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Effect of Column Spacing on the Behavior of Frame-Raft and Soil Systems

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Abstract: The objective of this study is to analyse a space frame-raft-soil system under static load to understand the influence of column spacing on the behavior of a soil-raft and frame. In the analysis, all three components space frame, raft and soil were considered as a single compatible unit. The analyses are carried out for linear and non-linear conditions, in which soil is treated as a homogeneous and isotropic continuum. The analyses are carried out by ANSYS finite element code. The results of four different column spacings are compared and the influence of the column spacing on settlement, the bending moment and contact pressure are studied. The settlement increases considerably with increases in column spacing. The column spacings resulted in the rafts of the two raft types rigid raft and flexible raft according to the bending moment in the raft. The column spacing has a marginal effect on the contact pressure. The results of two different raft thicknesses are compared and the influence of the raft thickness on settlement, the bending moment and contact pressure are also studied. The increase in raft thickness resulted in reduced settlement, an increased bending moment and reduced uniform contact pressure. The results of two soils with different Young's modulus are compared and the influence of Young's modulus on settlement bending moment and contact pressure is also studied.

Key words: Column spacing, raft thickness, soil modulus, space frame, Poisson's ratio of soil, homogeneous soil, non-linear soil, relative stiffness of superstructure

INTRODUCTION

Raft is a foundation that is generally used to support a heavily loaded structure, as well as a structure founded on heterogeneous deposits. The analysis of raft foundation has undergone various developments and currently it is being analyzed with sophistication by incorporating the interaction between structure, raft and soil including time dependent non-linear behavior. The oldest method is a rigid analysis, which is otherwise known as a conventional method. To properly evaluate the moments and forces in the foundation and superstructure, it is necessary to consider them as parts of a single compatible system. To overcome these difficulties, the sophisticated techniques, such as the Finite Element and Boundary Element technique are in current practice. Traditional methods of analyses have treated the raft as a loaded plate or a strip supported on a soil layer of linear elastic material. In the conventional method, contact pressure distribution is made static by assuming that the foundation element is a rigid plate on the Winkler medium, whereas in the soil line method, the relative flexibility of the foundation element was included. However, rigidity of the superstructure and continuity of soil mass are ignored in these methods. Vlasov and Leontiev proposed a two-parameter model in 1966 that accounts for the continuity of the soil medium and displacement.

Several continuum models have been developed assuming that soil is an isotropic, homogeneous and linearly elastic material. In the above mentioned methods, the focus was on the modelling of soil continuity and its influence on the contact pressure and moments. However, the relative stiffness of the foundation leads to a redistribution of the forces and moments on the superstructure.

Viladkar *et al*. (1990, 1992) contributed immensely in understanding soil-raft-structure interaction. Viladkar, developed a coupled FE procedure with non-linear idealization of soil using a hyperbolic stress-strain relationship. Subsequently Godbole *et al*. (1990) adopted the technique of a coupled finite-infinite element formulation for the general case of multi-storeyed plane frames with a combined soil- foundation system. The non-linear of soil mass relation was included to study its effect on the redistribution of shear force and bending moments in the structural members. Viladkar *et al*. (1994) extended the coupled finite element for the interaction analysis of the space frame-raft-soil system considering soil non-linearity. In this non-linear analysis, the stiffness of the

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structural slab was included as a part of superstructure. The proposed model was studied by analysing the multi-storeyed frame and it was concluded that moment redistribution takes place in the interaction analysis. Noorzaei *et al.* (1991, 1995a, b) studied the effect of the flexibility of the foundation beam on the entire interaction behavior of a plane frame, combined footing soil mass system. The coupled finite-infinite element formulation was adopted to physically represent the system and the nonlinearity of the soil media was also included. The non-linearity of the soil was included by hyperbolic stress-strain model. They concluded that the differential settlements, which influence the behavior of the structure-foundation-soil mass system, were considerably reduced with an increase in the rigidity of the foundation.

As the stiffness of the foundation increases, it also absorbs more moments and there is consequently a significant reduction in the bending moments of the superstructure members.

Viladkar *et al.* (1993) developed a model to include a time-dependent behavior at constant loading. They concluded that redistribution of shear forces, bending moment and torsional moments in the structure occur due to differential settlements rather than the total settlements. They compared the interacting results of the resulting structural behavior of with that when interaction is neglected.

Noorzaei *et al.* (1995a) continued the work of Viladkar as they analysed the interactions of space frame-raft-soil system.Analysis was carried out by modelling the superstructure as a Timoshenko beam element and Mindlin plate bending element for structural slabs and the raft, respectively with a hyperbolic model for the soil to account for the non-linear behavior. Noorzaei *et al.* (1995a) studied the soil-structure interaction of a plane frame, combined footing soil system, taking into account the elasto-plastic behavior of the soil including strain hardening characteristics. The elasto-plastic behavior with and without strain hardening was examined in their study. The axial forces and moments in the frame and the foundation varied significantly between the methods analysed and are higher for the strain hardening condition. In the next study, Noorzaei *et al.* (1995b) discussed elasto-plastic idealization of soil using six different yield criteria in the soil-structure interaction analyses and also compared the results with the results of non-linear analyses. They reported that, in general, the transfer of forces and moments takes place from exterior to interior columns when the soil remains in an elastic state.

Rao (1995) compared the realistic half-space continuum approach and the plane-strain approach and concluded that the realistic half-space continuum approach was superior to plane-strain approach.

Daniel and Ilamparuthi (2001) compared the Winkler model and elastic continuum model and reported higher settlement in the Winkler model than in the elastic continuum model. They compared the bending moments in the raft obtained by non-interactive analysis of elastic continuum with Wolfer method and conventional rigid method bending moments. The moments obtained by the conventional rigid method are always higher than the other two methods and the moments obtained by the Wolfer method lie between those of the other two methods.

Dutt and Roy (2002) compared the various models available in the literature and gave the strength and limitations of each model. They have emphasis to physical modelling, since it appears that this modelling of structure is straightforward.

Maharaj *et al.* (2004) developed a model by considering the frame and raft as an elastic material and the soil as an elastoplastic material by Drucker-Prager yield criterion. They concluded that the flexibility of raft increased the internal forces in the super structure. The flexible foundation undergoes more differential settlement than the stiff foundation. By increasing superstructure stiffness the differential settlement of foundation was reduced to almost zero. By increasing foundation thickness the differential settlement of foundation reduced to almost zero.

Conniff and Kionusis (2007) developed a model by replacing the soil mass by three-degree-of-freedom elastoplastic medium. They concluded that this model resulted in accurate settlements of the shallow foundations.

Manjeet (2006) developed a non-linear behavoiur of soil using the hyperbolic model. They concluded that non-linearity of soil mass plays an important role in the redistribution of forces in the superstructure.

Small (2001) proved that the use of simple spring models for the soil behavior can lead to erroneous results. He compared the results of simple finite layer techniques with three-dimensional finite element techniques. He showed that the type of structure and its stiffness have an effect on the deformation of the foundation. He proved that the results of instrumented structure have good agreement with the results of three-dimensional finite element techniques.

In their subsequent papers, Daniel and Ilamparuthi (2004, 2005 and 2007) had studied the effects of linear and non-linear soil and reported higher settlement for non-linear soil than linear soil and more uniform contact pressure and a higher bending moment for non-linear soil than linear soil. The interactive analysis was carried out by including the superstructure stiffness in the raft-soil. Moreover, they reported the change in contact pressure and bending moments due to changes in the stiffness of superstructure. In their next paper, the influence interaction was carried out by changing the thickness of the raft and modulus of the soil and they reported the changes in settlement, bending moment, contact pressure, axial force and moments in the columns and beam moments.

The literature review presented above suggests that all the early investigators represented the column spacing of the frame as a constant and they have not increased or changed the frame column spacing and the effects of the frame column spacing has not been analysed. Thus, in the present study, the effect of frame column spacing on the interaction of a space frame-raft and soil system is analysed.Further, parametric studies reported in the literature of soil-raft-structure interaction are limited. Therefore, in the present study, the importance of the relative stiffness of raft, thickness of raft and modulus of soil is emphasised. The study reported in the literature on the non-linear behavior of soils is also limited.

However, the soil behavior is non-linear irrespective of sand and clay. As a result, in the present study, the effect of non-linear behavior of soil is incorporated.For the nonlinear behavior of soil, the multi linear isotropic model (MISO) was adopted.

In the proposed study, different column spacings were carried out while including linear and non-linear elastic behavior of the soil. The column spacings in the frames were 3, 4.5, 6 and 7.5 m. In the analysis, all three components, namely soil, raft and superstructure, are analyzed as a single compatible unit. The influence of column spacing on settlement, bending moment and contact pressure were studied. Thus, the initial tangent modulus of the stress-strain curve obtained from the laboratory triaxial test on sand was adopted as the Young's modulus, Es.

A detailed parametric study was conducted by varying the relative stiffness of the raft, Krs and soil modulus Es. The relative stiffness Krs is determined based on the recommendation of Brown and Yu (1986), which is as follows:

$$\mathrm{Krs} = \frac{16E_rI_r\ (1-v_s^2)}{\pi E_sL^4}$$

The influence of these two parameters on (the forces and moments in the superstructure and) the raft were studied. Further, analyses were carried out to examine the effect of non Linear (NL) soil behavior, since soil exhibits inelastic and non-linear behavior from the beginning of loading.

Therefore, any model for the constitute soil behavior must account for this non-linearity. Various models that account for a non-linear response have been developed using the non-linear elastic approach theory.Among one is theory of non-linear elastic approach. This approach divides a non-linear stress strain curve into number of linear parts. Such an approach has been adopted here in the multi-linear isotropic (MISO) model. The details of MISO model adopted in this study are available in ANSYS[10] elemental library.

PROBLEM DETAILS

The analysis was carried out on a space frame (3 bay x 5 bay)-raft-soil system with five stories. The quarter raft plans and column positions are shown in Fig. 1a-d. The column spacings are 3, 4.5, 6 and 7.5 m. It is assumed that the raft is placed directly on the sand medium. In general, sand is treated as a non -homogeneous material in which sand modulus varies with depth. However, the trial analysis on the frame-raft-soil system including non-homogeneity demonstrated that the settlement was greatly influenced by non-homogeneity, but there was only a marginal difference in the differential settlement as well as member forces. Therefore, sand is assumed to have uniform property with depth. The stiffness contribution of the wall and slab are not included in the analysis.

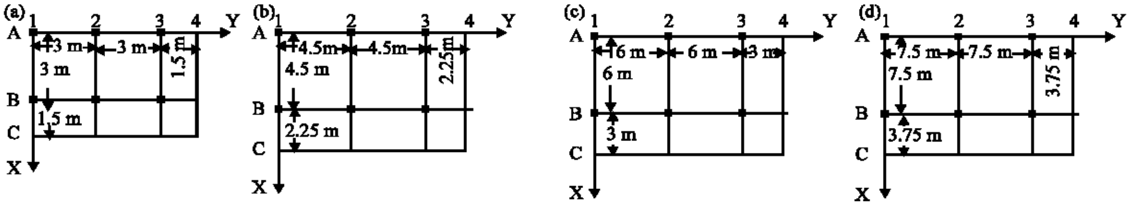

Fig. 1: Plan of quarter rafts and position of columns; (a) 3 m, column spacing, (b) 4.5 column spacing, (c) 6 m column spacing and (d) 7.5 column spacing

Table 1: Geometric and elastic properties of frame, raft and soil

	Column spacing, l (m)							
Column size	3		4.5		6		7.5	
Storey-1, 2, 3 (m)	0.5×0.5 m		0.5×0.5 m		0.5×0.5 m		0.5×0.5 m	
Storey-4, 5 (m)	0.4×0.4 m		0.4×0.4 m		0.4×0.4 m		0.4×0.4 m	
Column height (m)	3.5 m		3.5 m		3.5 m		3.5 m	
Effective span of beams, l (m)	3 m		4.5 m		6 m		7.5 m	
Load on inner beams (KN m^{-1})	24		29		35		52	
Load on outer beams (KN m^{-1})	28		26		28		38	
Raft size (L×B) (m)	15×9 m		22.5×13.5 m		30×18 m		37.5×22.5 m	
Krs	0.0012	0.012	0.0015	0.015	0.0011	0.011	0.0016	0.016
Soil L×B×D (m)	22.5×22.5×27 m		33.75×33.75×40.5 m		45×45×54 m		56.25×56.25×67.5 m	
Poisson' ratio of concrete	0.15		0.15		0.15		0.15	
Poisson's ratio of soil	0.35		0.35		0.35		0.35	
Elastic modulus of concrete (KN m^{-2})	2.5×10^7		2.5×10^7		$2.5x10^7$		2.5×10^7	
Initial tangent modulus of soil (Es) (MPa)	23	135	23	135	23	135	23	135

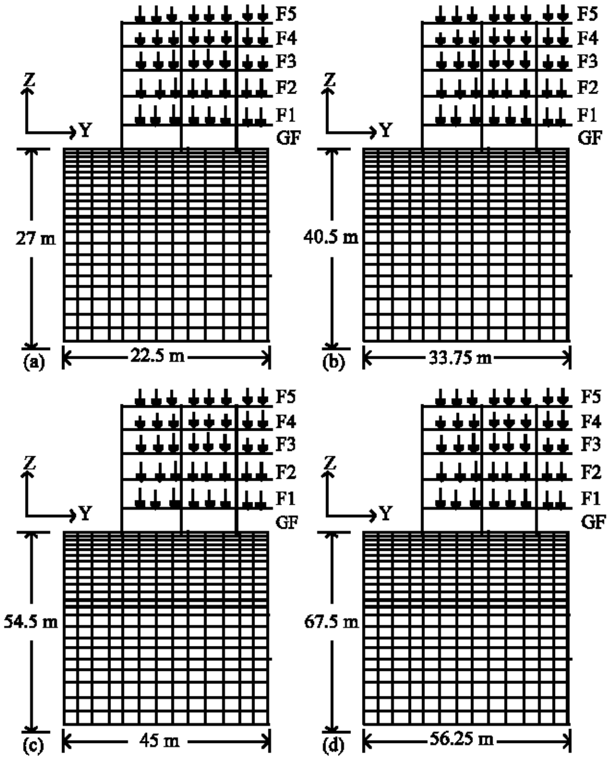

Fig. 2: Element discretization of frame-raft-soil; (a) 3 m, column spacing, (b) 4.5 column spacing, (c) 6 m column spacing and (d) 7.5 column spacing

The load on the slab, including self-weight and the weight of the wall, are considered and are applied as a uniformly distributed load on the beams. The geometric properties of frame and other properties adopted in the analysis are shown in Table 1.

FINITE ELEMENT MODEL

ANSYS finite element code is used. The finite element discretisation along a vertical section of the space frame of 3 bay x 5 bay adopted in this study is shown in Fig. 2a-d.

A two noded beam element (BEAM 4) with six degrees of freedom per node is adopted for the beams and columns of the superstructure. The connections between them are treated as rigid. The soil medium below the raft has been modelled using eight-node brick element (SOLID 45), having three degrees of translation freedom in the respective co-ordinate directions at each node. The soil was idealized as an isotropic homogeneous, half-space.For this analysis, the initial tangent modulus and Poisson's ratio (v_s) were the inputs. For the non-linear analysis (NL), multi-linear isotropic hardening (MISO) material was adopted, as stated in the earlier section.

To provide the required parameters as input for the MISO model, triaxial tests were conducted on Vellar river sand. The sand grain sizes used in the test varied between 1.15 and 3.85 mm with a uniformity coefficient of 2.94. The test was conducted at an average unit weight of 16.2 kN/m^3 under two different confining pressures. The stress-strain relations (Fig. 3) were provided as input along with the respective initial tangent modulus values.Poisson's ratio of the sand was generally between 0.20 and 0.40 and a value of 0.35 was therefore used in computations.

In order to fix the region of soil below the foundation, trial analyses were carried out and it was determined that the breadth and thickness of the soil medium was more than 2.5 times that of the least width of the foundations and that the variation in the settlement and contact pressures was marginal.

Therefore, the soil medium consideration in the quarter model extends 22.5 m in the x and y directions and 27 m in the z direction for the column spacing of 3 m, 33.75 m in the x and y directions and 40.5 m in the z direction for the column spacing of 4.5 m, 45 m in the x and y directions and 54 m in the z direction for the column spacing of 6 and 56.25 m in the x and y directions and 67.5 m in the z direction for the column spacing of 7.5 m as shown in the Fig. 2.

Vertical translation ceased at the bottom boundary, while lateral translation stopped at the vertical boundaries. The raft is modelled as a plate-bending element (Shell 93) with eight nodes having six degrees of freedom each. The moment is calculated in the raft per unit conta 174 length in the element co-ordinate system. The interface characteristics between the raft and soil were represented by the elements Targe I 70 and Conta 174.

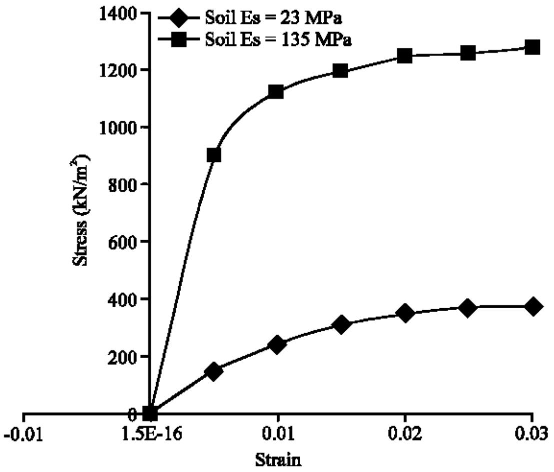

Fig. 3: Stress-strain curve of sand

The meshes in the soil medium were generated with fine meshes of size 0.5m close to the raft and with coarser meshes of size 1.5m further away from the raft. In the shell element of the raft, the meshes were generated with fine meshes of size 0.5m. The Ansys package was validated for the settlement result of Daniel and Illamparuthi (2007) as shown in the Fig. 19.

RESULTS AND DISCUSSION

The effects of various column spacings namely 3, 4.5, 6 and 7.5 m on their respective soil media, as shown in the Fig. 2 were analysed. The results of the effect of column spacing, effect of thickness of the raft, Krs, effect of young's modulus of soil, Es and effect of non-linearity of soil are presented below:

Settlement of raft: Figure 4 shows settlements along sections B1-B4 of rafts for the various column spacings namely 3, 4.5, 6 and 7.5 m, with Krs values of 0.0012, 0.0015, 0.0011 and 0.0016, respectively (Hereafter these Krs values are collectively called lesser Krs values and/or 1 time Krs values). The settlement was higher at the centre of the raft than the edge of the raft, irrespective of column spacing.

Figure 5 shows settlements along the sections B1-B4 of the raft for 3, 4.5, 6 and 7.5 m column spacings with Krs values of 0.012, 0.015, 0.011 and 0.016, respectively. (Hereafter these Krs values are collectively called higher Krs values and/or 10 times Krs values) Fig. 6 shows settlement variation for the various column spacings for the soil modulus of 23 MPa and for lesser and higher Krs

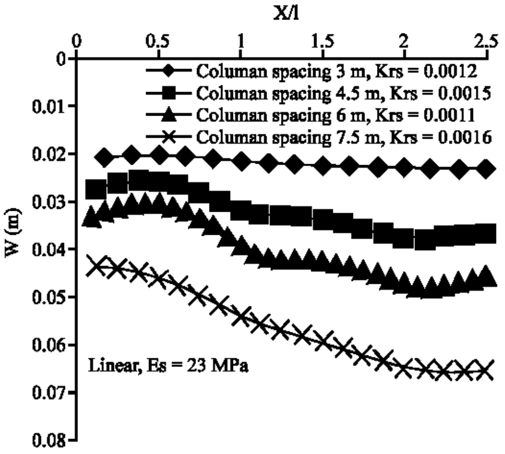

Fig. 4: Settlement variation of along B1-B4 of raft for various column spacings (linear, lesser krs value)

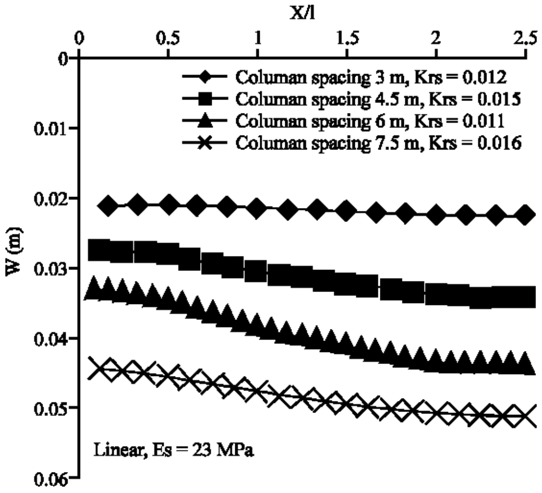

Fig. 5: Settlement variation of along B1-B4 of raft for various column spacings (linear, higher krs value)

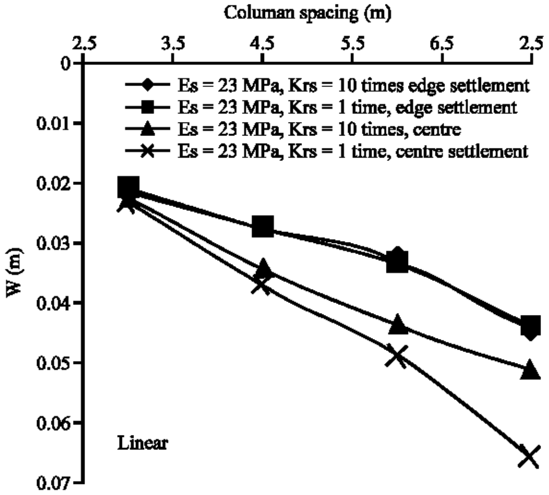

Fig. 6: Variation of settlement with column spacing (Es=23MPa, lessrr and higher krs values)

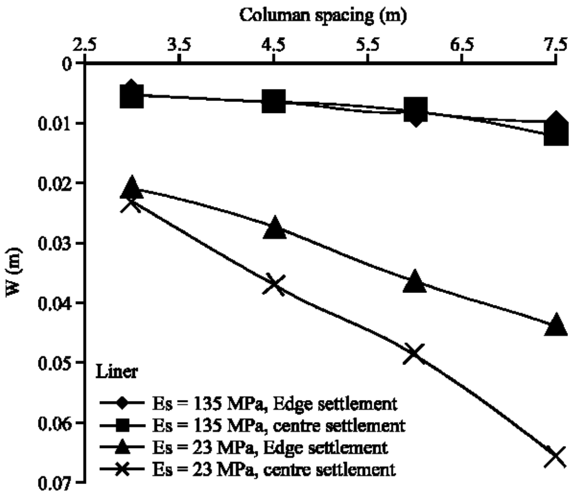

Fig. 7: Settlement variation with column spacing (Es = 23 MPa, Es = 135 MPa and lesser krs value)

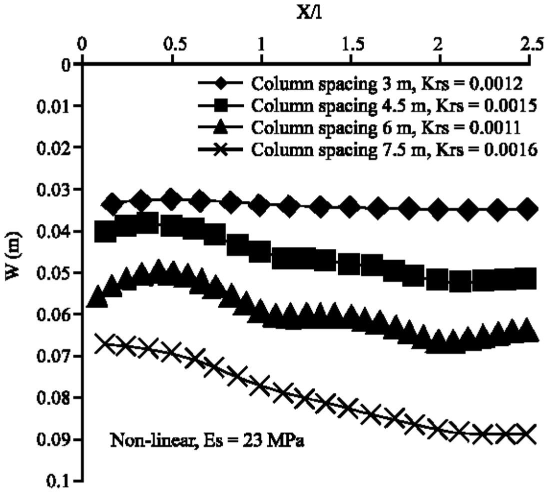

Fig. 8: Settlement variation along B1-B4 of raft for various column spacings (non-linear, lesser krs value)

values. Figure 7 shows settlement variation for the various column spacings, for the soil modulus of 23 MPa and 135 MPa and for lesser Krs value.

Figure 8 shows the settlements along sections B1-B4 of raft for the various column spacings of non-linear soil. Figure 9 and 10 show settlement variation for the various column spacings of linear and non-linear soil both at the edge and the centre of the raft.

Bending moment in the raft: Bending moment variation due to different column spacing was compared in Fig. 11 for the Es value of 23 MPa (the Krs values are shown in Fig. 11). The negative and positive moments indicate hogging and sagging moments, respectively. Figure 12 shows the moment variation for various column spacings for a soil modulus of 23 MPa and for lesser and higher Krs values. Figure 13 shows the moment variation for various column spacings for a soil modulus of 23 and 135 MPa and for lesser Krs values.

Figure 14 shows the moment variation for the various column spacings of linear and non-linear soils and for a soil modulus of 23 MPa. Span moment and inner support moments of non-linear soil showed a similar trend to that of linear soil.

Contact pressure below the raft: The contact pressure distribution along B1-B4 of the raft for various column spacings was shown in Fig. 15 for the soil modulus of

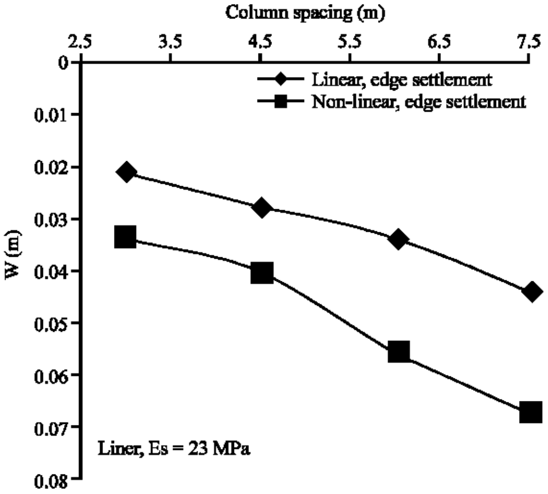

Fig. 9: Comparision of linear and non-linear settlement for different column spacings (edge settlement)

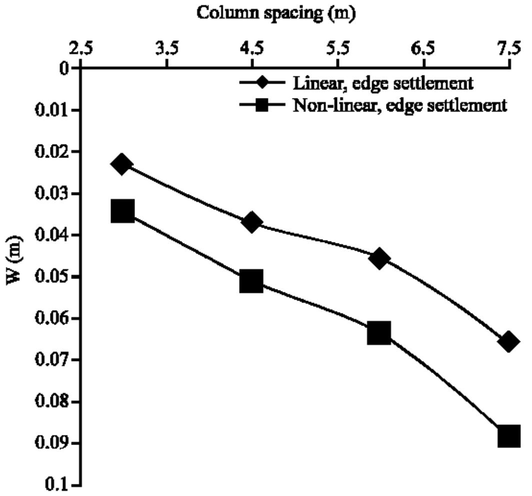

Fig. 10: Comparision of linear and non-linear settlement for different column spacings (centre settlement)

23 MPa and for lesser Krs values. The contact pressure distribution along B1-B4 of the raft for various column spacings was shown in Fig. 16 for the soil modulus of 23 MPa and for higher Krs values. The contact pressure distribution along B1-B4 of the raft for various column spacings is shown in Fig. 17 for the soil modulus of 135 MPa.

The contact pressure distribution for the non-linear soil along B1-B4 of the raft for various column spacings is shown in Fig. 18 for the soil modulus of 23 MPa and for lesser Krs values.

The effects of various column spacings namely 3, 4.5, 6 and 7.5 m on their respective soil media, as shown in the Fig. 2 were analysed. The importance of effect of column spacing, effect of thickness of the raft, Krs, effect of young's modulus of soil, Es and effect of non-linearity of soil are discussed and presented below.

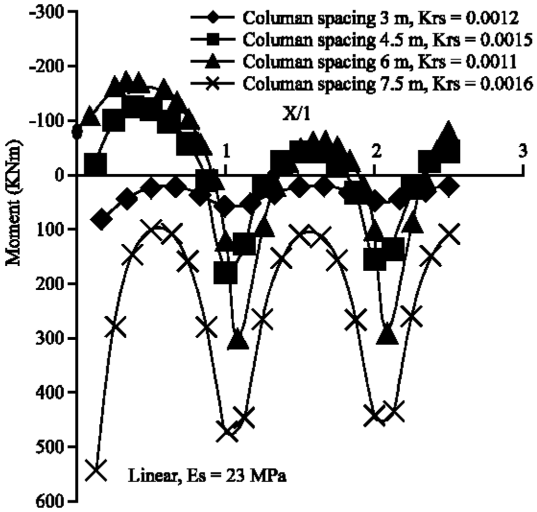

Fig. 11: Bending moment variation along B1-B4 of raft for various column spacing

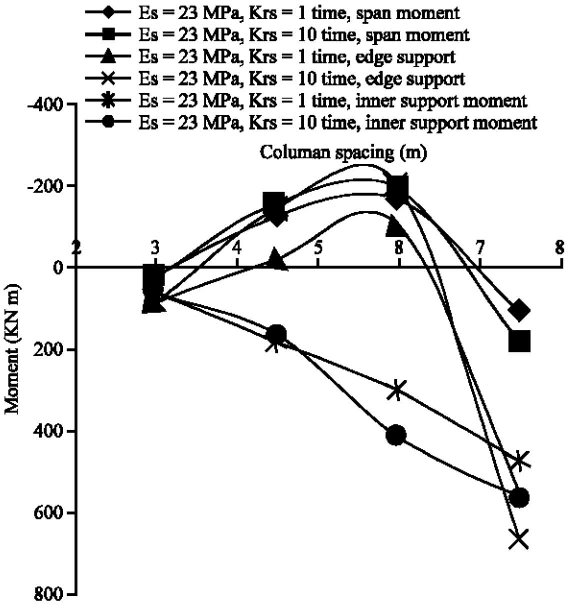

Fig. 12: Bending moment variation of with column spacing (Es=23 MPa, lesser and higher krs values)

The effect of column spacing: Figure 4 shows settlements along sections B1-B4 of rafts for the various column spacings with lesser Krs values. The settlement was highest for 7.5 m column spacing followed by that for the 6, 4.5 and 3 m column spacings.

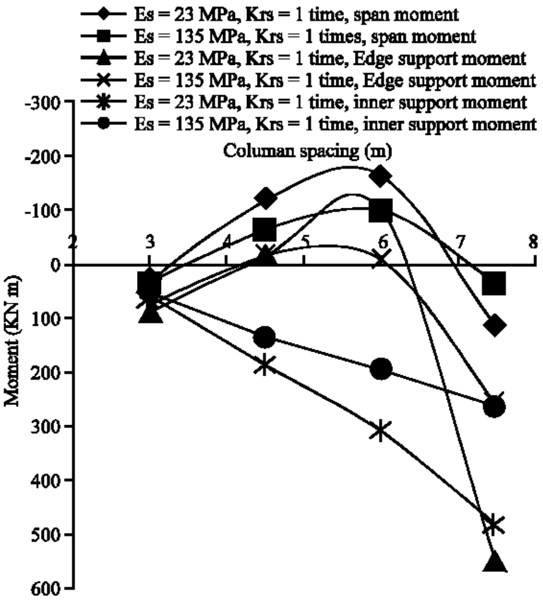

Fig. 13: Bending moment variation with column spacing (Es = 23 MPa, Es = 135 MPa and lesser krs values)

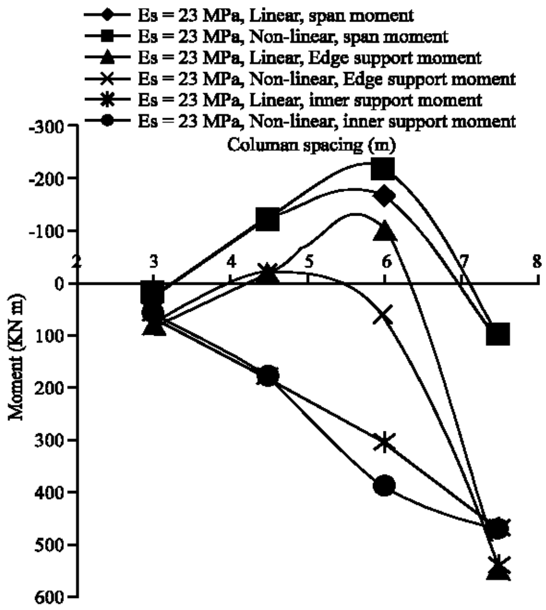

Fig. 14: Comparision of linear and non-linear bending moments for various column spacing

The settlement increased gradually as the column spacing increases from 3 to 7.5 m, as shown in Fig. 4. This was due to effect of column spacing, the objective of the paper. Figure 5 shows settlements along the sections B1-B4 for the various column spacings with higher Krs values. The raft with higher Krs values showed the similar

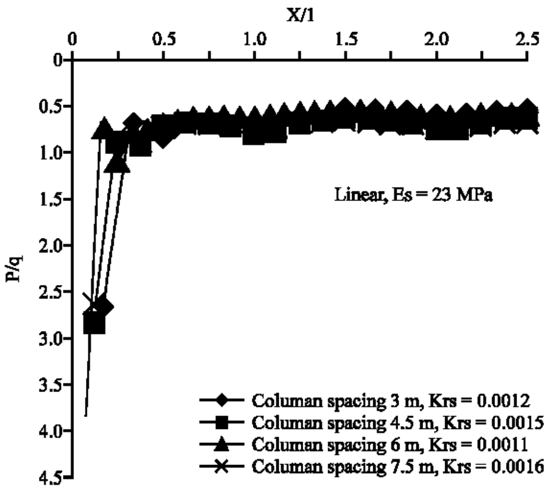

Fig. 15: Contact pressure distribution along B1-B4 of raft for various columns spacings (linear, lesser krs value)

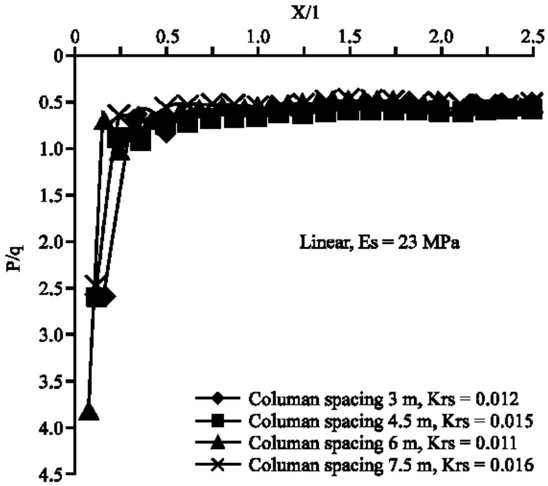

Fig. 16: Contact pressure distribution along B1-B4 of raft for various column spacings (linear, higher krs values)

trend of the rafts with lesser Krs values. However, the settlements were reduced considerably in the rafts with higher Krs values. The settlement increased with increases in column spacing at both the edge and centre of the raft, as shown in the Fig. 6. This result gave the important implication that the settlement increased with increases in column spacing of building frame. This was due to effect of column spacing, the objective of the study.

The effect of raft thickness: In Fig. 6, at the edge of rafts, rafts with higher Krs values had the same settlements as

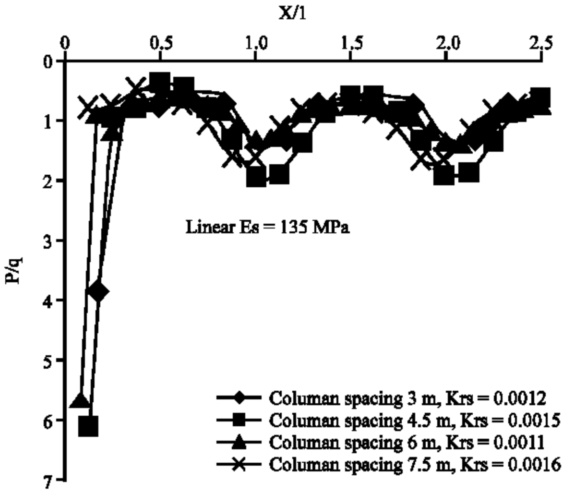

Fig. 17: Contact pressure distribution along B1-B4 of raft for various column spacings (linear, Es = 135 MPa, lesser krs values)

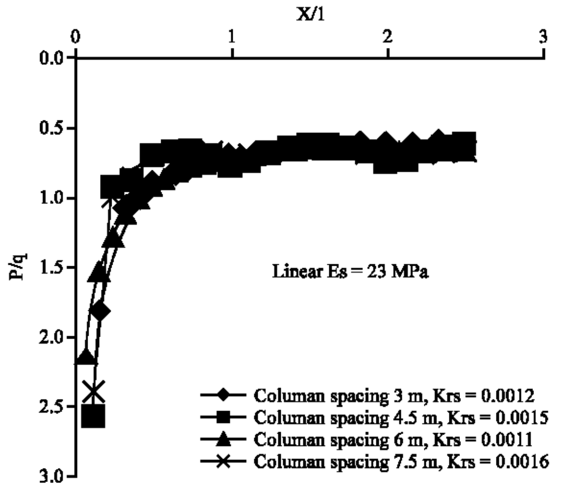

Fig. 18: Contact pressure distribution along B1-B4 of raft for various column spacing (non-linear, lesser krs values)

those of lesser Krs values, irrespective of column spacing. In Fig. 6, rafts with higher Krs values resulted in less settlement at the centre of the rafts than that of the rafts with lesser Krs value, irrespective of column spacing and for soil modulus of 23 MPa.

The observations made in this study are similar to the analysis of Viladkar *et al.* (1991), Maharaj *et al.* (2004) and Daniel and Illamparuthi (2007). These results gave the important implication that with higher raft thickness of foundation resulted in lesser settlement. This was due to effect of raft thickness, Krs, the objective of the study.

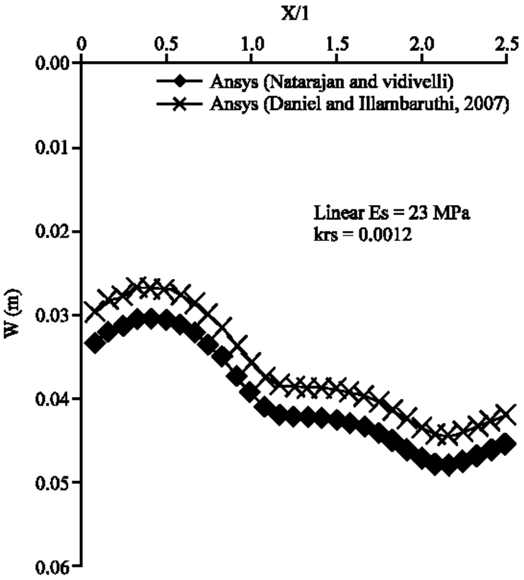

Fig. 19: Validation of ansys,settlement along b1-b4 of raft (Column spacing 6m, linear)

The effect of young's modulus of soil, Es: In Fig 7, the 135 MPa soil modulus showed a similar trend to that of soil with a 23 MPa modulus. However, the 135 MPa modulus of soil resulted in less settlement at both the edge and centre of the raft than the soils with a soil modulus of 23 MPa. For the 135 MPa soil modulus, the settlement at the centre of the raft was marginally higher than the settlement at the edge of the raft, irrespective of column spacings and the difference in settlement between the 3 m column spacing and 7.5 m column spacing of the raft was also small. In addition, for 23 MPa soil modulus, the settlement at the centre of the raft was greater than the settlement at the edge of the raft, irrespective of column spacings and the difference in settlement between the 3 m column spacing and the 7.5 m column spacing of the raft was also high. These results gave the important implication that with higher young's modulus of soil resulted in lesser settlement of the raft. This was due to effect of young's modulus of soil, Es, the objective of the study.

The effect of non-linearity of soil: In Fig. 9 and 10, the non-linear soil showed a similar trend of the linear soil. The settlement in non-linear soil also increased with column spacing. However, the settlement of non-linear soil was higher than that of linear soil. The non-linear soil showed higher settlement than linear soil as shown in the Fig. 9 and 10. These figures show substantial increases in the settlement of the raft, which is due to the non-linear effects of soil.

The results gave the implication that the settlement of the non-linear soil was higher than linear soil. This was due to the effect of non-linearity of soil, the objective of the study.

Bending moment in the raft

The effect of column spacing: Bending moment variation due to different column spacing was compared in Fig. 11. In general, the support moment increased with the increases in column spacing. Moments below the column locations were positive, except at the edge of the columns with 4.5 and 6 m spacing. The bending moment variation in 3 and 7.5 m column spacing showed rigid raft behavior, so that the moments, at both the support and the span were sagging. The bending moment variation with 4.5 and 6 m column spacings showed flexible raft behavior, so that support moments were sagging and span moments are hogging. The moment below the edge of the column of 7.5 m column spacing was the highest of all column spacings and it was 4.5 times higher than that of 3 m column spacing.

The moment variation in 3 m column spacing was much less than 4.5, 6 and 7.5 m column spacings and it showed very little variation between column locations and spans. The span moments were hogging for 4.5 and 6 m column spacing. Both the support moments and span moments were sagging in the 3 and 7.5 m column spacing. The support moment of 4.5, 6 and 7.5 m column spacing increased by 1.5, 2.75 and 5.12 times that of the 3 m column spacing support moment, respectively.

Figure 12 shows the moment variation for various column spacings. For the soil modulus of 23 MPa, the span moment and edge support moment of 4.5 and 6 m column spacings were hogging, whereas for 3 and 7.5 m column spacings, the span moment and edge support moment were sagging. However, all the inner support moments were sagging, irrespective of column spacing.

Inner support moments for higher Krs values were higher than those of lesser Krs values for 6 and 7.5 m column spacing, whereas, for 3 and 4.5 m column spacing, inner support moments were almost the same. The bending moment variation in 3 and 7.5 m column spacing showed rigid raft behavior. The bending moment variation with 4.5 and 6 m column spacings showed flexible raft behavior. This was due to the effect of column spacing, the objective of the study.

The effect of raft thickness: Span moments and edge support moments for higher Krs values were higher than those of lesser Krs values, irrespective of column spacing. So, the moment increased with increase in raft thickness. This was due to the effect of raft thickness, the objective of the study.

The effect of young's modulus of soil: Figure 13 shows the moment variation for various column spacings. Bending moment variation with a soil modulus of 135 MPa showed the same trend as that of 23 MPa soil, but 135 MPa soil has a lower moment than 23 MPa soil. This was due to the effect of young's modulus of soil, the objective of the study.

The effect of non-linearity of soil: Figure 14 shows the moment variation for the various column spacings of linear and non-linear soils. For non-linear soil, the edge support moment of 4.5 m column spacing was hogging, whereas for 3, 6 and 7.5 m column spacing, the edge support moments were sagging. This was due to the effect of non-linearity of soil, the objective of the study.

Contact pressure below the raft

The effect of column spacing: The contact pressure distribution along B1-B4 of the raft for various column spacings was shown in Fig. 15. At the centre part of the raft, the contact pressure for 6 and 7.5 m column spacing was slightly higher than that of the 3 and 4.5 m column spacings. The contact pressure distribution along B1-B4 of the raft for various column spacings is shown in Fig. 17 for the soil modulus of 135 MPa. At the centre part of the raft, the contact pressure for 6 m column spacing was slightly higher than that of the 3 and 4.5 m column spacings. However, the contact pressure for the 7.5 m column spacing lied between that of the 6 m column spacing and 4.5 m column spacing. There is only a marginal variation in the contact pressure below the raft due to the effect of column spacing, the objective of the study.

The effect of raft thickness: The contact pressure distribution along B1-B4 of the raft for various column spacings was shown in Fig. 16 for the soil modulus of 23 MPa and for higher Krs values.Contact pressure variation of higher Krs values showed the same trend as the lesser Krs values. There was no influence on the contact pressure due to the effect of raft thickness, the objective of the study.

The effect of young's modulus of soil: In addition, for a soil modulus of 135 MPa, the contact pressures at the column supports was higher than the soil modulus of 23 MPa. This was due to the effect of young's modulus of soil, the objective of the study.

The effect of non-linearity of soil: The contact pressure distribution for the non-linear soil along B1-B4 of the raft for various column spacings is shown in Fig. 18 for the soil modulus of 23 MPa and for lesser Krs values; at the column points, the contact pressure was the same for all column spacings. However, at the end span of the 6 and 7.5 m column spacings, the contact pressure was less than that of 3 and 4.5 m column spacings. This was due to effect of non-linearity of soil, the objective of the study.

CONCLUSIONS

Based on the analysis of the effect of column spacing on the behavior of a five storey, three bays by five-bays space frame-raft-soil systems, the following important conclusions were drawn:

- The column spacing has a major effect on settlement. The settlement increased considerably with the increases in column spacing. However, they were influenced by the relative stiffness of raft Krs and the soil modulus Es. Between the two parameters, Krs and Es, Es has a major influence on both the edge and centre settlements, indicating the significance of the soil modulus in determining raft performance
- Between the linear and non-linear analysis, settlement was greater in the non-linear analysis and the settlements were higher for higher column spacings
- The rafts with 4.5 and 6 m column spacings were flexible; thus the moments are in both the hogging and sagging regions. The rafts with 3 and 7.5 m column spacing were rigid rafts, so the moment is only in the sagging region
- The inner support moments increased as the column spacing increases. The span and edge support moments varied between the sagging and hogging moments and they were influenced by the two parameters: Krs and Es. The Krs and Es, irrespective of linear and non-linear analysis, influenced the raft bending moment equally
- In linear analysis, moments in the end span increased with as the Es value increased, while Krs altered the moments below the interior as well as the span moment in the interior panels of the raft. The reverse was true for the non-linear soil conditions
- The column spacing has a marginal effect on the contact pressure, but the two soil parameters, Krs and Es, influence the contact pressure. The modulus of soil has a greater influence on the contact pressure. At support points, the contact pressures were higher for a higher soil modulus

Variation in contact pressure was significant between the linear and non-linear soil conditions. Contact pressure distribution was more uniform in the non-linear case and its magnitude was less than that of linear soil, particularly in the end panels of the raft.

NOTATIONS

B: Width of the raft
E_b: Elastic modulus of beam
E_r: Young's modulus of raft
Es: Elastic modulus of soil
I_b: Moment of inertia of beam
If: Influence Factor
Ir: Moment of Inertia of raft
Ksb: Relative stiffness between soil and building
Krs: Relative stiffness between raft and soil
L: Length of raft
X: Distance along X axis
l: Span of the beam
P: Contact pressures from analysis
q: Contact pressure, Total load/Area of the raft
m: Number of storeys
V_s: Poisson's ratio of soil
w: Settlement of the raft

REFERENCES

Brown, P.T. and K.R. Yu, 1986. Load sequence and structure-foundation-interaction. J. Struct. Eng., 112: 481-488.

Conniff, D.E. and P.D. Kionusis, 2007. Elastoplastic medium for foundation settlements and monotonic soil-structure interaction under combined loadings. Int. J. Nume. Anal. Methods Geomechanics, 31: 789-807.

Daniel, T.D. and K. Ilamparuthi, 2001. Analysis of Raft foundation. Proceeding of the National Conference on Indian Geotechnical Conference, 2001, Indore, India, pp: 154-158.

Daniel, T.D. and K. Ilamparuthi, 2004. Analysis of raft with frame on layered foundation. Proceeding of the International Conference on Geosyn and Geoenvironment Engeering, 2004, Bombay, pp: 453-458.

Daniel, T.D. and K. Ilamparuthi, 2005. Effect of space frame on the behavior of raft foundation using 3-D FEM.Proceeding of the National Conference Advance in Geotechnical Engeering, 2005, Rourkela, pp: 306-313.

Daniel, T.D. and K. Illamparuthi, 2007. Influence of relative stiffness of soil-raft-system on the behavior of space frame. J. Struct .Eng., 34: 111-123.

Dutt, S.C. and R. Roy, 2002. 2002A critical review on idealization and modelling for interaction among soil-foundation-structure system. Comput. Struct., 80: 1579-1594.

Godbole, P.N., M.N. Viladkar and L. Noorzaei, 1990. Nonlinear soil structure interaction analysis using coupled finite-infinite elements. Comp. Struct., 36: 1089-1096.

Maharaj, D.K., A. Amruthavalli and K. Nishamathi, 2004. Finite element analysis for frame foundation interaction, ejge, 0413.http://www.ejie.com/2004/ppr0413/ ppr0413.htm.

Manjeet, H., 2006. Non-linear interaction analysis of in filled building frame-soil system. J. Struct. Eng., 33: 309-318.

Noorzaei, J., M.N. Viladkar and P.N. Godbole, 1991. Soil structure-interaction of space frame-raft-soil system-A parametric study. Comp. Struct., 40: 1235-1247.

Noorzaei, J., P.N. Godbole and M.N. Viladkar, 1993. Nonlinear soil structure interaction of plane frames-A parametric study. Comp. Struct., 49: 561-566.

Noorzaei, J., M.N. Viladkar and P.N. Godbole, 1994. Non-linear soil-structure interaction in plane frames. Eng. Comput., 11: 303-316.

Noorzaei, J., M.N. Viladkar and P.N. Godbole, 1995a. Elasto plastic analysis for soil structure interaction in framed structures. Comp. Struct., 55: 797-807.

Noorzaei, J., M.N. Viladkar and P.N. Godbole, 1995b. Influence of strain hardening on soil- structure interaction of framed structures. Comp. Struct., 55: 789-795.

Rao, P.S., K.V. Rambabu and M.M. Allam, 1995. Representation of soil support in analysis of open plane frames. Comput. Struct., 81: 917-925.

Small, J.C., 2001. Practical solutions to soil-structure interaction problems. Prog. Struct. Eng. Mater., 3: 305-314.

Viladkar, M.N., P.N. Godbole and J. Noorzaei, 1991. Soil structure interaction in plane frames using coupled finite-infinite elements. Comput. Struct., 39: 535-546.

Viladkar, M.N., J. Noorzaei and P.N. Godbole, 1992. Space frame-raft-soil interaction including effect of raft thickness.Comput.Struct., 43: 93-106.

Viladkar, M.N., G. Ranjan and R.P. Sharma, 1993. Soil-tructure interaction in the time domain. Comput. Struct., 46: 429-442.

Viladkar, M.N., J. Noorzaei and P.N. Godbole, 1994. Interactive analysis of space frame raft soil system considering soil non-linearity. Comput. Struct., 51: 343-356.