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Vertical Stresses in Soil below a Three Dimensional Structure due to Reinforced Soil Structure Interaction

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ABSTRACT: Numerous problems in civil engineering involve interaction between the structures and the soil. This interaction plays a significant role in the response of a structure and may change the magnitude of displacements, stresses and other responses of a structure in comparison with the non-interactive analysis. In the non-interactive analysis, the structure is assumed to be resting on fixed supports and shall not undergo any relative motions. In Soil Structure Interaction (SSI) analyses, the displacements and stress resultants are found to deviate considerably from non-interactive analysis there by rendering the non-interactive analysis as unrealistic and it is absolutely necessary to consider SSI in the analysis and design of structures.

In the present paper, the response of a three dimensional structure is studied in Reinforced Soil Structure Interaction (RSSI). RSSI refers to the interaction between the reinforced soil and the structure. Comparative numerical studies have also been carried out by using finite element analyses to study the effects of a 3D frame resting on unreinforced and reinforced soil by developing programmes, SSI-LIN, SSI-NLIN, RSSI-LIN and RSSI-NLIN for both the linear and non-linear analyses. SSI-LIN and RSSI-LIN are the programs developed to conduct linear analyses and SSI-NLIN and RSSI-NLIN are the programs developed to conduct nonlinear analyses. They are used to study displacements, stresses in soil and member end forces in the structure. The present paper discusses only the effects of SSI and RSSI analyses on stresses in soils.

In this study, macro element approach is adopted as modelling the geogrid proves to be very difficult with apertures of size 33 × 25 mm. This is due to limitations of software and prolonged execution time. The vertical pressure at various points are not affected much in non-linear RSSI analysis compared to non-linear SSI. However there is reduction in longitudinal and transverse stresses in non-linear RSSI analysis compared to non-linear SSI. There is also a change in the pressure bulb below foundation level. Hence it is important to conduct RSSI studies.

Keywords: Geo-grid, SSI, RSSI, macro-element, FEA, reinforced soil.

I. INTRODUCTION

Very few researches have been carried out on soil–structure interaction effect by considering three dimensional space frames. SSI studies that consider the yielding of structures and non–linearity of soil are few, especially those involving investigations on the effects of non-linearity of SSI system on the overall behaviour in terms of displacements and stresses [5]. Boudaa *et al.*, (2019) conducted static interaction analysis between beam and layered soil using a two-parameter elastic foundation. They presented shear deformations to show the crucial influence on the beam, on the structure and on the interface behaviors [6].

Few researchers have applied the finite element analysis to study super structure – raft /combined footing soil as a single compatible unit [1, 2]. The SSI studies conducted by a few researchers clearly showed that a two-dimensional plane frame SSI analysis might substantially over or underestimate the actual interaction effect in a space frame [3, 4]. The interactive behaviour of the 3D frame-Isolated footing-soil system was studied [5].

Studies on linear and Non-linear SSI analyses of structure resting on raft foundation showed that the both the maximum and differential settlements in soil tend to be more in non-linear analysis in comparison to the linear analysis. Researchers found that the maximum vertical stresses reduce in non-linear analysis in comparison with the linear analysis. However the stress resultants, in the frame varied (either decreased or increased) based on their location in non-linear analysis when compared to linear analysis [6]. Sufficient studies have been carried out on SSI for structures resting on unreinforced soil. But Reinforced soil-structure interaction (RSSI) involving the structures supported on reinforced soil is still unexplored. The analysis that considers the structure-foundation- reinforced soil as a single system is coined as Reinforced Soil Structure Interaction (RSSI) analysis in the current work. In this study, macro element approach is adopted as modelling the geogrid proves to be very difficult with apertures of size 33 × 25 mm. This is due to limitations of software and prolonged execution time.

II.MATERIALS AND METHODOLOGY

In this study, a software has been developed based on finite element has been developed to carry out the SSI and RSSI analyses. The structure chosen for the current study is depicted in Fig. 1 and taken from Rajashekhar *et al.*, [5]. SSI analysis is performed on the structure resting on isolated footings of size 2m × 2m supported on the soil mass of size 153 × 95 × 20m and beams carrying uniformly distributed load (UDL) of 31kN/m. In RSSI analysis the isolated footings of the structure are underlain by geogrid and the Reinforced Soil-Structure is analysed for the same loads.

Linear SSI analysis of space frame-footing -soil system: The physical model used for the interactive analysis consists of a four storey, five bay by three bay, space frame-isolated footings-soil system. The isometric view of the space frame-isolated foundation-soil system is shown in Fig. 1. The layout details of the frame are shown in Fig. 2.The details of the SSI problem used for validation are presented in Table 1.

Finite element formulation in the SSI analysis of the frame-isolated footings -soil system is as shown in Fig. 3(a, b, c). The soil which is semi-infinite media is modelled with 43 × 10 × 27 layers along the longitudinal, vertical and transverse directions respectively resulting in 11.610 brick elements. Each footing of size 2 x 2m is modelled as four plate elements measuring 1m x 1m.

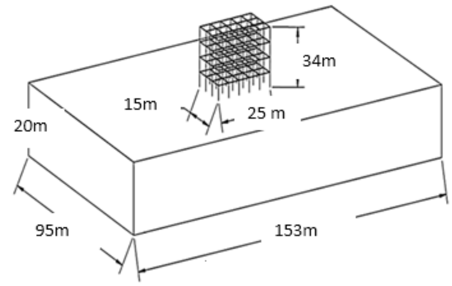
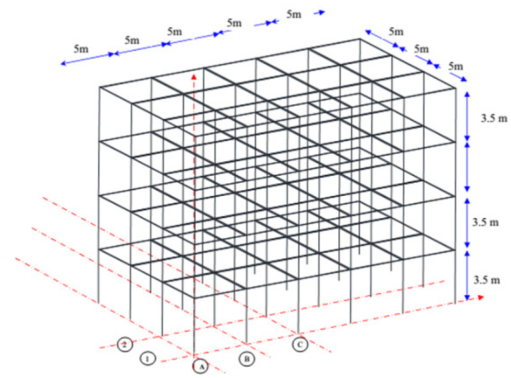
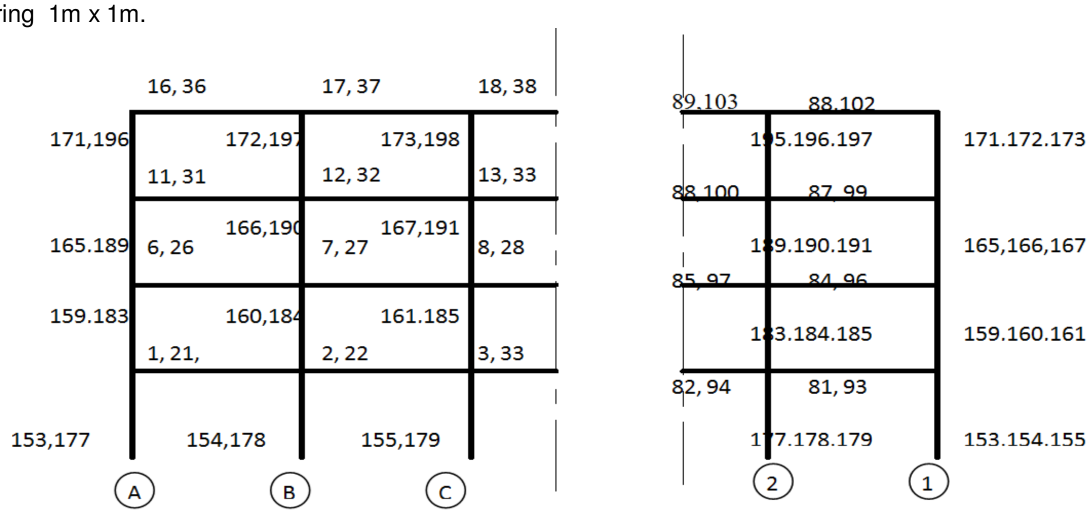


Fig.1. Structure-footing-soil system [5].



(a)



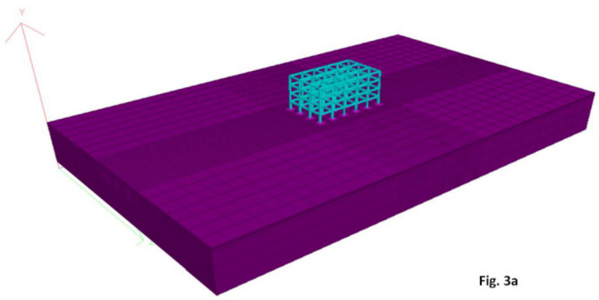
(b)

Fig. 2. Details of quarter frame [5].

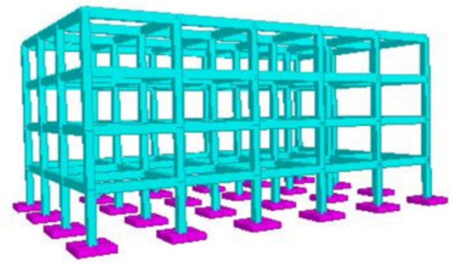
Table 1: Details of the SSI Problem used for Validation[5].

S. No.	Structure	Component	Details
1.	Frame	No. of storeys	5
		No. of bays	5 × 3
		Storey height	3.5m
		Bay width	5m
		Beam size	0.3m × 0.6m
		Column size	0.4m × 0.4m
		Footing size	3.0 × 3.0 × 0.4m
2.		Soil mass	153.0 × 95.0 × 10
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

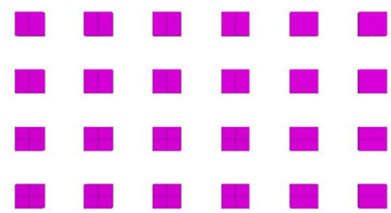
The number of plate elements used is 96. The number of beam elements along the longitudinal direction (X-direction) is 80.72 along the transverse (Z-direction) and 96 along the vertical (Y-direction). The graphs are plotted in terms of dimensionless Parameters X/L and Z/B where L and B are dimensions of the frame along X and Z directions as shown in Fig. 3 (a).
The various structural components of the system with their respective degrees of freedom are depicted in Fig. 4 and are modelled as follows:
–Beams and columns 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. 4 (a).
– Eight-noded brick element with three translational degrees of freedom per node is used to model the soil mass and is shown in Fig. 4 (b).



(a) Frame Isolated footing soil system.



(b) Structure Foundation system.



(c) Reference axis and arrangement of isolated footings.

Fig. 3.

– Plate elements with five degrees of freedom per node i.e., three translational degrees of freedom and two rotational degrees of freedom are used to model the individual footing and is shown in Fig. 4.

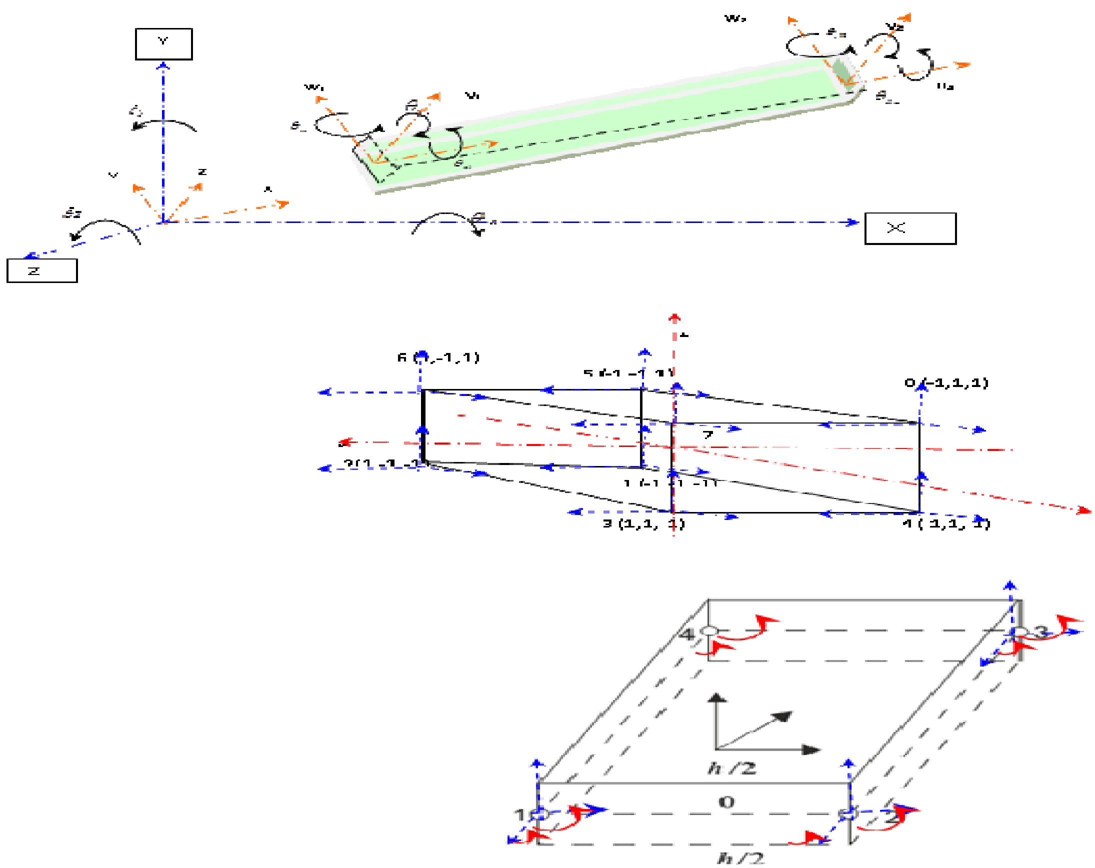


Fig. 4.

Validity of the proposed physical model: The settlements of the isolated footings obtained from the proposed analysis are tabulated in Table 4 and their comparison with Rajashekhar *et al.,* [5] suggests that there is a very good agreement between the values of settlement obtained in both the studies. This justifies the finite element mesh extent considered.

Linear RSSI analysis of space frame-footing soilsystem: To carry out linear RSSI analysis, the frame-footing-reinforced soil used is modelled as shown in the Figs. 6 and 7.

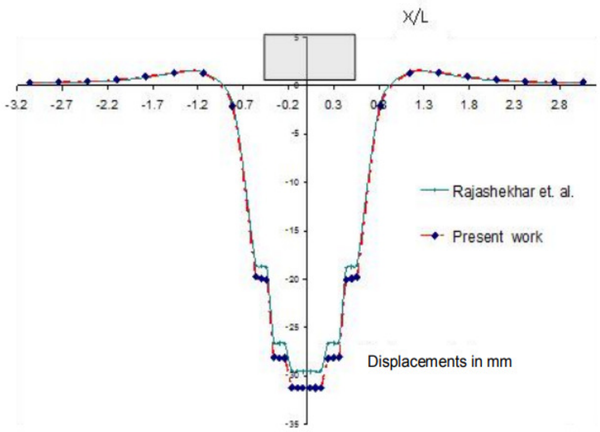


Fig. 5. Comparative settlements in mm at the centre in the present work and the referred work (Swamy *et. al.* (2011).

Below each 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 2m × 2m and the sizes of geogrid used are 4m x 4m. The geometric details of geo-grid are shown in Fig. 8. Properties of geogrid are given in Table 2.

Table 2: Properties of Geo-grids used [9].

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

The geogrid used is made of apertures of size 33 × 25 mm as shown in Fig. 8 (b). For a 1m × 1m size geogrid the number of apertures are 30 x 40 in mutually perpendicular directions as shown in Fig. 8 (a). It is difficult to model the geogrid with apertures shown in Figure 8a due to enormous execution time and software limitation, macro element approach is adopted [8]. This method overcomes the tedious process of modelling the geo-grid with small apertures. A 2 dimensional rectangular element having 4 nodes with 2 degrees of freedom per node as shown in Fig. 8 (c) is used to model the geo-grid of 1m × 1m with aperture size of 33 × 25mm (shown in Fig. 8 (a).

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

Non-Linear SSI and RSSI analyses of space frame-footing -soil system: The finite element model for non-linear SSI 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 non-linear analysis the soil is modelled as hypoelastic material. The Hypoelastic parameters were obtained from the experimental work done by Rao (2001) [8]. The soil used has a liquid limit of 54, plastic limit of 40,plasticity index of 14, shrinkage limit of 20, water content of 28%, specific gravity of 2.65 and wet density of 18.18kN/m^3 (Krishnamoorthy and Rao, 1995). The hypoelastic model parameters used in Non-linear SSI and RSSI Analysis [8] are presented in Table 3. To conduct nonlinear RSSI analysis, the frame-footing-reinforced soil model adopted is same as that adopted in linear RSSI model (Fig. 6).The stiffness matrix of the macro element for geogrid is given by Eqn. 1.The arrangement of footings with the geogrids below foundations is shown in Fig. 9. The macro elements representing geogrid in plan are shown in Fig. 10.

Table 3: Hypoelastic model Parameters used in Non-linear SSI and RSSI Analysis [8-10].

Model Parameters		Soil
K Modulus	λ/V_i	0.02
	κ/V_i	0.003
	P cons	21000 kPa
J	A	100
Modulus	N	100
G	E	0.001
Modulus	F	0.56

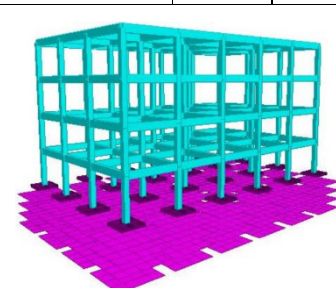


Fig. 6. Frame- footing –reinforcement model.

Table 4: Vertical and Horizontal Displacements in Reinforced Soil for different analyses.

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	12.98mm 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
Non-Linear 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
Non-Linear 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

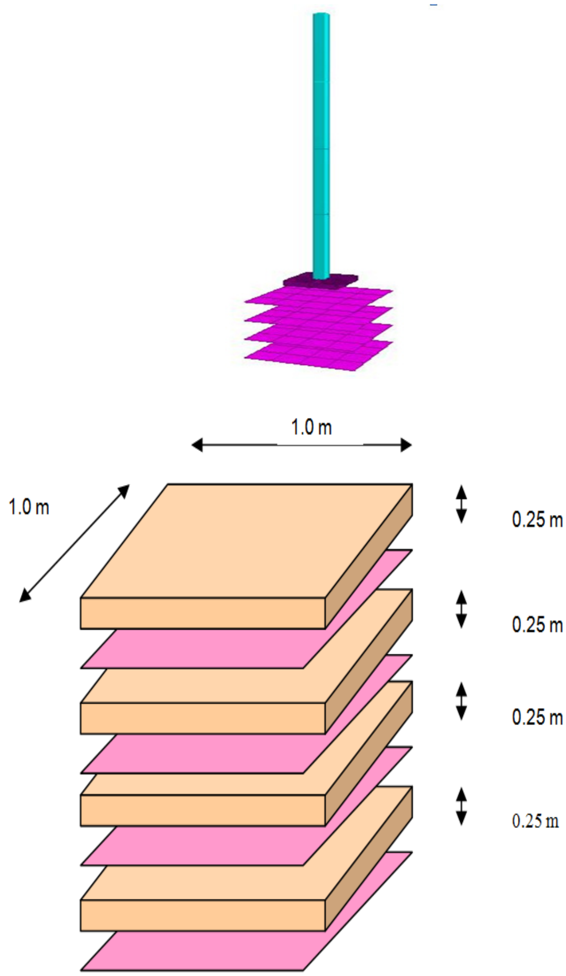


Fig. 7. Arrangement of geogrid (a) Modelling of column-foundation- Geogrid (b) soil-geogrid arrangement represented as macroelement in RSSI analysis.

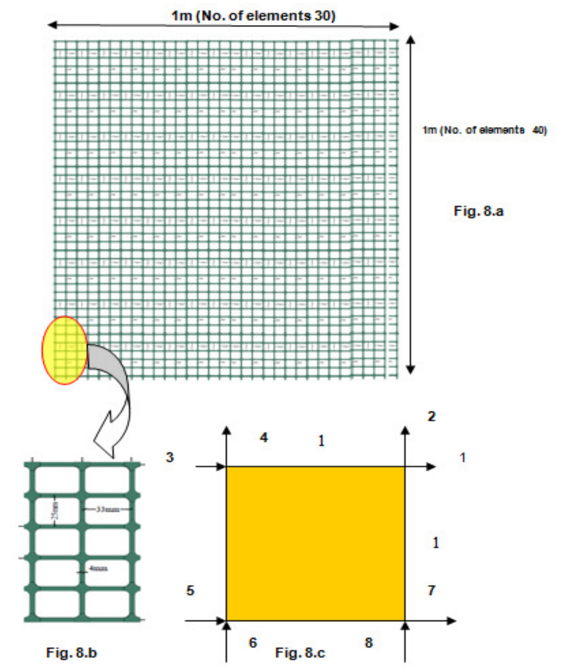
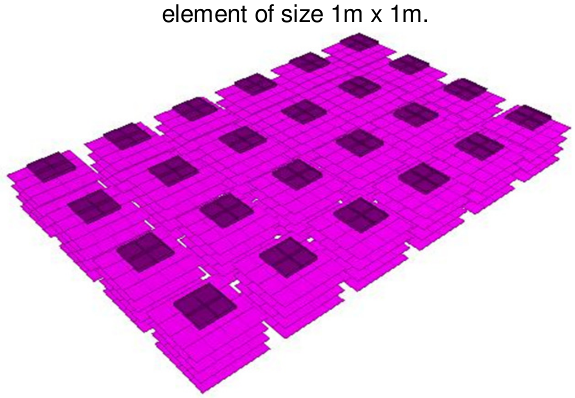
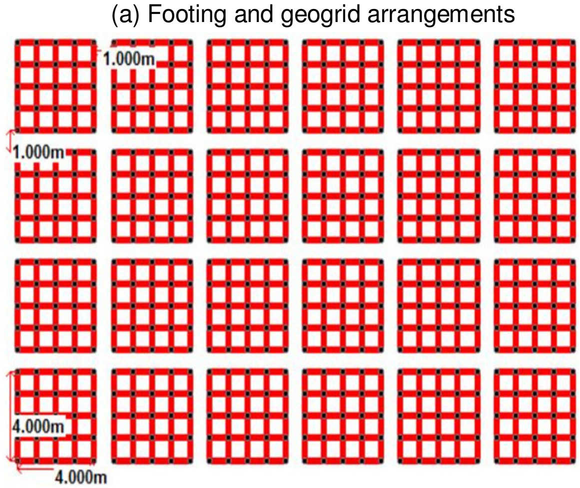


Fig. 8. Details of Geogrid and Macro element (a) Geogrid of size 1m x 1m with apertures (b) Geometrical details of geogrid (c) Geogrid represented as macro element of size 1m x 1m.



(a) Footing and geogrid arrangements



(b) FEM modelling of geogrid.

Fig. 9

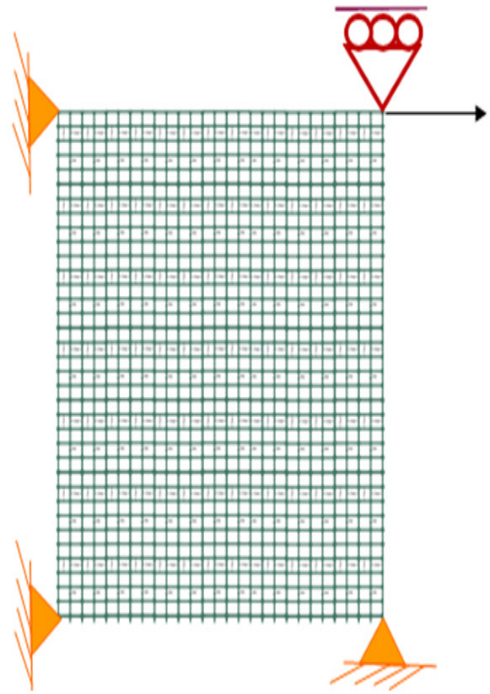


Fig. 10. Evaluation of first column elements of stiffness matrix of macro-element.

III. RESULTS AND DISCUSSION

Vertical stress contours at foundation level obtained in the linear SSI are shown in Fig. 11(a, b) shows the stress distribution at section A-A. Fig. 11(c) shows variation of stresses at foundation level along longitudinal sections taken across one breadth for different values of Z/B. The maximum stresses of 0.041 N/mm2 occur at X/L= +0.33 and Z/B= +0.55.

Vertical stress contours at foundation level in the linear RSSI are shown in Fig. 12 (a, b) shows stress distribution at section A-A. Fig. 12 (c) shows variation of stresses at foundation level along longitudinal sections taken across breadth for different values of Z/B. The maximum stresses of 0.04379 N/mm^2 occur at X/L= +0.33 and Z/B= +0.55.

Vertical stress contours at foundation level obtained in nonlinear SSI are shown in Fig. 13 (a, b) shows stress distribution at section A-A. Fig. 13 (c) shows variation of vertical stresses at sections taken along X-direction located across different positions in Z-direction. The maximum stresses of 0.056 N/mm^2 occur along X/L= +0.33 and Z/B= +0.2167

Vertical stress contours at foundation level obtained in nonlinear RSSI analysis are shown in Fig. 14 (a, b) shows stress distribution at section A-A. Fig. 14 (c) shows variation of vertical stresses at sections taken along X-direction located across different positions in Z-direction. The maximum stresses of 0.056 N/mm^2 occur at X/L= +0.33 and Z/B= +0.2167.

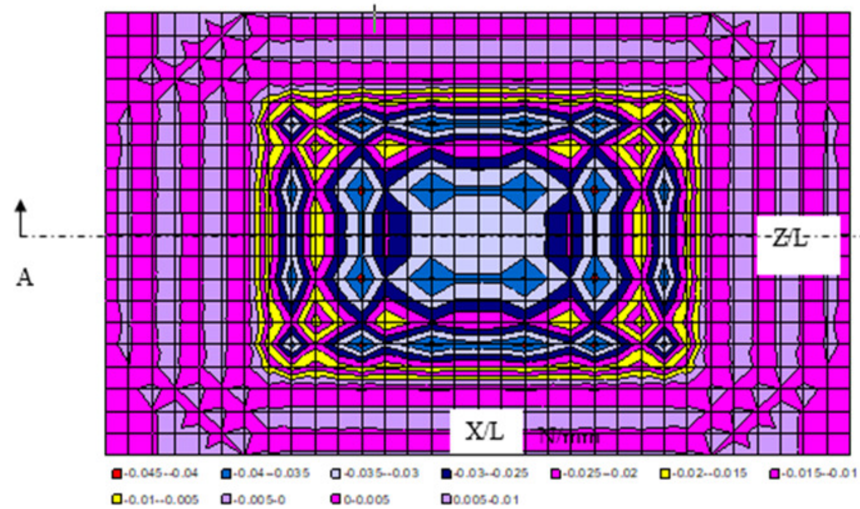


Fig. 11.a

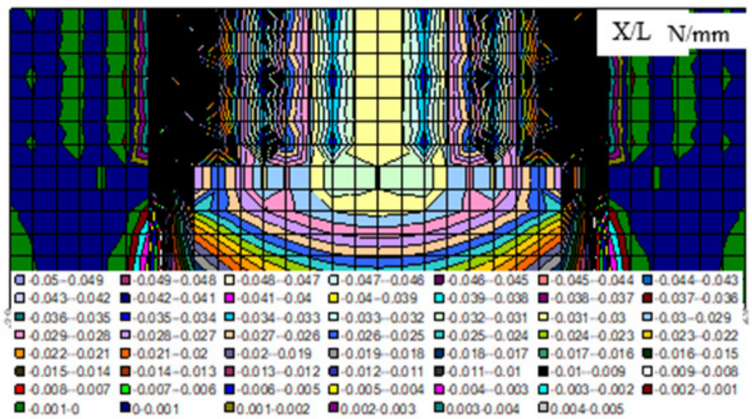


Fig. 11.b

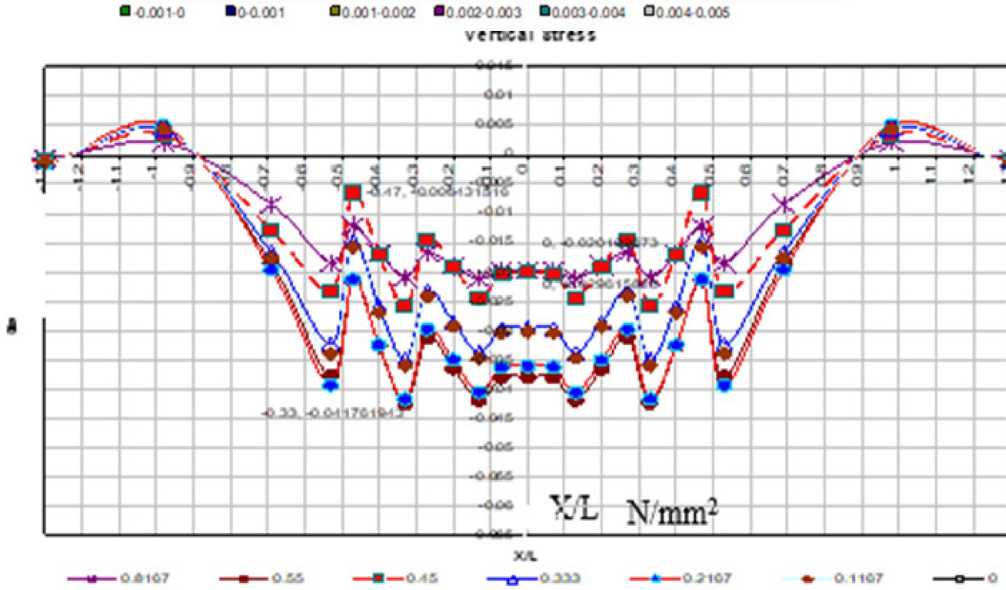


Fig. 11.c

Fig. 11. Vertical stresses in N/mm^2 linear SSI analysis (a) Contours of vertical stresses at footing level (b) Vertical stresses along longitudinal section at centre (c) Vertical stresses at foundation level along longitudinal sections for different values of Z/L.

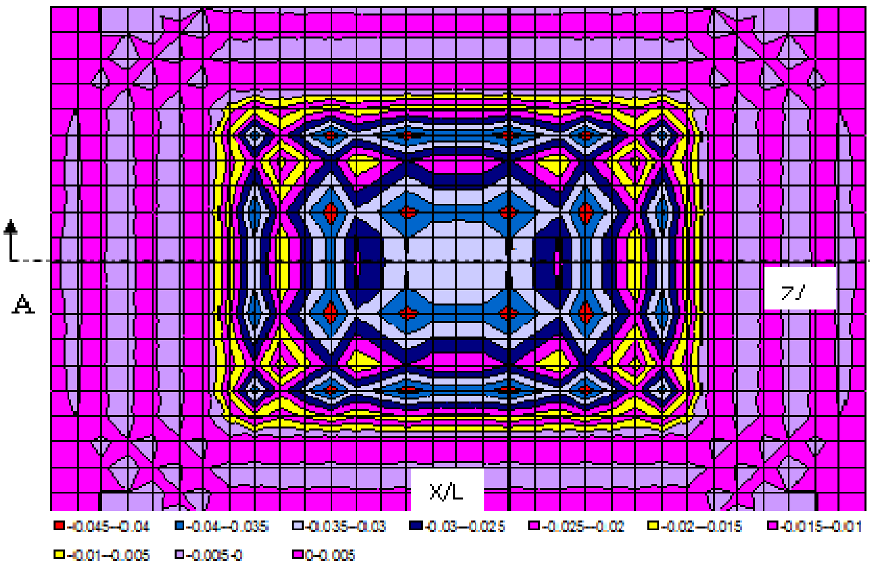


Fig. 12a

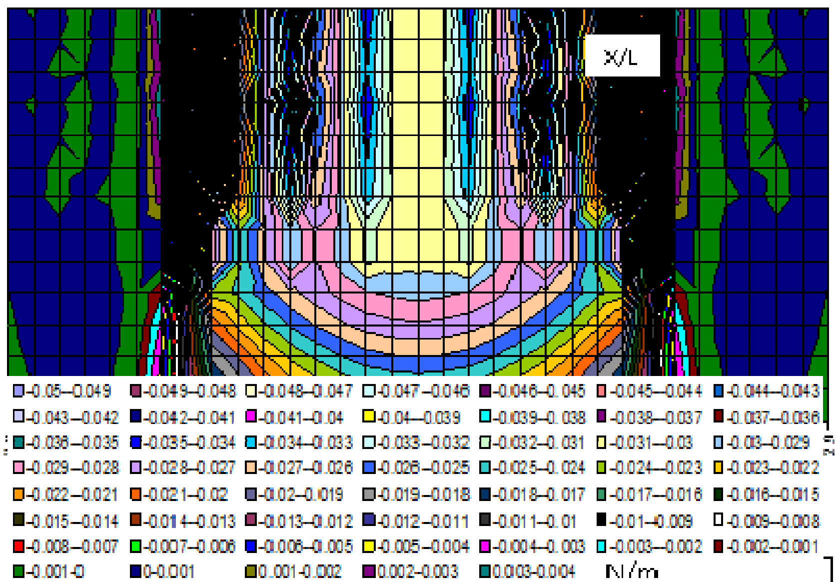


Fig. 12b

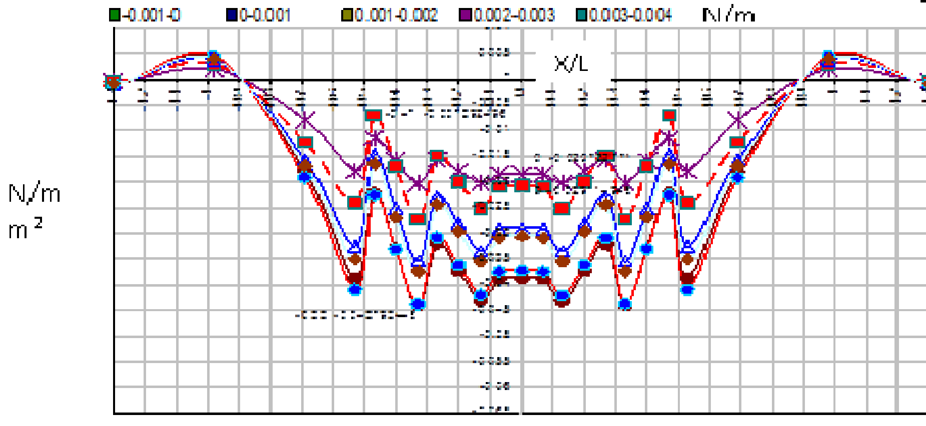


Fig. 12c

Fig. 12. Vertical stresses in N/mm^2 linear RSSI analysis (a) Contours of vertical stresses at footing level (b) Vertical stresses along longitudinal section at centre (c) Vertical stresses at foundation level along longitudinal sections for different values of Z/L.

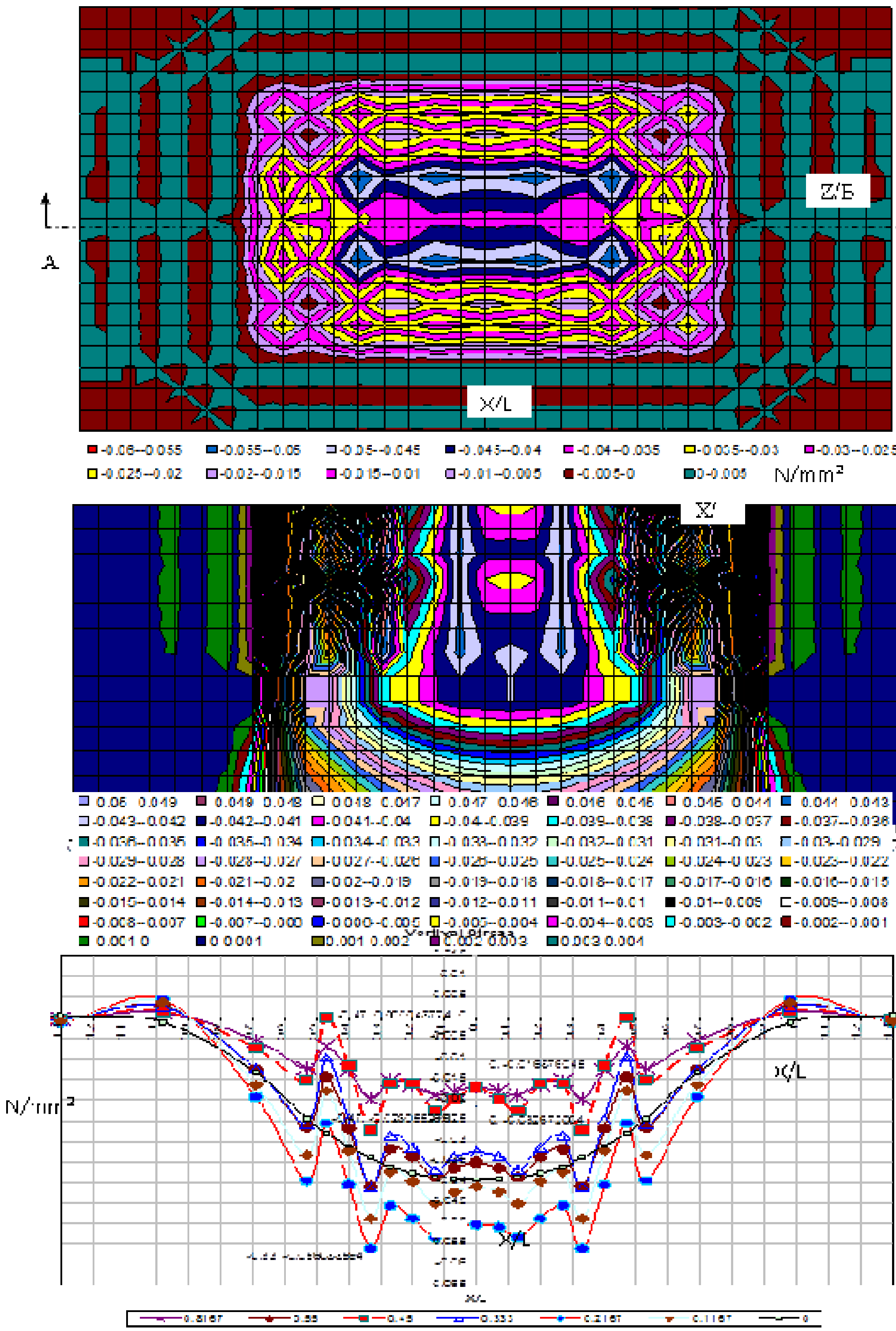


Figure 13a

Fig. 13b

Fig. 13c

Fig. 13. Vertical stresses in N/mm^2 Nonlinear SSI analysis (a) Contours of vertical stresses at footing level (b) Vertical stresses along longitudinal section at centre (c) Vertical stresses at foundation level along longitudinal sections for different values of Z/L.

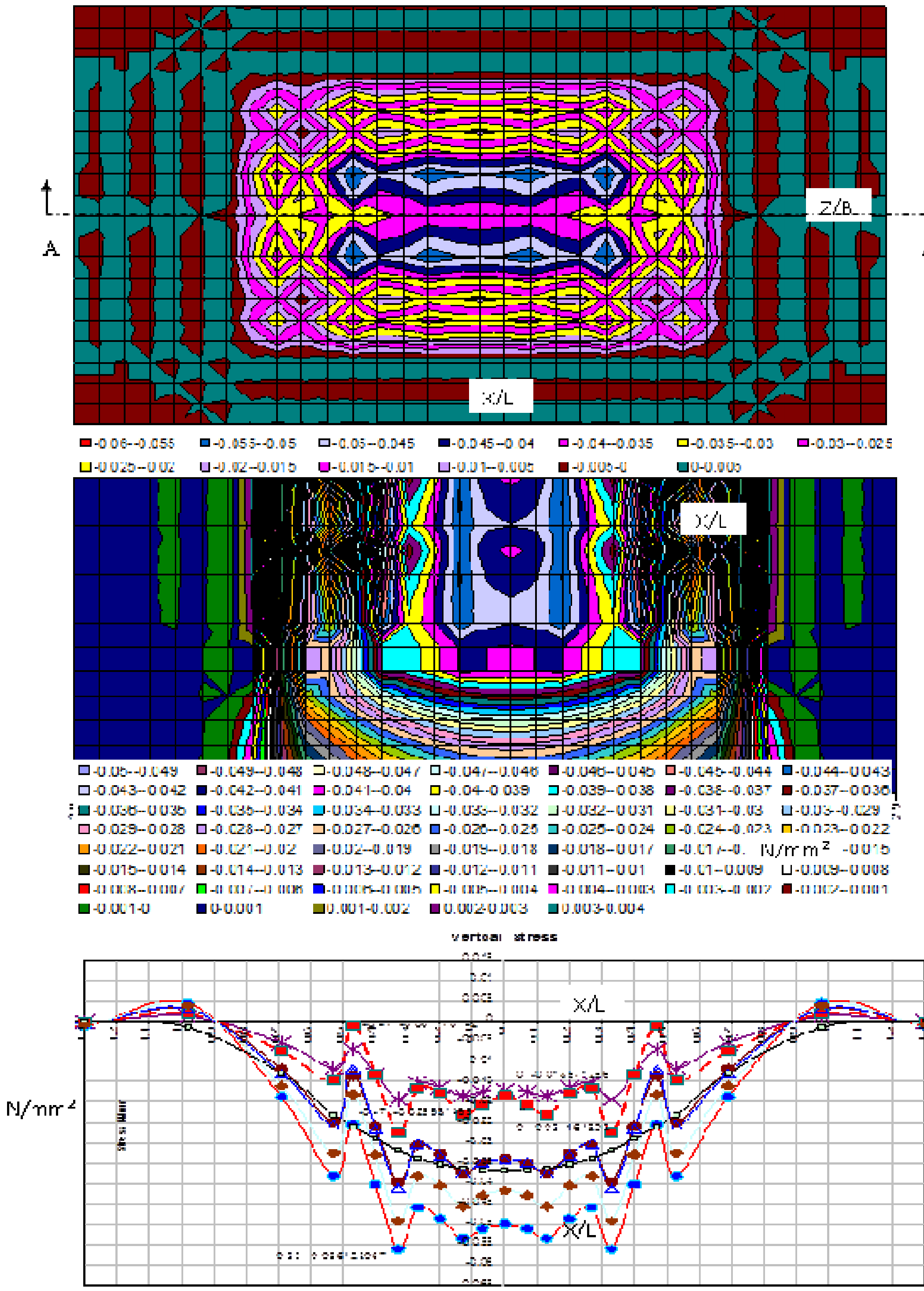


Fig. 14 a

Fig. 14 b

Fig. 14 c

Fig. 14. Vertical stresses in N/mm^2 Nonlinear RSSI analysis (a) Contours of vertical stresses at footing level (b) Vertical stresses along longitudinal section at centre (c) Vertical stresses at foundation level along longitudinal sections for different values of Z/L.

IV. CONCLUSIONS

– In non-linear SSI analysis, the vertical contact pressure of the footings follows the same trend as that of vertical displacement.

– The vertical pressure at various points are not affected much in non-linear RSSI analysis compared to non-linear SSI. However there is reduction in longitudinal stresses by 56% and transverse stresses by 35% in non-linear RSSI analysis compared to non-linear SSI.

– There is also a change in the pressure bulb below foundation level. In the horizontal direction, there is a reduction in longitudinal stress at various points in non-linear RSSI analysis when compared to the non-linear SSI analysis which is exactly reverse of the trend in linear analyses. Similarly same trend is observed in transverse direction.

– The contact pressure on isolated footings follows the same trend as that of vertical displacements. In the longitudinal direction, the contact pressure at various points has increased. However, this increase has been compensated by a corresponding reduction in the contact pressure at various other points along longitudinal sections. This is logical as the total soil reaction offered must be equal to the total applied load on the structure-foundation system.

– The maximum vertical stresses in linear RSSI analysis are 6% more than linear SSI analysis. But the horizontal stresses are reduced by 8.4% and 18.7% in longitudinal and transverse directions respectively. This seems to indicate that aspect ratio building affects lateral components of contact stresses between foundation and soil.

V. FUTURE SCOPE

– The studies can extended further by using a different interface element.

– Model scale experiments can be carried out on RSSI studies.

– RSSI studies can be conducted for dynamic analysis too.

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