	190	1	1.22	1.01	28.09	39.62	28.01	39.52
166	2	25.05	1.55	56.95	33.84	56.92	33.76	190	2	1.83	1.55	28.39	39.93	28.32	39.86
167	1	25.22	-0.29	60.08	7.47	60.15	7.46	191	1	1.22	-0.29	30.2	9.05	30.13	9.04
167	2	25.05	-0.39	59.49	7.48	59.47	7.47	191	2	1.83	-0.39	30.49	9.05	30.43	9.04
171	1	29.99	29.65	59.22	61.12	59.12	61.04	195	1	0.97	29.65	23.83	66.9	23.77	66.83
171	2	36.29	35.93	70.15	72.49	70.05	72.41	195	2	-0.13	35.93	24.62	79.18	24.55	79.11
172	1	29.99	0.12	65.46	32.61	65.37	32.55	196	1	0.97	0.12	28.73	38.72	28.68	38.67
172	2	36.29	-0.83	77.36	34.2	77.27	34.13	196	2	-0.13	-0.83	29.9	40.76	29.84	40.71
173	1	29.99	-0.64	68.28	7.1	68.21	7.09	197	1	0.97	-0.64	30.95	8.65	30.91	8.64
173	2	36.29	-0.46	80.65	7.82	80.57	7.81	197	2	-0.13	-0.46	32.31	9.47	32.25	9.47

Table 7(b) Normalized moments at the nodes of columns

Member No	Nodes	Uncoupled vs Non-interactive		Coupled vs Non-interactive		Coupled vs Uncoupled		Member No	Nodes	Uncoupled vs Non-interactive		Coupled vs Non-interactive		Coupled vs Uncoupled	
		My_2/My_1	Mz_2/Mz_1	My_3/My_1	Mz_3/Mz_1	My_3/My_2	Mz_3/Mz_2			My_2/My_1	Mz_2/Mz_1	My_3/My_1	Mz_3/Mz_1	My_3/My_2	Mz_3/Mz_2
153	1	-0.27	-1.04	0.23	-0.69	-0.86	0.668	177	1	1.05	-0.78	-1.88	-0.37	-1.78	0.477
153	2	1.29	1.01	1.51	1.16	1.17	1.148	177	2	-6.56	1.30	-7.88	1.48	1.20	1.138
154	1	-0.02	25.25	0.52	22.28	-24.7	0.882	178	1	-1.40	19.69	-5.32	14.28	3.79	0.725
154	2	1.58	-5.57	1.82	-6.57	1.15	1.180	178	2	-9.33	-10.2	-11.1	-12.0	1.19	1.179
155	1	0.06	-20.5	0.62	-20.4	9.72	0.997	179	1	-2.21	-18.2	-6.60	-17.2	2.98	0.942
155	2	1.70	-0.35	1.94	-0.35	1.14	1.000	179	2	-10.4	3.31	-12.4	3.96	1.19	1.198
159	1	2.35	2.52	2.30	2.48	0.98	0.987	183	1	-18.6	2.76	-18.5	2.72	0.99	0.986
159	2	2.18	2.29	2.16	2.28	0.99	0.995	183	2	-60.8	2.52	-60.5	2.51	1.00	0.995
160	1	2.61	-25.1	2.56	-25.1	0.98	1.000	184	1	-23.0	-30.2	-22.9	-30.2	0.99	0.998
160	2	2.43	-55.2	2.41	-55.2	0.99	1.000	184	2	-74.5	-66.3	-74.1	-66.3	1.00	1.000
161	1	2.72	389.5	2.66	391.0	0.98	1.004	185	1	-24.9	467.0	-24.7	468.5	0.99	1.003
161	2	2.53	-51.0	2.51	-51.2	0.99	1.004	185	2	-80.4	-61.9	-80.0	-62.2	1.00	1.005
165	1	2.05	2.17	2.05	2.17	1.00	1.000	189	1	19.13	2.39	19.05	2.39	1.00	1.000
165	2	2.05	2.17	2.04	2.17	1.00	0.999	189	2	12.95	2.39	12.90	2.38	1.00	0.999
166	1	2.28	33.14	2.28	33.04	1.00	0.997	190	1	23.02	39.23	22.96	39.13	1.00	0.997
166	2	2.27	21.83	2.27	21.78	1.00	0.998	190	2	15.51	25.76	15.48	25.72	1.00	0.998
167	1	2.38	-25.8	2.39	-25.7	1.00	0.999	191	1	24.75	-31.2	24.70	-31.2	1.00	0.999
167	2	2.37	-19.2	2.37	-19.2	1.00	0.999	191	2	16.66	-23.2	16.63	-23.2	1.00	0.999
171	1	1.97	2.06	1.97	2.06	1.00	0.999	195	1	24.57	2.26	24.51	2.25	1.00	0.999
171	2	1.93	2.02	1.93	2.02	1.00	0.999	195	2	-189	2.20	-189	2.20	1.00	0.999
172	1	2.18	271.8	2.18	271.3	1.00	0.998	196	1	29.62	322.7	29.57	322.3	1.00	0.999
172	2	2.13	-41.2	2.13	-41.1	1.00	0.998	196	2	-230	-49.1	-230	-49.0	1.00	0.999
173	1	2.28	-11.1	2.27	-11.1	1.00	0.999	197	1	31.91	-13.5	31.87	-13.5	1.00	0.999
173	2	2.22	-17.0	2.22	-17.0	1.00	0.999	197	2	1.05	-0.78	-1.88	-0.37	-1.78	0.477

observed that the axial forces in the columns of the structure obtained from both from the uncoupled and coupled analyses are 0.86 to 1.28 times the axial forces obtained from the non-interactive analysis. The shear forces in the *Y* direction are 2.04 to 2.64 times those of the non-interactive analysis irrespective of uncoupled or coupled analysis. The shear forces in the *Z* direction are 1.95 to 2.62 times those of the non-interactive analysis irrespective of coupled or uncoupled analysis.

The bending moments on the columns of the structure with absolute values more than 10kNm are considered for discussion. In Table 7(b), the bending moments about the *Y*-axis are 1.29 to 2.72 and

Table 8 Comparison of responses

Sl No	Response	Un-coupled analysis/ Non-interactive analysis	Coupled analysis/ Non-interactive analysis	Coupled analysis/ uncoupled analysis
1	Maximum displacement	–	–	0.9989
2	Maximum differential settlement	–	–	0.999
3	Min/Min to Max/Max(Longitudinal stress)	–	–	0.5393 to 1.1493
4	Min/Min to Max/Max (Transverse stress)			1.02 to 1.1451
5	Min/Min to Max/Max (Vertical stress)			0.803 to 1.0589
6	Axial forces in *X*-beams	1.59 to 8.94	2.55 to 9.48	1 to 1.13
7	Axial forces in *Z*-beams	-2.78 to 4.45	-3.31 to 6.13	1 to 1.19
8	Axial forces in columns	0.86 to 1.28		1
9	Shear forces in *X*-beams	0.64 to 1.139		1 to 1.2
10	Shear forces in *Z*-beams	0.64 to 1.39		0.9 to 1.02
11	Shear forces in columns in *Y*-direction	2.04 to 2.64		1
12	Shear forces in columns in *Z*-direction	1.95 to 2.62		1
13	Moments in *X* Beams	-0.16 to 2.46		0.9 to 1.161
14	Moments in *Z* Beams	-0.26 to 2.46		0.754 to 1.076
15	Moments in columns about *Y*-axis	1.29 to 2.72	1.51 to 2.66	0.98 to 1.17
16	Moments in columns about *Z*-axis	1.01 to 2.8	1.16 to 2.72	0.98 to 1.2

1.51 to 2.66 times those of the non-interactive analysis for the uncoupled and coupled analyses, respectively. The bending moments about the *Z*-axis are1.01 to 2.8 and 1.16 to 2.72 times those of the non-interactive analysis for the uncoupled and coupled analyses respectively.

The maximum end moments about the *Y* and *Z* axes obtained from the coupled analysis are 1.004 and 1.003 times the end moments obtained from the uncoupled analysis.

Overall comparison of the responses are listed in Table 8.

5. Conclusions

The following are the conclusions drawn from the numerical results obtained for the example with the geometry and material data prescribed in this study:

1. The response of the structure does change significantly in the soil-structure-interaction analysis when compared to the non-interactive analysis.
2. The end actions for the beams and columns are different in coupled and uncoupled analyses for the structure resting on isolated footings, where as end actions for beams and columns were same in the structure supported by mat foundation. Therefore, the inclusion of interface elements between the isolated footing and soil has much effect on the member end actions that are to be evaluated.
3. However, the presence or absence of interface elements does not affect the settlements or differential settlements in the present study. Whereas for structures supported by mat foundation, both the settlements and differential settlements are affected.
4. The stresses in the soil increase with the coupling of horizontal displacements between the

footing and soil.

5. Interface elements may be implemented only when the stresses in the soil are to be evaluated.
6. In nonlinear analysis the interface element may play a crucial role when the constitutive relations of the soil depend on the state and increment of the stress and strain.

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