Effect of vertical reinforcement on settlement and displacement in reinforced soil under a three-dimensional framed structure

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Abstract. Soil reinforcement is a technique for improving the mechanical properties of soil. In recent years, the use of reinforced soils has increased widely due to its satisfactory performance and cost effectiveness. Many studies have been carried out on reinforced soil with conventional horizontal reinforcement. The main disadvantage of horizontal alignment of reinforcement is that it requires large scale excavation of soil, which destroys the strength of soil developed over the years and is also expensive.

In this research, studies have been carried out on soil reinforced with vertical reinforcement by considering soil-structure interaction. For this purpose, a four storey 3-dimensional frame structure with isolated footing resting on both un-reinforced and reinforced soil has been considered. Soil has been reinforced with HYSD bars of Fe 500 grade and reinforcement is provided only below footings. The frame section and soil continuum has been modelled and analysed using finite element-based software program SAP2000. The size of the soil mass considered is 153x95x20m.

Parametric studies have been carried out by varying reinforcement length and reinforcement spacing. The study revealed that the displacements in soil can be reduced by the inclusion of vertical reinforcement. Settlement is reduced in the range of 4.45% to 16.79%. Horizontal displacement along longitudinal and transverse direction is reduced in the range of 7.37% to 26.31% and 8% to 33.24% respectively. Differential settlement in reinforced soil is reduced by 30.34% when compared with that of un-reinforced soil.

Keywords: Reinforced soil, Settlement, Soil-structure interaction, SAP 2000, Vertical reinforcement

1 Introduction

Soil Structure Interaction is an interdisciplinary field which involves the study of structural engineering, foundation engineering and geotechnical engineering [1]. Soil Structure Interaction (SSI) is a process in which the response of soil influences the motion of the structure and the motion of the structure influences the response of the soil. In this case neither the structural displacements nor the ground displacements are independent from each other. When SSI is taken into consideration the soil properties, travel path and the geometry of the soil medium influence the ground motions imposed on the foundation of the structure [2].

Reinforced soils have been widely used in geotechnical structures as a result of their satisfactory performance and cost effectiveness [3]. Reinforced soil is most commonly used in embankments and retaining walls. The main disadvantage of horizontal alignment of reinforcement is that it requires large scale excavation of soil, which destroys the strength of soil developed over the years. Further the soil has to be compacted after placing reinforcement [4].

Numerous studies have been carried out on the effect of SSI under static and dynamic loading and also on reinforced soil foundations and retaining walls. The study on behavior of interaction of plane frame on elastic foundation with shear and normal moduli of subgrade reactions was carried out by Aljanabi et al. [5]. Simplified approach for soil-structure interaction analysis was developed and studied for 2D skeletal RC frame resting on isolated footing with different soil types by Al-Shamrani and Al-Mashary [6]. Improvement of bearing capacity of loose sand using flexible reinforcement was carried out by Puri et al. [7]. The study on soil reinforced with multilayer horizontal and vertical reinforcement was carried out by Zhang et al. [8]. The effect of SSI on 3D space frame with pile foundation and embedded in clayey soil was studied by Chore et al. [9]. The interactive and non-interactive analysis of a space frame-raft foundation-soil system was carried out by Thangaraj and Ilamparuthi [10]. The interactive behavior of the 3D frame with isolated footing which is resting on unreinforced soil was studied by Rajashekhar Swamy et al. [11]. The relevance of interface elements in SSI of 3D frame with Raft foundation resting on unreinforced soil was studied by Rajashekhar Swamy et al. [12]. Studies on Reinforced Soil-Structure-Interaction analysis of 3-D space frame resting on soil reinforced with horizontal geogrids was carried out by Nayana [13].

The above literature review reveals the number of studies carried out on SSI and very few studies carried out on soil reinforced with conventional horizontal reinforcement. However, the studies on structure resting on reinforced soil with vertical reinforcement by considering the soil structure interaction has not yet been carried out. Therefore, it is necessary to study the effect of vertical reinforcement in reinforced soil by considering SSI.

2 Problem Definition

The present study is carried out on the structure shown in Fig. 1. The structure under consideration is selected from the literature Rajashekhar Swamy et al. (2011). The details of the structure and properties of the materials are given in Table 1. As the soil is semi-infinite, the size of the soil mass considered is 153 x 95 x 20 m as shown in Fig. 1

3 Modelling and Formulation

Table 1. Details of structure and material properties (Rajashekhar Swamy et al.).

Sl. No.	Structure	Component	Details	Unit
1	Frame	No of Storeys	4	m
		No of bays	5x3	
		Storey height	3.5	m
		Bay width	5	m
		Beam size	300x600	mm
		Column size	400x400	mm
2	Footing		2.0x2.0x0.2	m
3	Soil Mass		153x95x20	m
4	Elastic Modulus of Soil		1.33×10^4	kN/m^2
5	Poisson's Ratio of Soil		0.45	
6	Elastic Modulus of Concrete		2.73×10^7	kN/m^2

Finite element method is adopted to study behavior of the frame-isolated footing-reinforced soil system. Soil has been vertically reinforced with 25mm diameter HYSD bar of Fe 500 grade and reinforcement is provided only below footings. Modelling and linear analysis of superstructure along with supporting system and soil is done in finite element-based software program SAP2000. Table 2 gives the details of element types used for modelling.

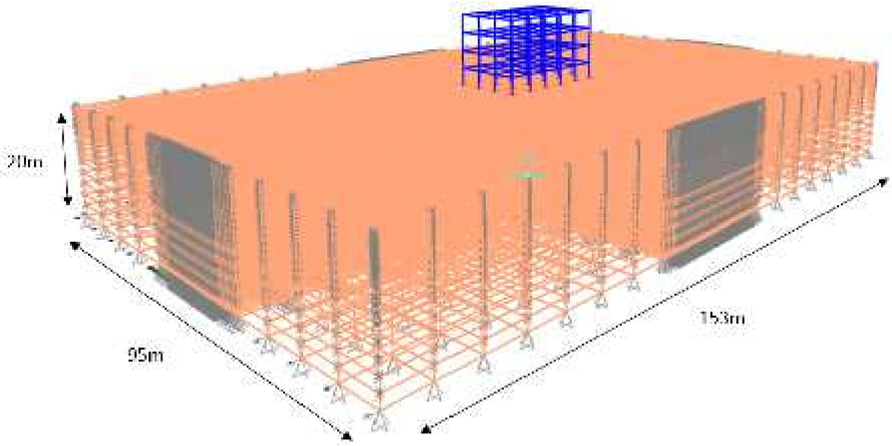


Fig. 1. 3D view of Space frame resting on unreinforced soil.

3.1 Super-Structure

Beams and columns of the superstructure frame are modelled using three-dimensional two nodded beam element with six degrees of freedom per node.

3.2 Sub-Structure

Isolated 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. Soil is modelled using eight nodded brick element with three translational degrees of freedom per node. Reinforcement in the soil is modelled using three-dimensional two nodded beam element with six degrees of freedom per node

4 Parametric Studies on Single Flexible Isolated Footing

The parametric study has been carried out on single flexible isolated footing of size 2.0 x 2.0 x 0.2m for two parameters, i) Reinforcement length (U) and ii) Reinforcement spacing (S). The soil boundary is assumed to be six times the width of the footing with the properties mentioned in Table 1.

Table 2. Details of element type.

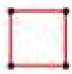
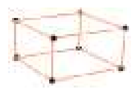
Sl. No.	Component	Element Type	Figure
1	Beams, Columns & Reinforcement	2- nodded beam element with six degrees of freedom per node	
2	Isolated Footing	4- nodded plate element with five degrees of freedom per node	
3	Soil Mass	8- nodded brick element with three degrees of freedom per node	

Table 3. Reinforcement details.

Sl. No	Material	Diameter	Spacing	U/B ratio
1	Fe 500 grade HYSD bar	25mm	250mm	0.5,0.75,1,1.25,1.5,1.75,2,2 25 and 2.5
			500mm	0.5,0.75,1,1.25,1.5,1.75,2,2.25 and 2.5
			1000mm	0.5,0.75,1,1.25,1.5,1.75,2,2.25 and 2.5

A non-dimensional parameter 'U/B' where, U is the length of reinforcement and B is the width of footing has been considered to determine the optimum length of reinforcement. The analysis is carried out for different U/B ratios of 0.5, 0.75, 1, 1.25, 1.5, 1.75, 2, 2.25 and 2.5 for reinforcement spacing of 250, 500 and 1000mm. Reinforcement details are given in Table 3. A total 30 combinations of single flexible isolated footing resting on reinforced soil were developed and analyzed with area load of 187.5 kN/m^2 applied on the footing top. A graph of differential settlement v/s reinforcement spacing for different U/B ratios are plotted and shown in Fig. 2 and Fig. 3.

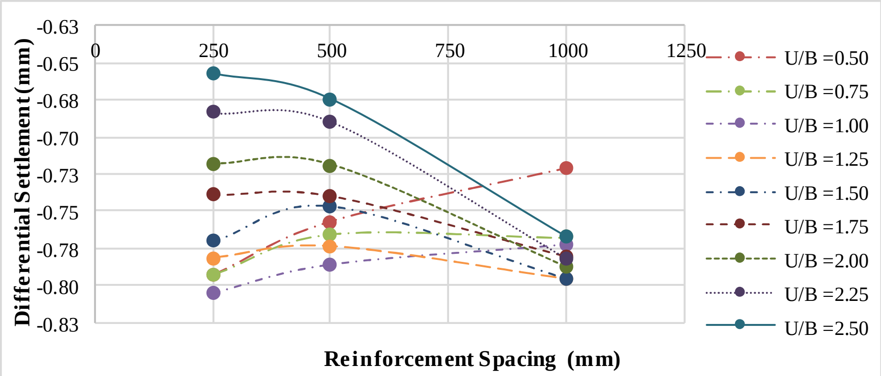


Fig. 2. Differential settlement v/s reinforcement spacing.

From the plot between differential settlement and reinforcement spacing, it was observed that the values of differential settlement decreased with increase in reinforcement spacing for all the U/B ratios of 0.50, 0.75 and 1.00.

Further, the study is carried out by performing static analysis on 3D space frame structure resting on reinforced soil for U/B ratios of 0.50, 0.75 and 1.00 for reinforcement spacing of 250, 500 and 1000mm.

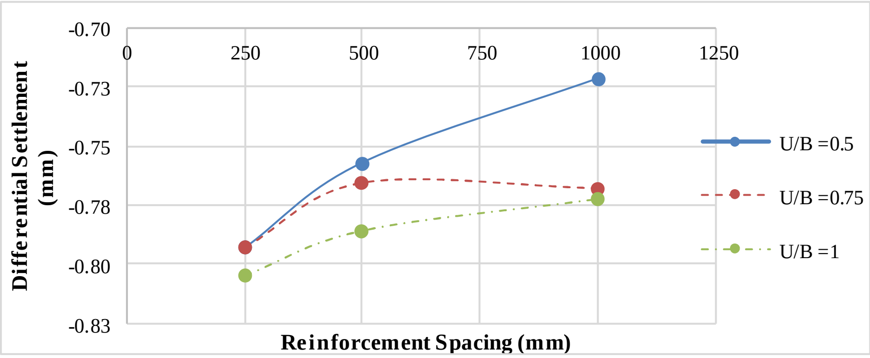


Fig. 3. Differential settlement v/s reinforcement spacing for U/B ratios of 0.5, 0.75 and 1.00.

5 Analysis of Space frame resting on unreinforced and reinforced soil

To understand the effect of vertical reinforcement, the study is carried out on space frame resting on unreinforced and reinforced soil under static load of 31kN/m. A total nine combinations of space frame resting on reinforced soil were developed and analyzed for reinforcement spacing of 250, 500 and 1000mm and the U/B ratios of 0.5, 0.75 and 1.00 (obtained from parametric study) under two cases by providing (i) Vertical reinforcement below all footings as shown in Fig. 4a and (ii) Vertical reinforcement only below internal footings as shown in Fig. 4b.

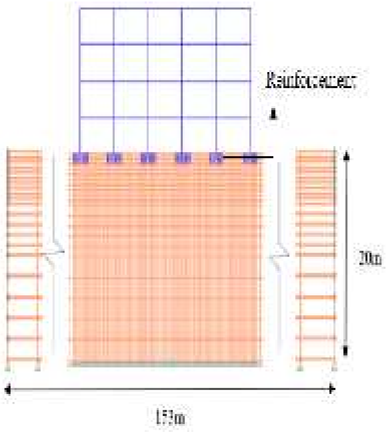


Fig. 4a. Front view of Space frame resting on reinforced soil (reinforcement below all footings).

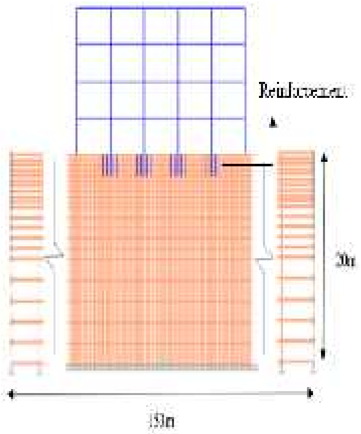


Fig. 4b. Front view of Space frame resting on reinforced soil (reinforcement below internal footings only).

6 Results and Discussions

The structure resting on unreinforced soil is analyzed initially and these results are taken as reference to compare the results of structure resting on reinforced soil for all the cases. The vertical settlement obtained are plotted against X/L in the longitudinal direction. The maximum vertical settlement in unreinforced soil is 115.81mm with differential settlement of 17.61. The maximum horizontal displacement in unreinforced soil along longitudinal direction is 3.90mm and across transverse direction is 4.82mm.

6.1 Effect of vertical reinforcement on vertical settlement and horizontal displacements in soil when reinforcement is provided below all footings

Fig. 5, 6 and 7 show the plot of vertical settlement below the structure in unreinforced and reinforced soil for reinforcement spacing of 250mm, 500mm and 1000mm. The comparison of maximum vertical settlement and differential settlement in unreinforced and reinforced soil is given in Table 4. The maximum horizontal displacement along longitudinal direction and transverse direction have been compared between unreinforced and reinforced soil and is tabulated in Table 5.

Table 4. Comparison of max. vertical settlement and differential settlement in unreinforced and reinforced soil.

Sl. No	Spacing (mm)	U/B ratio	Max. Vertical Settlement (mm)			Differential Settlement (mm)		
			Unreinforced Soil	Reinforced Soil	%Difference	Unreinforced Soil	Reinforced Soil	%Difference
1	250	0.50	115.81	110.66	-4.45	17.67	16.74	-5.26
		0.75		108.75	-6.10		16.41	-7.13
		1.00		107.14	-7.49		16.20	-8.31
2	500	0.50		112.18	-3.13		17.16	-2.86
		0.75		110.22	-4.84		16.81	-4.86
		1.00		108.52	-6.29		16.51	-6.56
3	1000	0.50		113.49	-2.01		17.48	-1.07
		0.75		112.02	-3.27		17.28	-2.20
		1.00		110.61	-4.49		17.08	-3.33

6.2 Effect of vertical reinforcement on vertical settlement and horizontal displacement in soil when reinforcement is provided only below internal footings

Fig. 8, 9 and 10 show the plot of vertical settlement below structure in unreinforced soil and reinforced soil for reinforcement spacing of 250mm, 500mm and 1000mm.The comparison of maximum vertical settlement in unreinforced and reinforced soil is given in Table 6. The maximum reduction in both vertical settlement and differential settlement occurred for U/B ratio of 1.00 and for reinforcement spacing of 250mm. The maximum horizontal displacement along longitudinal direction and transverse direction have been compared between unreinforced and reinforced soils. Table 7 gives the details of comparison of horizontal displacements in unreinforced and reinforced soil.

Table 5. Comparison of horizontal displacement in unreinforced and reinforced soil.

Sl. No	Horizontal Displacement (mm)	U/B ratio	Un-reinforced Soil	Reinforced Soil					
				Spacing = 250mm	% Difference	Spacing =500mm	% Difference	Spacing = 1000mm	% Difference
1	Max. Horizon-tal displacement in longitudinal direction	0.50	3.90	3.25	-16.79	3.49	-10.72	3.62	-7.37
		0.75		3.05	-21.95	3.29	-15.81	3.51	-10.18
		1.00		2.87	-26.31	3.11	-20.42	3.35	-14.02
2	Max. Horizon-tal displacement in transverse direction	0.50	4.82	3.69	-23.41	4.13	-14.39	4.44	-8.0
		0.75		3.43	-28.68	3.85	-20.17	4.23	-12.30
		1.00		3.22	-33.24	3.61	-25.15	4.03	-16.44

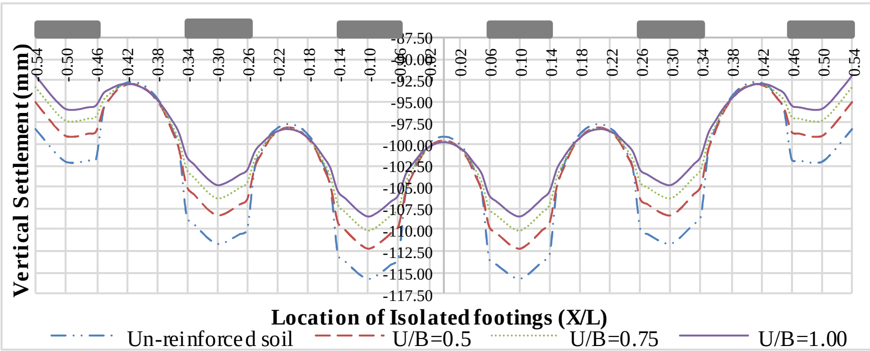


Fig. 5. Plot of vertical settlement in unreinforced and reinforced soil for S = 250mm.

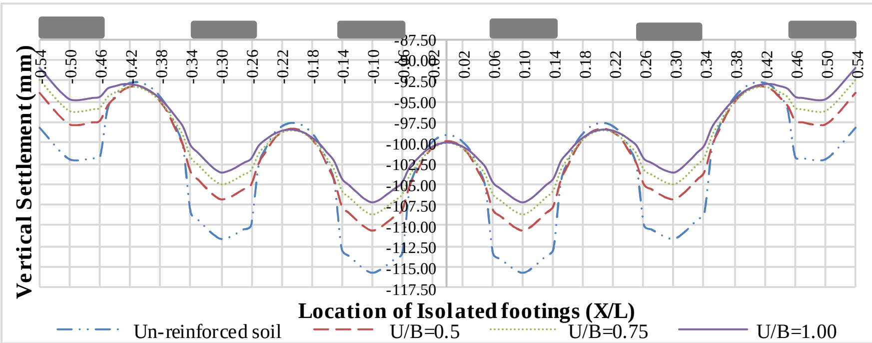


Fig. 6. Plot of vertical settlement in unreinforced and reinforced soil for S = 500mm.

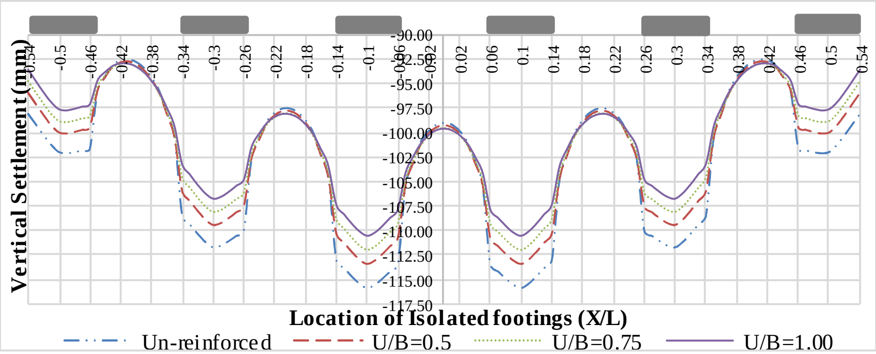


Fig. 7. Plot of vertical settlement in unreinforced and reinforced soil for S = 1000mm.

Table 6. Comparison of max. vertical settlement and differential settlement in unreinforced and reinforced soil (reinforcement below internal footings).

Sl. No	Spacing (mm)	U/B ratio	Max. Vertical Settlement (mm)			Differential Settlement (mm)		
			Unreinforced Soil	Reinforced Soil	% Difference	Unreinforced Soil	Reinforced Soil	% Difference
1	250	0.50	115.81	112.01	-3.28	17.67	14.56	-17.6
		0.75		110.55	-4.54		13.36	-24.39
		1.00		109.28	-5.64		12.31	-30.34
2	500	0.50		113.16	-2.29		15.51	-12.24
		0.75		111.69	-3.56		14.31	-19.07
		1.00		110.39	-4.68		13.23	-25.12
3	1000	0.50		114.13	-1.45		16.29	-7.81
		0.75		113.05	-2.38		15.41	-12.79
		1.00		111.99	-3.30		14.53	-17.77

Table 7. Comparison of horizontal displacement in unreinforced and reinforced soil.

Sl. No	Horizontal Displacement (mm)	U/B ratio	Un-reinforced Soil	Reinforced Soil					
				Spacing = 250mm	% Differ-	Spacing =500mm	% Differ-	Spacing = 1000mm	% Differ-
1	Max. Horizontal displacement in longitudinal	0.50	3.90	3.63	-7.11	3.72	-4.76	3.79	-3.02
		0.75		3.51	-10.18	3.60	-7.88	3.71	-5.07
		1.00		3.40	-13.01	3.49	-10.7	3.62	-7.37
2	Max. Horizontal displacement in transverse di-	0.50	4.82	3.78	-21.63	3.92	-18.72	4.44	-8.15
		0.75		3.50	-27.43	3.80	-21.21	4.15	-13.95
		1.00		3.12	-35.31	3.45	-28.47	3.87	-19.76

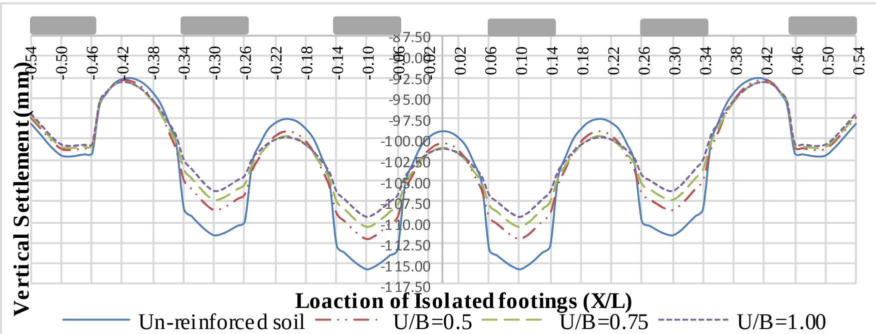


Fig. 8. Plot of vertical settlement in unreinforced and reinforced soil for S = 250mm (reinforcement below internal footings).

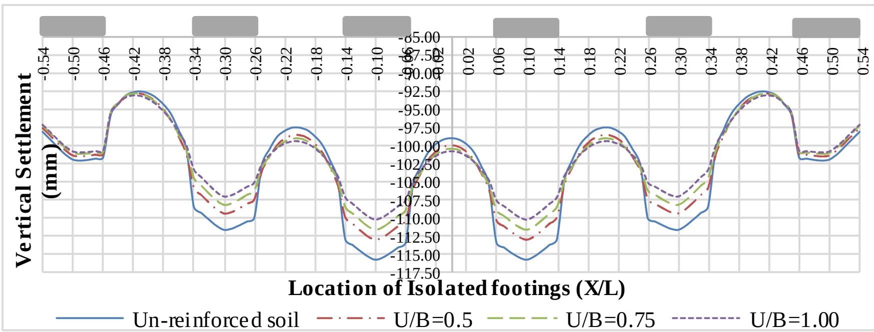


Fig. 9. Plot of vertical settlement in unreinforced and reinforced soil for S = 500mm (reinforcement below internal footings).

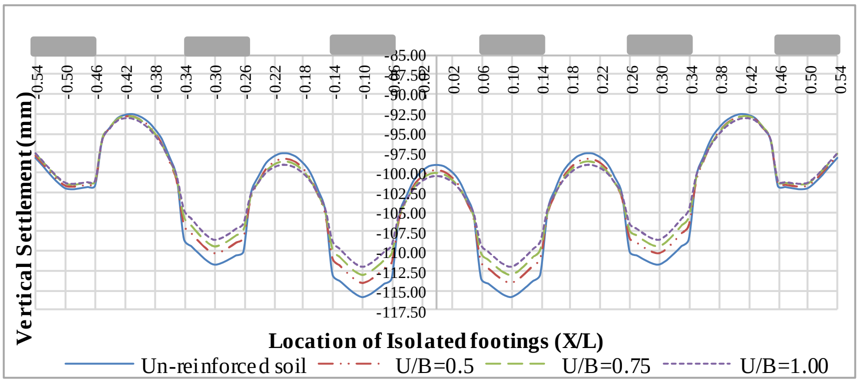


Fig. 10. Plot of vertical settlement in unreinforced and reinforced soil for S = 1000mm (reinforcement below internal footings).

7 Conclusions

The following are the conclusion drawn:

- Inclusion of vertical reinforcement in soil reduces the vertical settlement and horizontal displacements in soil
- Reduction in vertical settlement increases with decrease in reinforcement spacing and increase in U/B ratio.
- The maximum reduction in vertical settlement is 7.49% for a reinforcement spacing of 250mm and for U/B ratio of 1.00 when reinforcement is provided below all footings. Whereas, the reduction is 5.64% when reinforcement is provided only below internal footings.
- The maximum reduction in the differential settlement when vertical reinforcement is provided below all footings was found to be 8.31% for 250mm reinforcement spacing and U/B ratio of 1.00.
- The maximum reduction in the differential settlement when vertical reinforcement is provided only below internal footings was found to be 30.34% for 250mm reinforcement spacing and U/B ratio of 1.00.
- Horizontal displacement along longitudinal direction is reduced in the range of 7.37% to 26.31% when reinforcement is provided below all footings and 3.02% to 13.01% when reinforcement is provided only below internal footings.
- Horizontal displacement along transverse direction is reduced in the range of 8.00% to 33.24% when reinforcement is provided below all footings and 8.15% to 35.13% when reinforcement is provided only below internal footings.
- Reinforcement spacing of 250mm and U/B ratio of 1.00 was observed to be the optimum reinforcement spacing and length.

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