Effect of Reinforced Soil–Structure Interaction on Foundation Settlement Characteristics of a Three-Dimensional Structure

Nayana N. Patil, H. M. Rajashekar Swamy and R. Shivashankar

1 Introduction

A limited number of studies have been conducted on soil–structure interaction effect considering three-dimensional space frames. SSI studies that take into account the yielding of structures and soil nonlinearity are scarce, especially investigating the effects of nonlinearity of SSI system on overall behaviour in terms of displacements and stresses.

King and Yao [1] and Roy and Dutta [2] were the few researchers who made use of the finite element method to consider superstructure—raft/combined footing–soil as a single compatible unit. The SSI studies conducted by Noorzaei et al. [3] and Viladkar et al. [4] clearly indicated that a two-dimensional plane frame SSI analysis might substantially overestimate or underestimate the actual interaction effect in a space frame. The interactive behaviour of the 3D frame-isolated footing–soil system was studied by Rajashekhar Swamy et al. [5]. Rajashekhar Swamy et al. [6] conducted linear and nonlinear SSI analyses of structure resting on raft foundation to find the maximum settlement as well as differential settlements in soil increase in nonlinear analysis when compared to linear analysis. They observed that maximum vertical stresses decrease in nonlinear analysis when compared to linear analysis. However, the stress resultants, in members of the frame, were found to vary (either decrease or increase) depending on location in nonlinear analysis when compared to linear analysis. SSI studies have been carried out for structures supported on unreinforced soil. But reinforced soil–structure interaction (RSSI) dealing with

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structures supported on reinforced soil is yet to be explored. The analysis that treats structure–foundation–reinforced soil as a single system is coined as reinforced soil–structure interaction (RSSI) analysis in this work.

2 Motivation and Objective

Numerous studies have been carried out for structures supported on unreinforced soil. But reinforced soil–structure interaction (RSSI) dealing with structures supported on reinforced soil is yet to be explored.

3 Methodology

Finite element software has been developed to carry out the SSI and RSSI analyses. The structure under consideration has been chosen from Rajashekhar Swamy et al. [6]. SSI analysis is performed on the structure with isolated footings (2 m × 2 m) supported on the soil mass of size 153 m × 95 m × 20 m and beams carrying uniformly distributed load (UDL) of 31 kN/m. In RSSI analysis, the isolated footings of structure are underlain by geogrid and the reinforced soil–structure is analysed for the same loads.

4 Linear SSI Analysis of Space Frame-Footing–Soil System

The proposed physical model has been used for the interactive analysis of a four-storey, five-bay-by-three-bay, space frame-isolated footing–soil system. Figure 1 shows the isometric view of the space frame-isolated foundation–soil system. The layout details of the frame are shown in Fig. 2. The geometrical and material properties of the frames, its components and the isolated foundation are presented in Table 1.

Finite element formulation in the SSI analysis of the frame-isolated footing–soil system is as shown in Fig. 3a–c. The soil is modelled with 43 × 10 × 27 layers in the longitudinal, vertical and transverse directions, respectively, resulting in 11,610 brick elements. Each footing of size 2 × 2 m is modelled by four plate elements of size 1 m × 1 m. The number of plate elements used is 96. The number of beam elements in the longitudinal direction (*X*-direction) is 80, 72 in transverse (*Z*-direction) and 96 in the vertical (*Y*-direction). The graphs are plotted in terms of dimensionless parameters *X*/*L* and *Z*/*B* where *L* and *B* are dimensions of the frame in *X* and *Z* directions as shown in Fig. 3a.

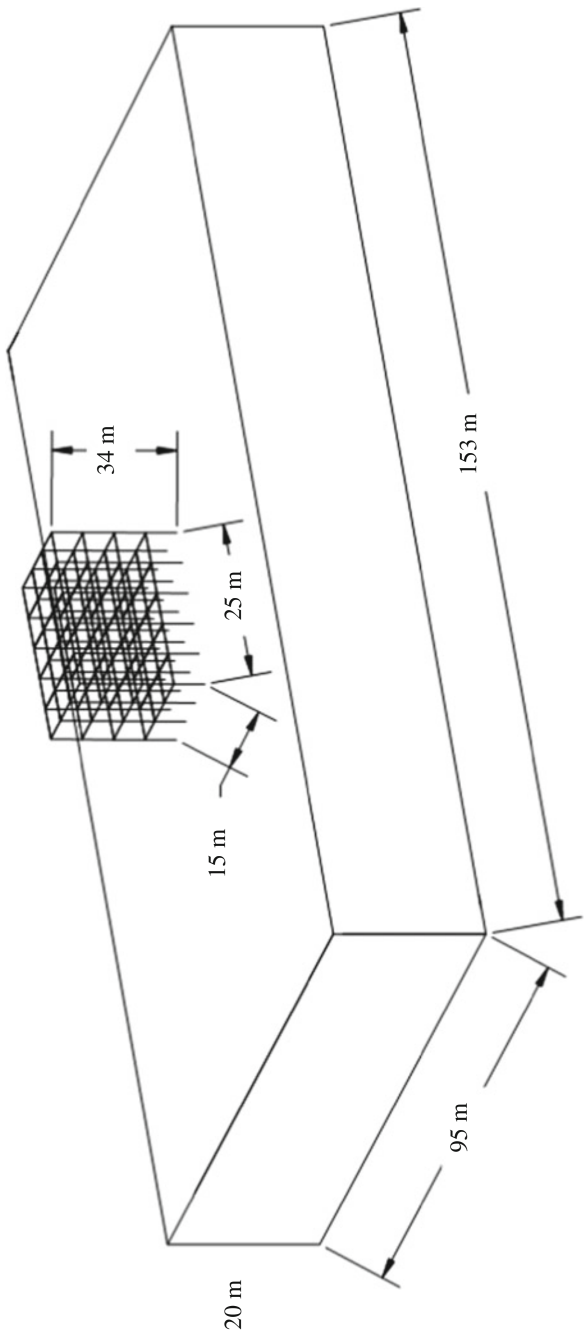

Fig. 1 Structure–footing–soil system [6]

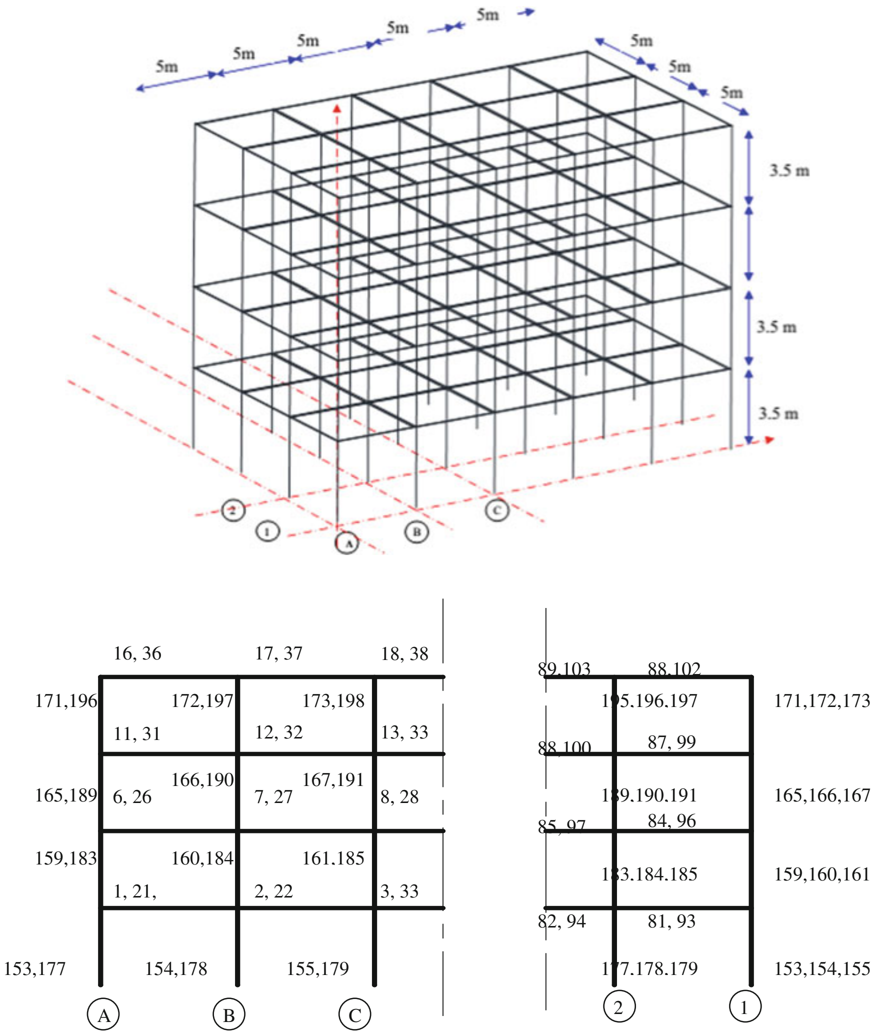

Fig. 2 Details of quarter frame [6]

The various components of the system with respective degrees of freedom are shown in Fig. 4 and are modelled as follows:

1. Columns and beams are modelled as one-dimensional beam elements with six degrees of freedom per node (three translational and three rotational degrees of freedom) as shown in Fig. 4a.
2. Soil mass is modelled as eight-node brick element with three translational degrees of freedom per node as shown in Fig. 4b.

Table 1 Details of the validation of SSI problem [6]

Sl. No.	Structure	Component	Details
1	Frame	No. of storeys	5
		No. of bays	5 × 3
		Storey height	3.5 m
		Bay width	5 m
		Beam size	0.3 m × 0.6 m
		Column size	0.4 m × 0.4 m
		Footing size	3.0 m × 3.0 m × 0.4 m
2		Soil mass	153.0 m × 95.0 m × 0.0 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}

3. Individual footing is modelled using plate elements with five degrees of freedom per node, i.e. three translational degrees of freedom and two rotational degrees of freedom as shown in Fig. 4c.

5 Validity of the Proposed Physical Model

Figure 5 shows the settlements of the isolated footings obtained from the proposed analysis and their comparison with Rajashekhar Swamy et al. [6]. Glance at the figure suggests that there is a very good agreement between the values of settlement. This justifies the finite element mesh extent considered.

6 Linear RSSI Analysis of Space Frame-Footing–Soil System

To conduct linear RSSI analysis, the frame-footing–reinforced soil model used is as shown in Figs. 6 and 7. Under each column footing, four layers of geogrid are laid at *D*/*B* ratios of 0.25, 0.5, 0.75 and 1 as shown in Fig. 6. The size of isolated footing is 2 m × 2 m, and the sizes of geogrid are 4 m × 4 m. The geometric details of geogrid are shown in Fig. 8. Properties of geogrid are given in Table 2.

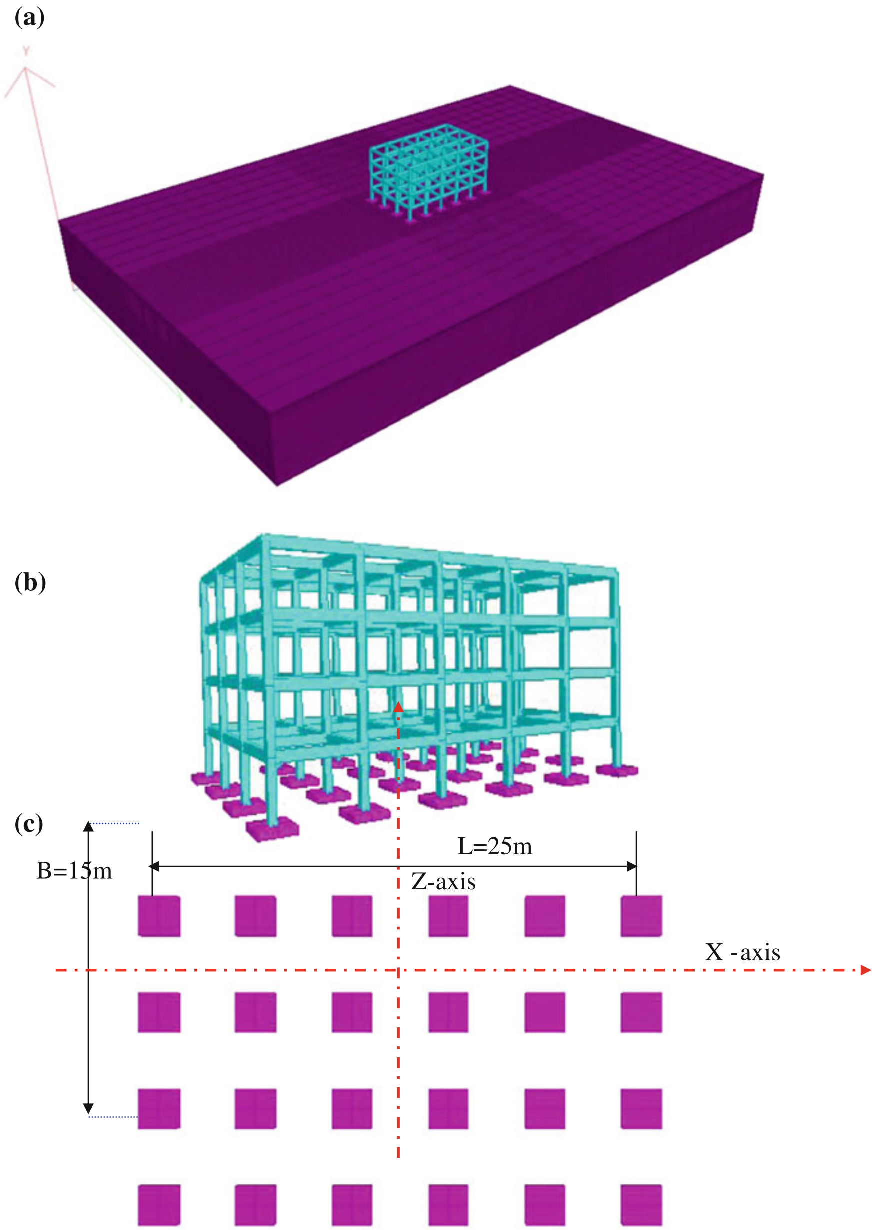

Fig. 3 **a** Frame-isolated footing–soil system, **b** structure foundation system, **c** reference axis and arrangement of isolated footings [8]

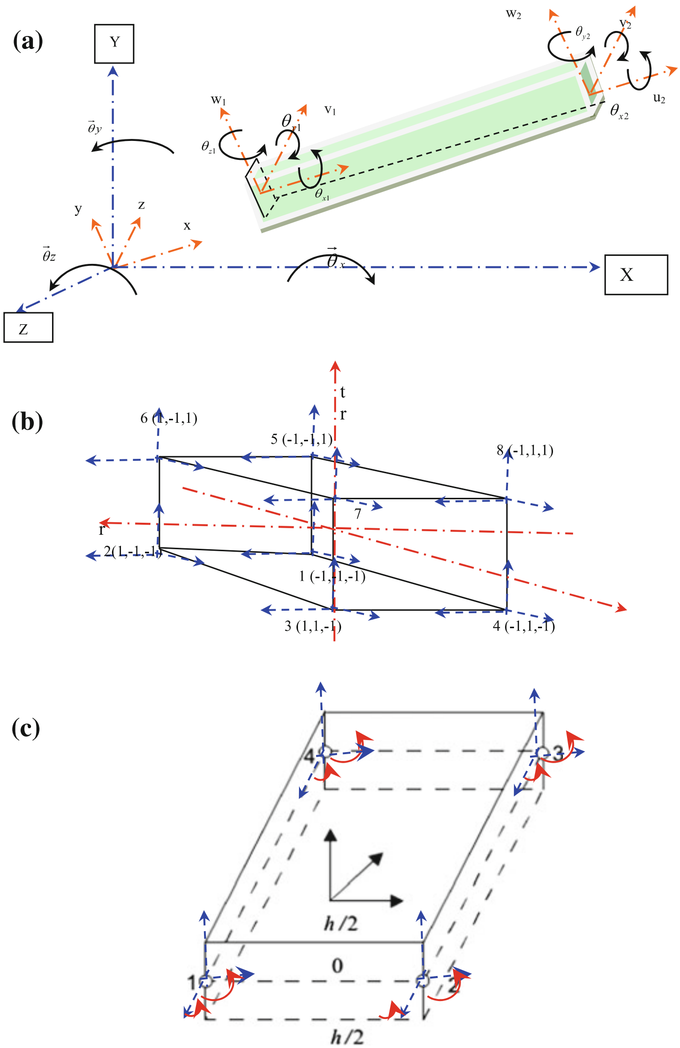

Fig. 4 Details of element types **a** Euler–Bernoulli beam element used for beams and columns, **b** brick element for soil, **c** plate element used for footing [8]

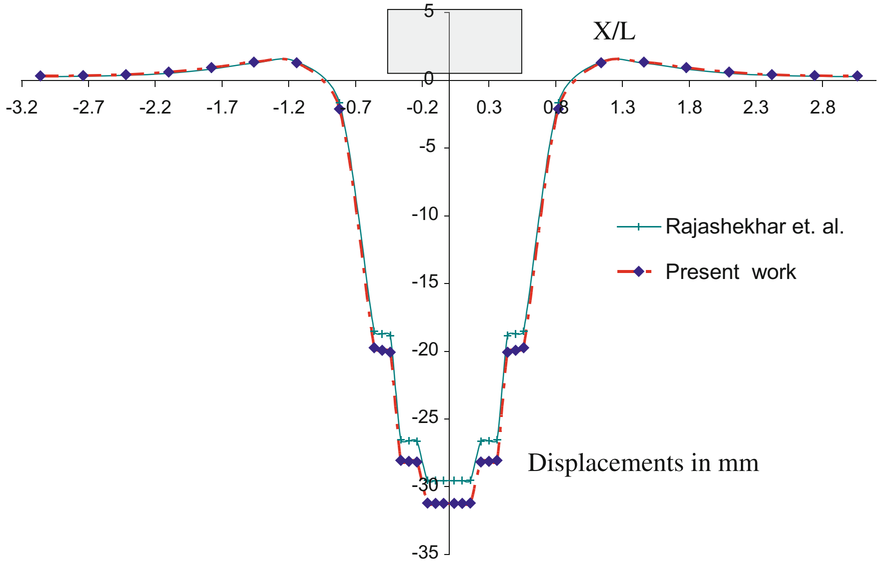

Fig. 5 Comparative settlements in mm at the centre in the present work and the referred work [6]

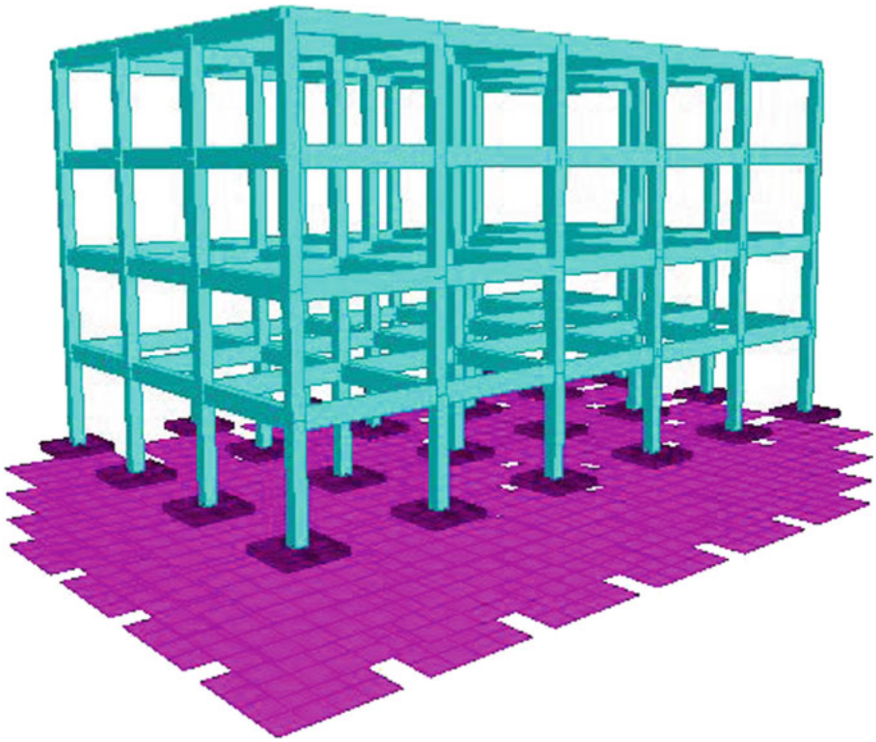

Fig. 6 Frame-footing–reinforcement module [8]

Table 2 Properties of geogrids used for the study [8]

Properties	Values
Rib thickness (mm)	0.75
Aperture size (MD/XD) (mm)	25/33
Junction thickness (mm)	2.8
Tensile strength at 5% strain (kN/m)	8.46 (MD), 13.42 (XD)
Aperture shape	Rectangular
Colour	Black
Type of polymer used	Polyethylene

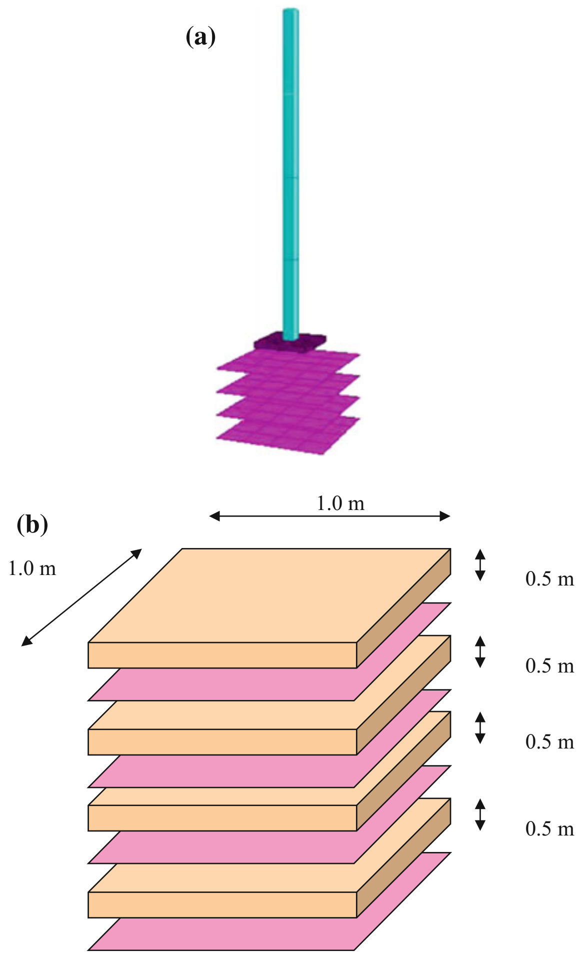

Fig. 7 Arrangement of geogrid: **a** modelling of column–foundation–geogrid and **b** soil–geogrid arrangement represented as macroelement in RSSI analysis [8]

Geogrid consists of apertures of size 25 × 34 mm as shown in Fig. 8b. For a 1 m × 1 m-size geogrid, the number of apertures are 30 × 40 in mutually perpendicular directions as shown in Fig. 8a. Since modelling the geogrid with apertures shown in Fig. 8a proves to be difficult, due to software limitation and enormous execution time, macroelement approach is adopted. This method overcomes the tedious process of modelling the geogrid with small aperture sizes and is validated elsewhere by the authors.

The geogrid of 1 m × 1 m with aperture size of 33 mm × 25 mm (shown in Fig. 8a) is modelled using two-dimensional rectangular element having four nodes with two degrees of freedom per node as shown in Fig. 8c.

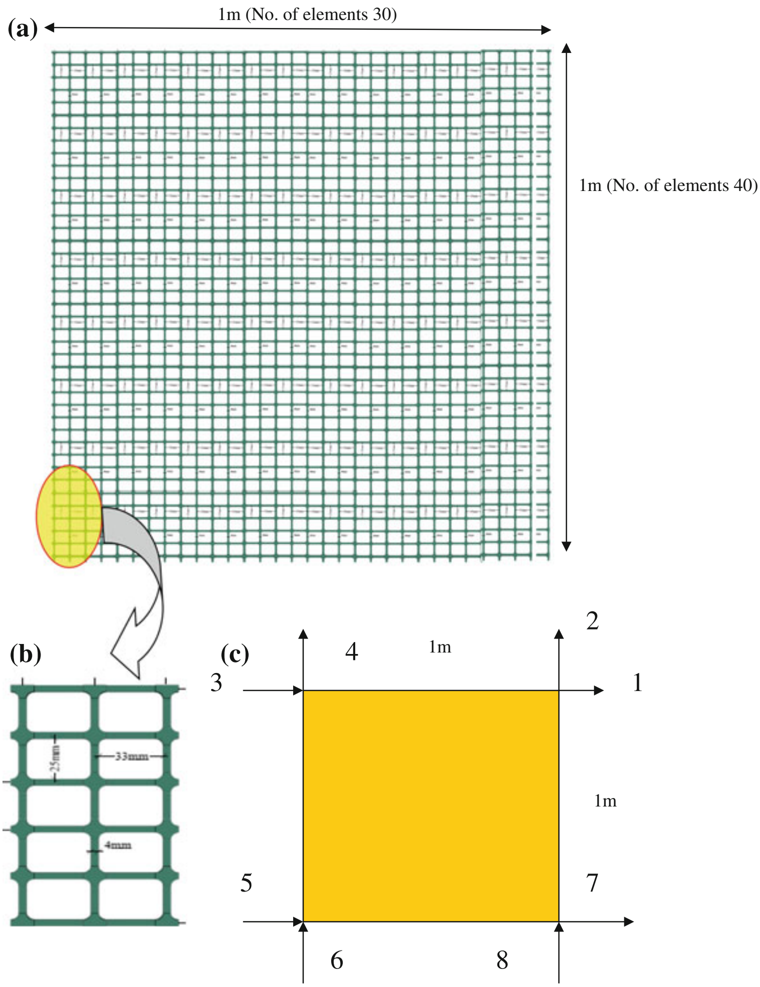

Fig. 8 Details of geogrid and macroelement: **a** geogrid of size 1 m × 1 m with apertures, **b** geometrical details of geogrid, **c** geogrid represented as macroelement of size 1 m × 1 m [8]

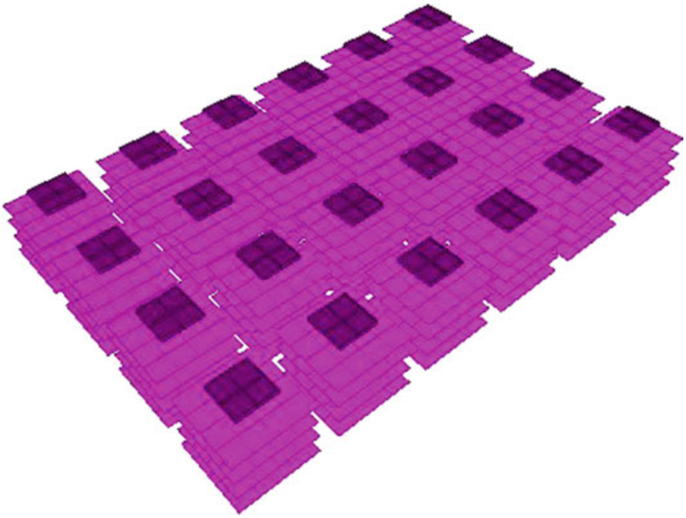

Fig. 9 Footing and geogrid arrangements [8]

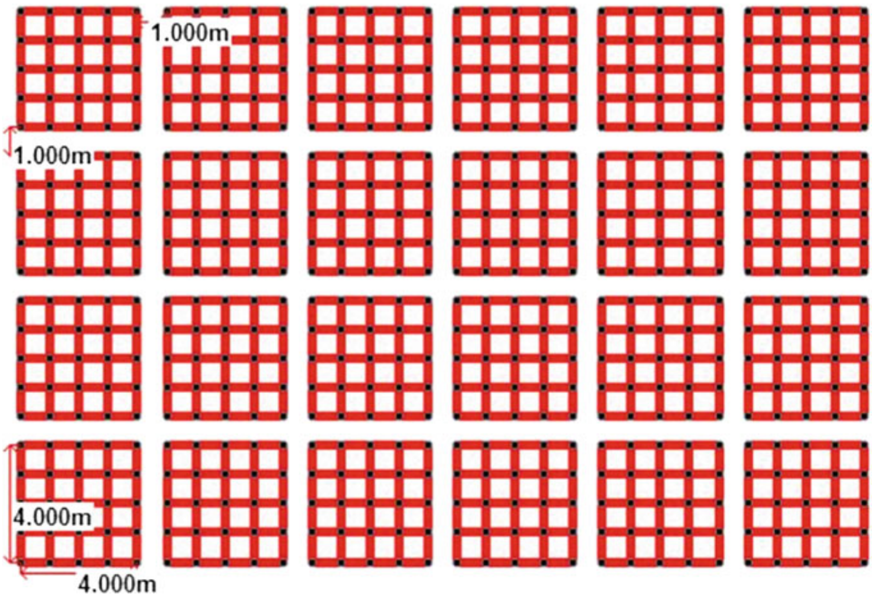

Fig. 10 FEM modelling of geogrid [8]

$$[\mathrm{K}] = \begin{pmatrix} 83.39 & 25.017 & -60.753 & -2.082 & -17.423 & -25.018 & -5.214 & -2.082 \\ 25.017 & 88.66 & -2.083 & -5.411 & -25.017 & -17.826 & 2.082 & -65.423 \\ -60.753 & -2.083 & 83.39 & -25.017 & -5.214 & 2.082 & -17.423 & 25.018 \\ 2.082 & -5.411 & -25.017 & 88.66 & -2.082 & -65.423 & 25.017 & -17.826 \\ -17.423 & -25.018 & -5.214 & -2.052 & 83.39 & 25.017 & -60.753 & 2.082 \\ -25.017 & -17.826 & 2.082 & -65.423 & 25.017 & 88.66 & -2.083 & -5.411 \\ -5.214 & 2.082 & -17.423 & 25.019 & -60.753 & -2.083 & 83.39 & -25.017 \\ -2.082 & -65.423 & 25.017 & -17.826 & 2.082 & -5.411 & -25.017 & 88.66 \end{pmatrix} \quad (1)$$

Figure 9 shows the arrangement of footings and geogrid below foundations. Figure 10 shows the arrangement of macroelements representing geogrid in plan.

7 Nonlinear SSI and RSSI Analyses of Space Frame-Footing–Soil System

The finite element model for nonlinear SSI nonlinear analysis is similar to the model used in linear SSI analysis as shown in Figs. 1 and 2, except for nonlinear material property of soil. In nonlinear analysis, the soil is modelled as hypoelastic material. The hypoelastic parameters were obtained from the experimental work done by Krishnamoorthy and Rao [7]. The model properties are mentioned in Tables 3 and 4. To conduct nonlinear RSSI analysis, the frame-footing–reinforced soil model adopted is same as that adopted in linear RSSI model (Fig. 6).

8 Results and Discussions

The location of a point in soil is expressed in terms of dimensionless parameters *X*/*L* and *Z*/*B*. The terms *L* and *B* are length and breadth of building along *X* and *Y* directions as shown in Fig. 3a. All the output parameters or responses related to semi-infinite media are plotted both in two-dimensional and three-dimensional graphs during the course of study.

8.1 Displacements in Linear SSI Analysis

Figure 11a shows the vertical deformation at foundation level in the longitudinal direction of the soil mass. Maximum vertical displacement and horizontal displacements are presented in Table 5. Figure 11b, c shows the displacement

Table 3 Properties of soil used in nonlinear SSI and RSSI analyses (after Krishnamoorthy and Rao [7])

Properties	Values
Liquid limit	54
Plastic limit	40
Plasticity index	14
Shrinkage limit	20
Water content	28
Specific gravity	2.65
Wet density (kN/m^3)	18.18

Table 4 Hypoelastic model parameters used in nonlinear SSI and RSSI analyses (after Krishnamoorthy and Rao [7])

Model parameters		Values
K modulus	$\lambda\backslash V_i$	0.02
	$\kappa\backslash V_i$	0.003
	P'cons	21,000 Pa
J modulus	*A*	100
	N	100
G modulus	*E*	0.001
	F	0.56

contours at foundation level and along the longitudinal section. Figure 12a, b shows the longitudinal displacements, at foundation levels, and Fig. 12c, d shows the transverse displacements at foundation levels.

8.2 Displacements in Linear RSSI Analysis

Figure 13a shows the vertical deformation at foundation level along the longitudinal direction of the soil mass. Maximum vertical displacement and horizontal displacements are presented in Table 5. Figure 13b, c shows the displacement contours at foundation level and along longitudinal section taken at centre. Figure 14a, b shows the longitudinal displacements at foundation levels, and Fig. 14c, d shows the transverse displacements at foundation levels.

Figure 15a, b shows lateral displacements at foundation level along *X* and *Z* directions found to reduce by 42 and 45.8%, respectively, in linear RSSI analysis with respect to linear SSI analysis. Figure 16 shows the vertical displacements in linear SSI and RSSI analyses at foundation level along longitudinal line at *Z*/*B* = 0.0. It is observed that the vertical displacements are reduced merely by 3.72% in RSSI analysis when compared to linear SSI.

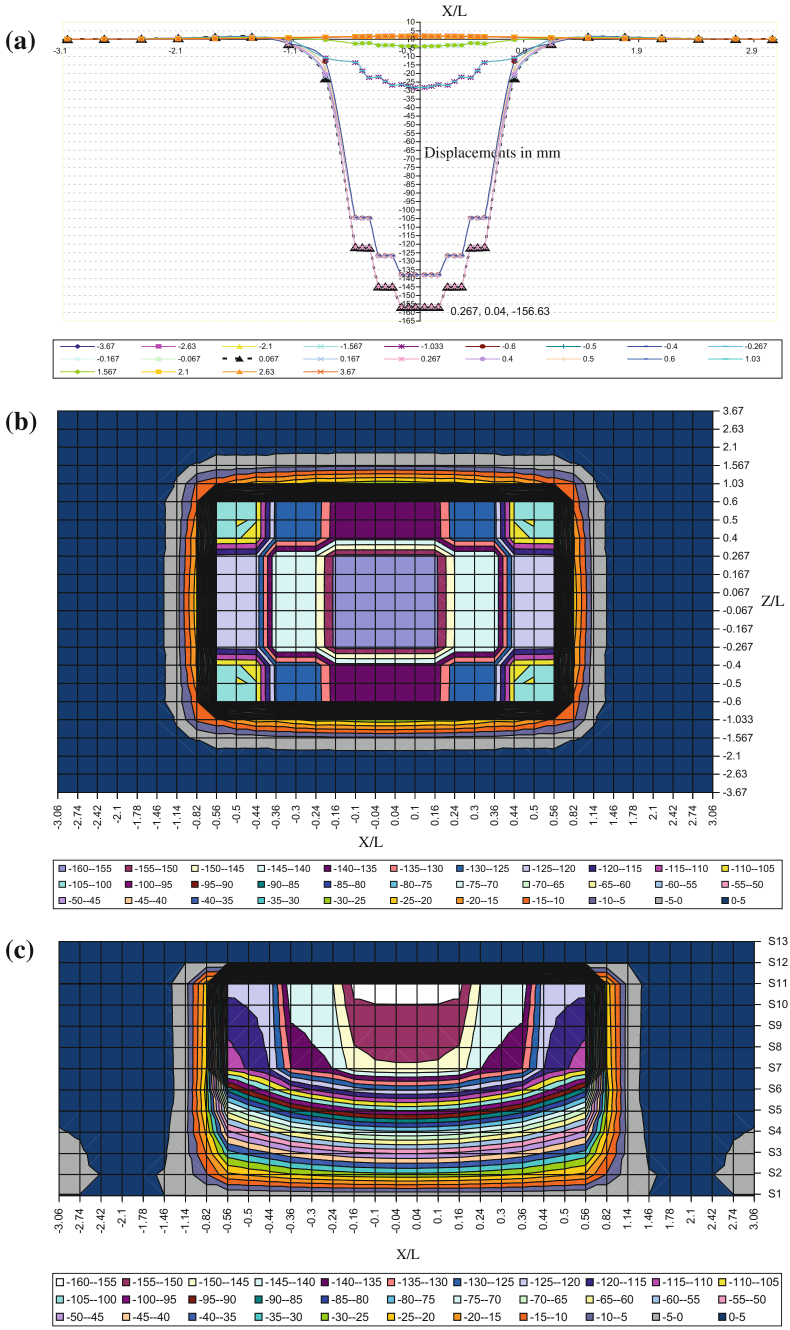

Fig. 11 Vertical displacements in mm in linear SSI analysis: **a** vertical displacements at foundation level, **b** contours of vertical displacements at footing level, **c** vertical displacements along longitudinal section [8]

Table 5 Vertical and horizontal displacements in reinforced soil for different analyses [8]

Type of analysis	Axis	*X*/*L*	*Z*/*B*	Maximum displacement
Linear SSI	*X*-axis	0.267	0.04	−156.63 mm vertical
		0.82	0.167	9.69 mm horizontal
	Z-axis	1.03	0.04	12.98 mm horizontal
Linear RSSI	*X*-axis	0.267	0.16	−150.8 mm vertical
		0.82	0.167	5.62 mm horizontal
	Z-axis	1.03	0.04	7.03 mm horizontal
Nonlinear SSI	*X*-axis	0.16	0.267	−185.3 mm vertical
		0.82	0.167	11.32 mm horizontal
	Z-axis	0.04	1.03	12.925 mm horizontal
Nonlinear RSSI	*X*-axis	0.16	0.267	−173.8 mm vertical
		0.04	1.03	9.72 mm horizontal
	Z-axis	0.04	1.03	10.98 mm horizontal

8.3 Deformation and Settlements in Nonlinear SSI Analysis

Figure 17a shows the vertical deformation at foundation level in the longitudinal direction of the soil mass. Figure 17b shows displacement contours at foundation level. Figure 17c shows displacements along longitudinal section. Figure 18 shows horizontal displacements along longitudinal and transverse directions. In Fig. 18a, b, longitudinal displacements at foundation levels are shown. Similarly, in Fig. 18c, d, transverse displacements at foundation levels are shown.

8.4 Deformation and Settlements in Nonlinear RSSI Analysis

Figure 19a shows the vertical deformation at foundation level in the longitudinal direction of the soil mass. Figure 19b shows displacement contour at foundation level. Figure 19c shows displacements along longitudinal section. Maximum lateral displacements along *X* and *Z* directions are reduced by 14 and 15% in nonlinear

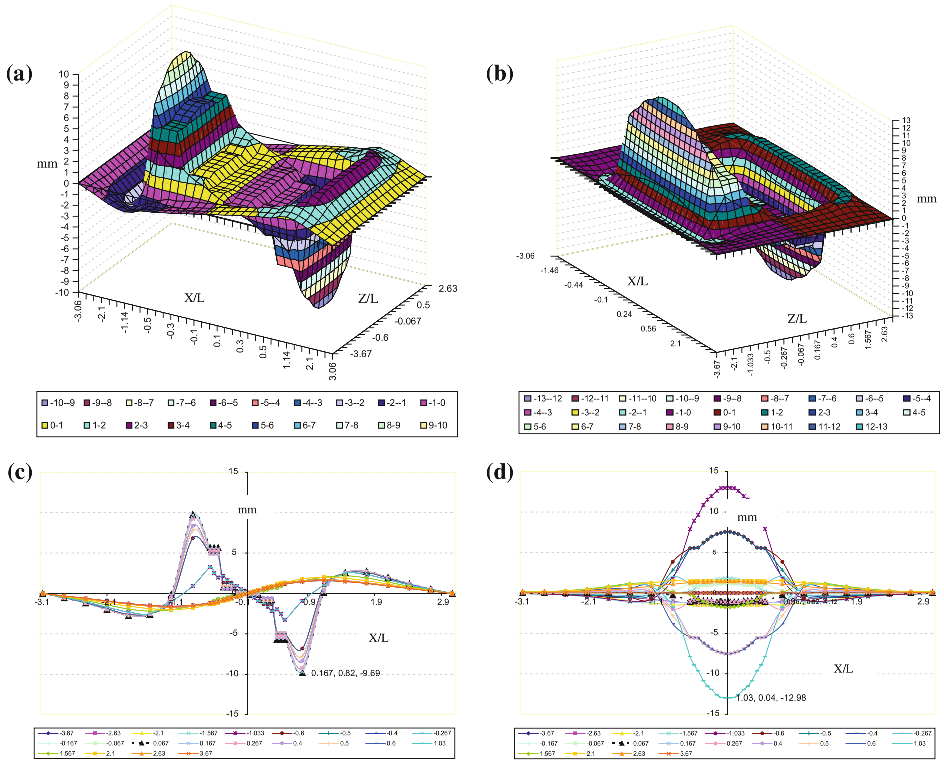

Fig. 12 Horizontal displacements in mm in linear SSI analysis: **a** and **b** longitudinal displacements at foundation level; **c** and **d** transverse displacements at foundation level [8]

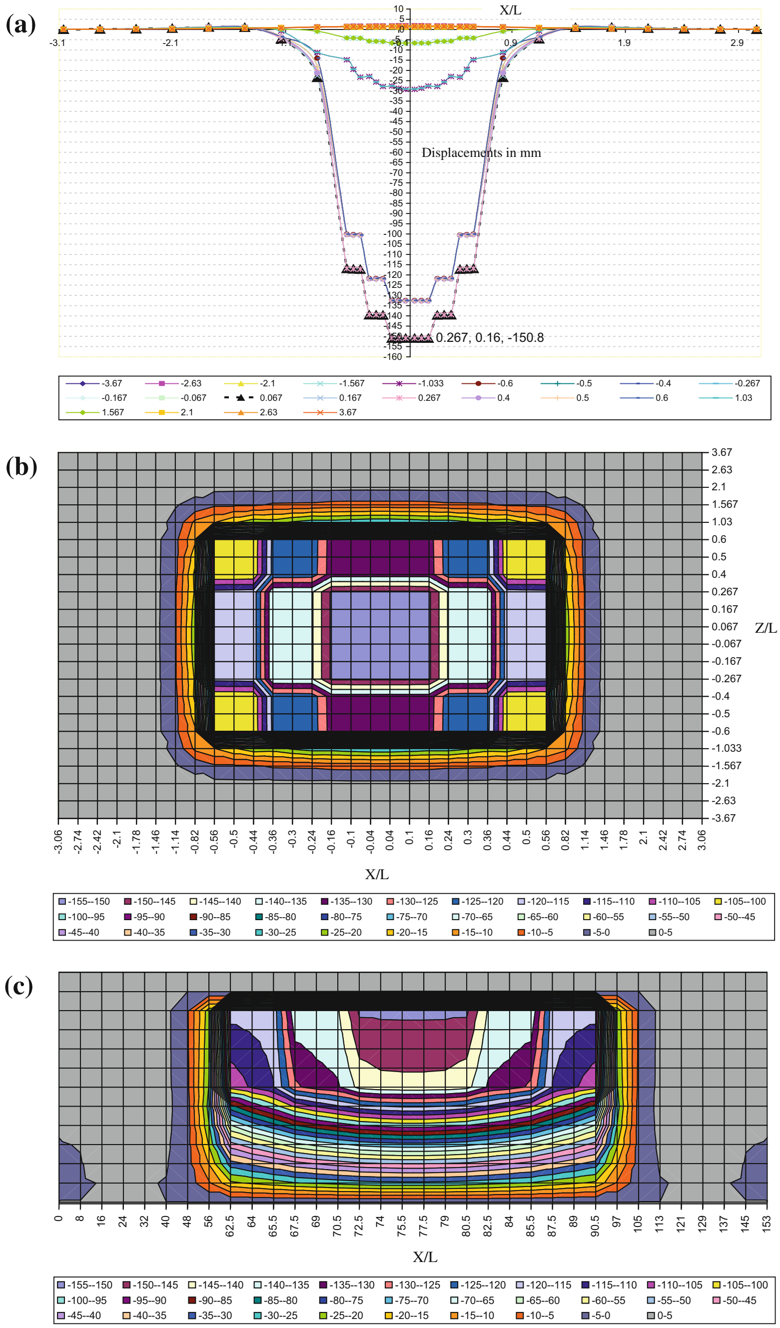

Fig. 13 Vertical displacements in mm in linear RSSI analysis: **a** vertical displacements at foundation level, **b** contours of vertical displacements at footing level, **c** vertical displacements along longitudinal section at centre [8]

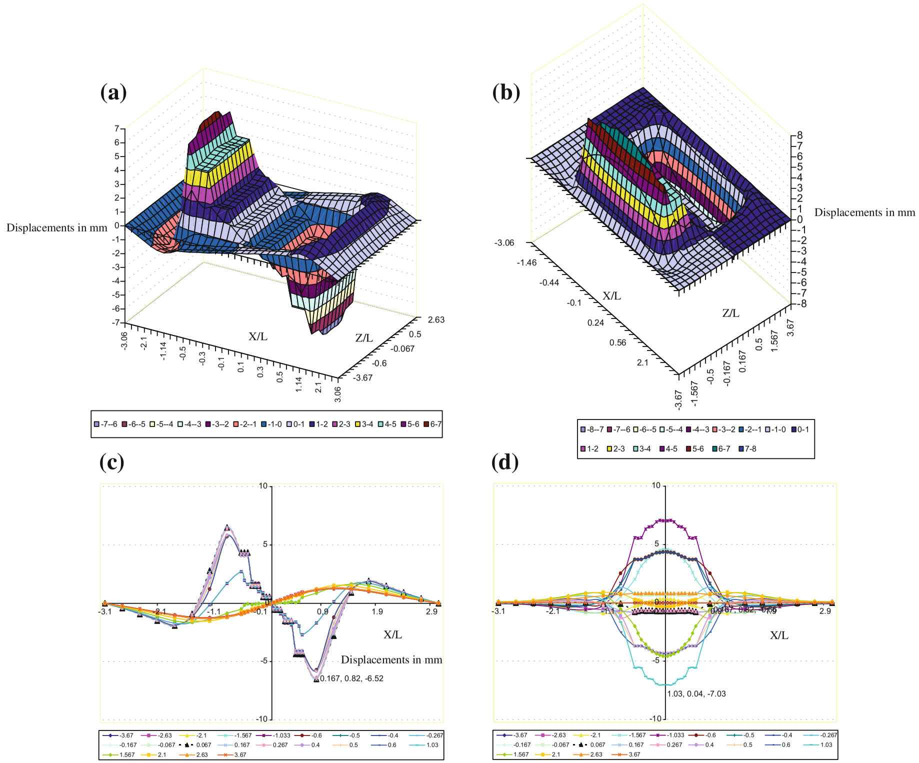

Fig. 14 Horizontal displacements in mm in linear RSSI analysis: **a** and **b** longitudinal displacements at foundation level; **c** and **d** transverse displacements at foundation level [8]

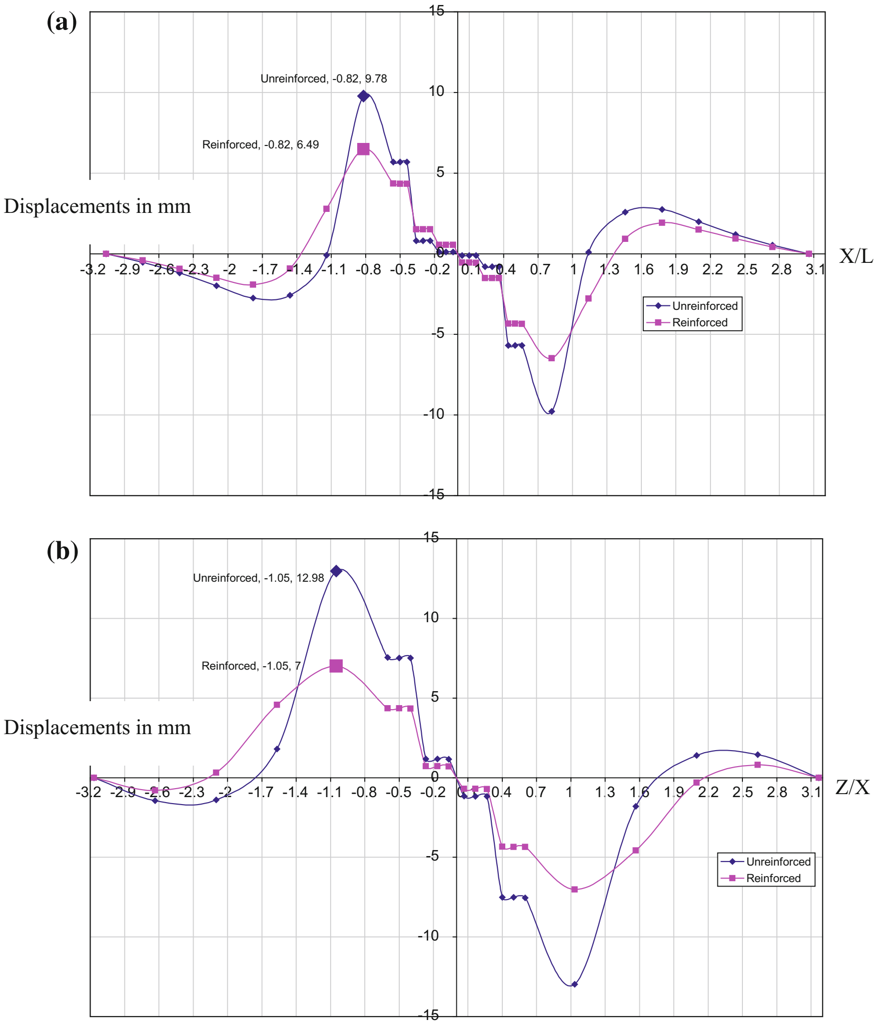

Fig. 15 Horizontal displacements in mm in linear RSSI analysis: **a** longitudinal displacements at foundation level and **b** transverse displacements at foundation level [8]

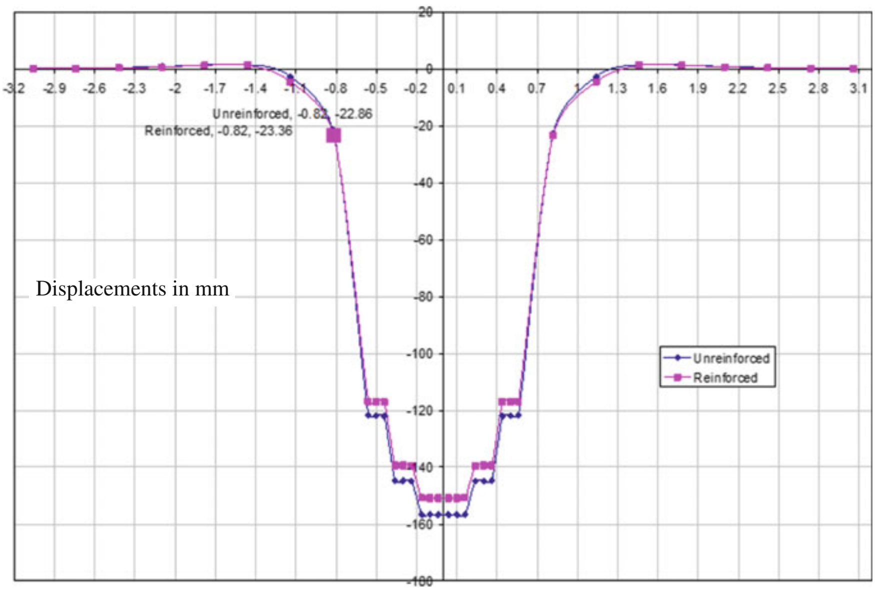

Fig. 16 Vertical displacements in mm in linear SSI and RSSI analyses at foundation level [8]

RSSI analysis when compared to nonlinear SSI analysis. But the vertical displacements are reduced merely by 6.2%.

Figure 20 shows horizontal displacements along longitudinal and transverse directions. In Fig. 20a, b, longitudinal displacements at foundation levels are shown. Similarly, in Fig. 20c, d, transverse displacements at foundation levels are shown.

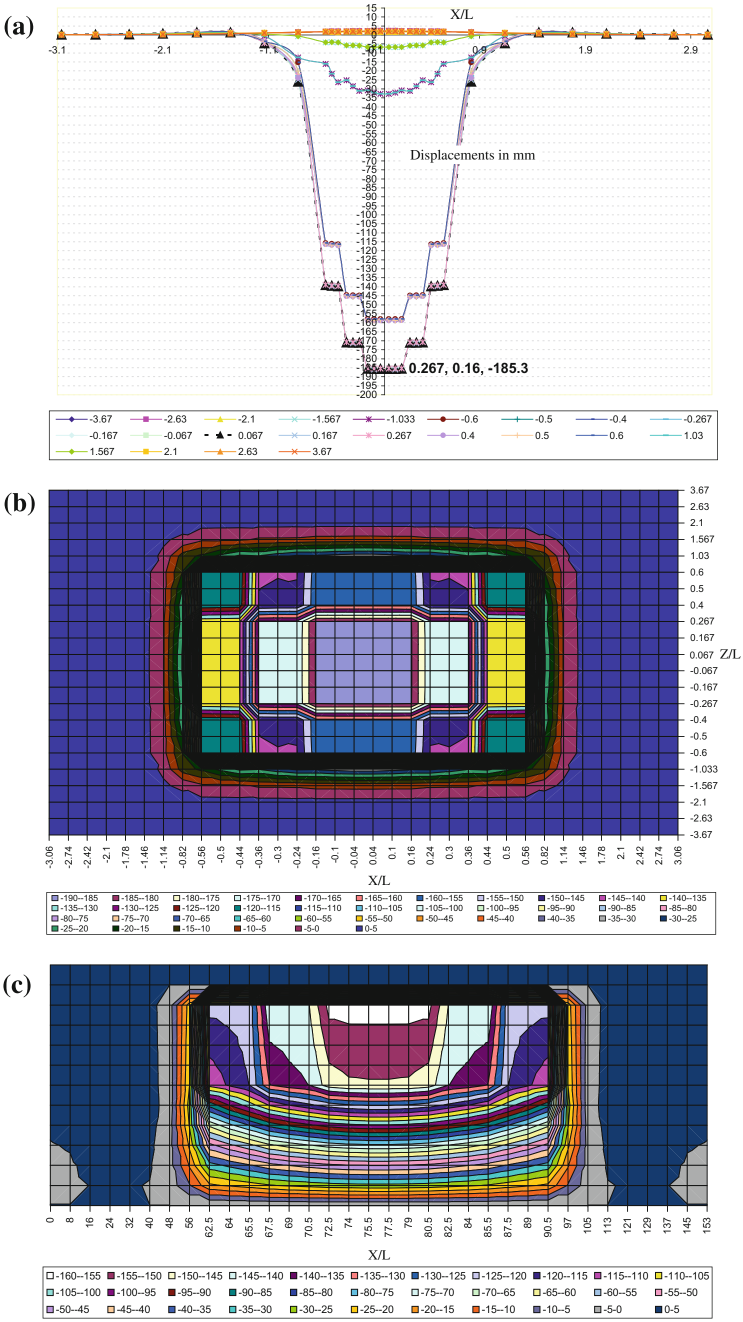

Fig. 17 Vertical displacements in mm in nonlinear SSI analysis: **a** vertical displacements at foundation level, **b** contours of vertical displacements at footing level, **c** vertical displacements along longitudinal section at centre [8]

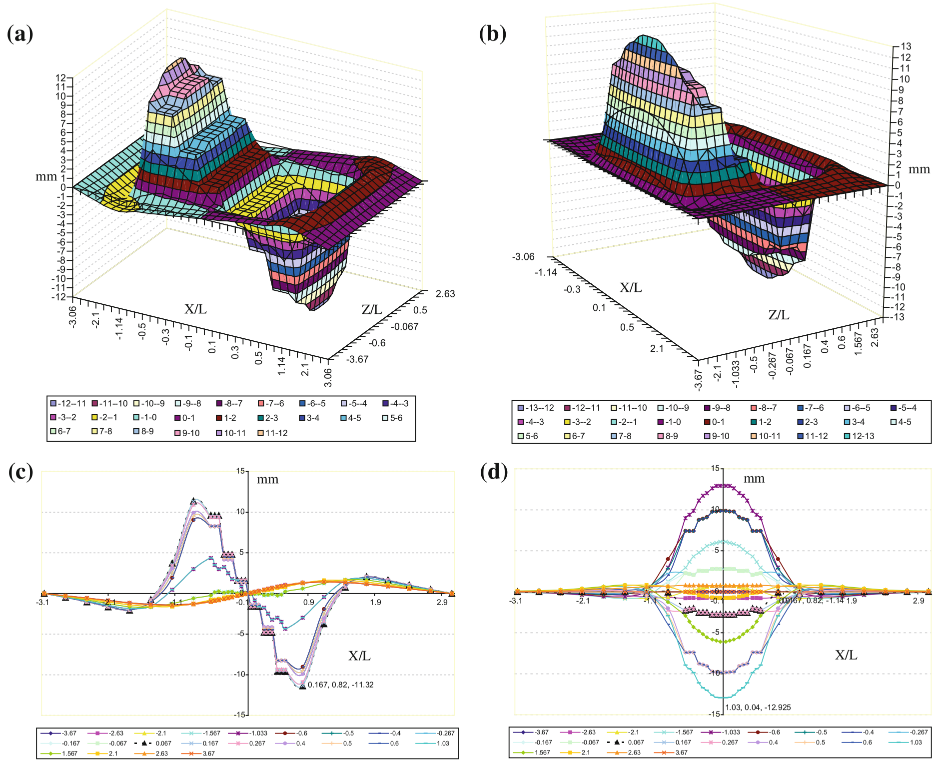

Fig. 18 Horizontal displacements in mm in nonlinear SSI analysis: **a** and **b** longitudinal displacements at foundation level; **c** and **d** transverse displacements at foundation level [8]

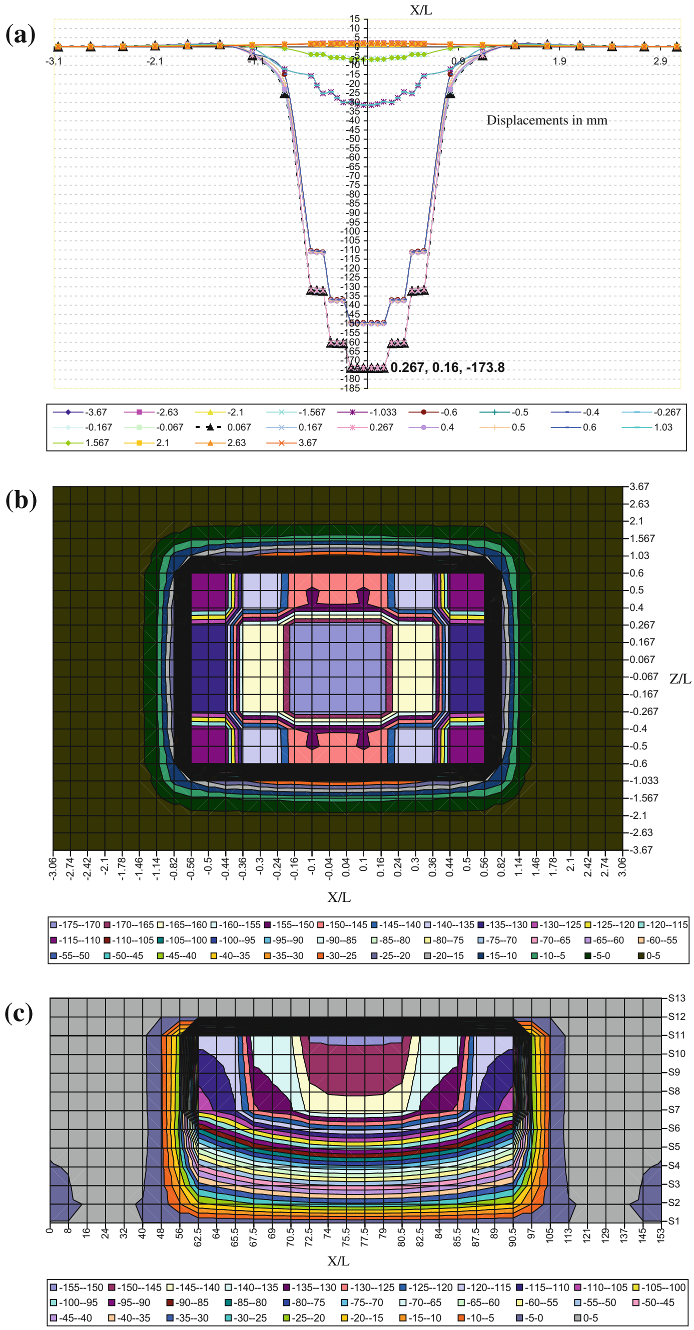

Fig. 19 Vertical displacements in mm in nonlinear RSSI analysis: **a** vertical displacements at foundation level along longitudinal directions, **b** contours of vertical displacements at footing level, **c** vertical displacements along longitudinal section at centre [8]

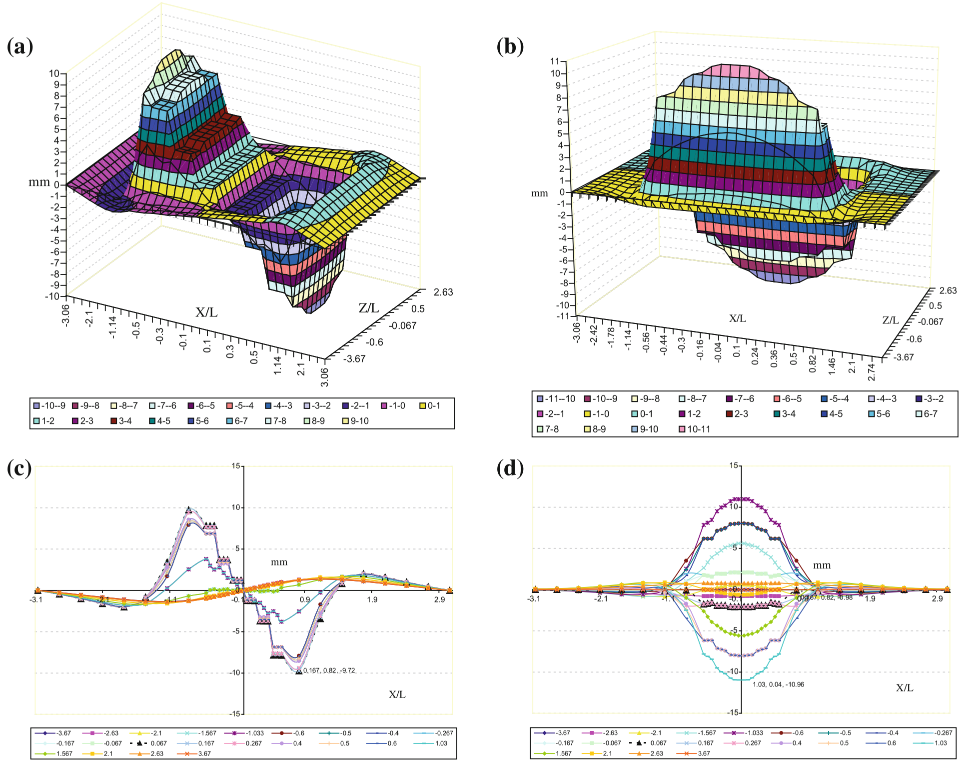

Fig. 20 Horizontal displacements in mm in nonlinear RSSI analysis: **a** and **b** longitudinal displacements at foundation level; **c** and **d** transverse displacements at foundation level [8]

9 Conclusions

1. Maximum lateral displacements along *X* and *Z* directions are reduced by 42 and 45.8% in linear RSSI analysis when compared to linear SSI analysis.
2. The vertical displacements are reduced merely by 3.72%. Maximum lateral displacements along *X* and *Z* directions are reduced by 14 and 15% in nonlinear RSSI analysis when compared to nonlinear SSI analysis.
3. The vertical displacements are reduced merely by 6.2%. As a result, the axial forces in beams have been increased in ground floor and have been reduced in higher floors.
4. Any change in the differential settlement, contact pressure and foundation stiffness results in significant changes in the moments and forces in the superstructure. In RSSI analysis, horizontal displacements and horizontal stresses have been reduced compared to SSI analysis as a consequence of shear forces which have been reduced in columns. Under RSSI analysis, the performance of the structure results in reduced displacements and member end actions resulting in economic structures.

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