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Numerical analyses of soil-mat foundation and space frame system

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Abstract. In most of the design offices, analysis of the frame is carried out without considering the effect of the rigidity of mat. The analysis of the superstructure without modelling the foundation properly and conversely analysing the foundation system without considering the stiffness of the superstructure may mislead the estimation of the forces. This paper examines the parameters, which affect the interaction and they are grouped into relative stiffness factors k_{rs} and k_{sb}. An interaction analysis is performed for the five storeyed space frame of 3 bays × 5 bays, using ANSYS finite element code. The soil was treated as an isotropic, homogenous and elastic half space medium and the following conclusions were drawn from the analyses. The differential settlement is reduced due to interaction and the performance of the mat depends on k_{sb} values. The moments M_x and M_y in the corner column at all the storey levels are higher in the case of the interaction analysis than in the conventional analysis. The axial forces in the peripheral columns increased and to that extent, the inner column axial loads are reduced. In the beam, more variation is seen in the support moments than in the span moments.

Keywords: interaction; frame; mat; stiffness; settlement; forces; moments.

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1. Introduction

In any structure, the superstructure and the foundation founded on soil constitute a complete structural system. Neither can be analysed without considering the other. Analysis of a framed structure (superstructure) without modelling its foundation system and without considering its rigidity may mislead the estimation of forces, bending moments and settlements. It is, therefore necessary to carry out the analysis considering the soil, the foundation and the superstructure, which form a single compatible unit. The superstructure in the conventional design procedure is usually analysed by isolating it from the soil-foundation medium, assuming that the superstructure is fixed at the foundation level and that no interaction takes place. Such an analysis neglects the flexibility of the foundation and the compressibility of the soil mass. Further the effect of deformations of the foundation on the redistribution of forces in the superstructure is also ignored in the conventional design. Due to the compressibility of the soil medium, foundations undergo horizontal and vertical displacements and rotations. In order to maintain the equilibrium and compatibility between soil,

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foundation and the frame, the redistribution of forces must take place within the system. In this research a framed structure of 3 bay × 5 bay supported on a foundation system known as mat is considered to evaluate the influence of thickness of mat and modulus of soil on forces and deformation of the frame. A mat is a shallow foundation, which is normally adopted in situations where other types of shallow foundation is not suitable because of low bearing capacity of soil, non homogeneous nature of soil and higher differential settlement than permissible limit. It is a RCC slab resting on soil medium covering the area below to the foot print of the building and supports all the columns of a frame. In this study plain flat concrete slab without pedestal is considered as a mat.

2. The interaction analysis of the Soil-Mat-Plane frame

The present discussion considers the development of the interaction analysis taking into account the influence of the stiffness of the frame. Each element of the system is considered to have linear stress-strain characteristics.

Grasshoff *et al*. (1957) analysed a plane frame on a combined footing to bring out the effect of the rigidity of the superstructure and the condition of fixity of columns with the foundation on the bending moment and the contact pressure. The analyses were carried out for the perfect flexibility and perfect rigidity conditions of the frame with supports to the foundation being either hinged or fixed. The pressure at any selected point was obtained by considering the vertical equilibrium between the applied loads on the combined footing and the soil pressure acting underneath and the deformation of the beam and the sub soil. Haddadin (1971) studied the use of the sub-structure technique for the linear interaction analysis of a seven storey, 3 bay plane frame. In most of the cases it was assumed that the columns were pinned with the foundation bases for simplicity, which quite often was not a satisfactory representation, because columns were built monolithically with the mat. The supporting soil was considered a linear elastic material. King and Chandrasekaran (1974) formulated a finite element procedure and analysed a plane frame supported on a combined footing in which the frame and the combined footing were discretised into beam bending elements and the soil mass into plane rectangular elements. A zero thickness friction element was also adopted to represent mat-soil interface. This element was, however, useful only in the presence of the lateral loads. A semi-analytical method to study the effect of the rigidity of the superstructure on the performance of the foundation was also proposed.

Bhandari and Rao (1977) in their paper on “Concept of rigidity in foundation analysis” brought out the contribution of the modulus of deformation of the soil, the thickness of the foundation slab and the stiffness of the superstructure to the relative rigidity factor through experimental and analytical works. In their analysis Borowicka’s (1939) expression was used for the relative stiffness factor which assumed a flexible superstructure and showed that the relative rigidity factor was not sensitive to small errors in the estimation of the soil modulus but depended significantly on the foundation slab thickness. They also pointed out that the Poisson’s ratio has a very little effect on the relative rigidity factor. It is stated that the maximum bending moment and the maximum shear in a footing increase with an increase in the relative rigidity including the contact pressure at the edges. But at the centre of the foundation slab the contact pressure decrease with increase in the relative rigidity.

Ramanathan and Pujar (1976) evaluated out the importance of rigidity of the superstructure by analysing a seven storey plane frame founded on individual footings. They first analysed the plane frame by assuming that it was supported on an unyielding base. The forces and the moments obtained were used to calculate the total settlement of all the footings without considering the rigidity of the frame. The column loads were then recalculated by taking into account the relative displacement between the footings. The settlements of all the footings then again calculated using the recalculated column loads. Finally, the authors showed that the rigidity of the superstructure reduced the differential settlement within the acceptable limits, and the influence of the rigidity of the superstructure on the behavior of the foundation depended on the soil model chosen to represent the foundation soil. Brown (1977) examined the effect of linear soil creep with regard to differential settlements of the structure. It was shown that for a flexible footing the differential settlement tends to increase unless restrained by the structural stiffness. However, a large value of relative stiffness of footing tends to reduce the differential settlement. Sharada Bai *et al*. (1985) carried out an interaction analysis of a plane frame supported on isolated footings wherein soil medium was represented first by Winkler and then by the elastic half-space models. In this research work the importance of the interaction analysis was established by the following conclusions. The bending moment at the column ends and the axial force in the exterior columns decrease with an increase in the relative stiffness, whereas the bending moments at the beam ends and in the footings and the axial forces in the interior columns increase with an increase in the relative stiffness.

Brown *et al*. (1986) examined the effect of the sequence of construction on the interaction behaviour and found that the effective stiffness of a building during construction is about half the stiffness of the completed structure. Viladkar *et al*. (1991) studied the soil-structure interaction of a plane frame using the coupled finite-infinite-element. In this study, the concentration was on developing a coupled FE procedure with the non-linear idealization of the soil using the hyperbolic stress-strain law. Initially, a method was proposed for the interaction analysis of the framed structure founded on isolated footings. Subsequently an attempt was made to represent a coupled finite-infinite element formulation for the general case of a multistoreyed plane frame on a combined soil system. The constitutive relation for the non-linear behaviour of the soil mass was included to study its effect on the redistribution of the shear force and bending moments in the structural members, and also the settlement and the contact pressure distribution in the foundation. Noorzaei *et al*. (1993) continued the work of Viladkar for the interaction analysis of the space frame-mat-soil system by modelling the superstructure as a system of Timoshenko beam elements and Mindlin plate bending elements for the structural slabs and the mat. To account for the non-linear behaviour of soil hyperbolic model was used. A parametric study was reported on the effect of the variation of the mat and the slab thickness on the behaviour of the space frame. Hora and Sharm (2007) analysed a plane frame of two storey two bay in filled frame-foundation beam soil system considering linear elastic behaviour of the superstructure (including in-fill). The elasto-plastic interaction analysis has been carried out considering the subsoil to yield according to various yield criteria. The results of the elasto- plastic interaction analysis were compared with conventional and linear elastic interaction analysis. They concluded that, the collapse load for the in filled frame foundation beam soil system is marginally less compared to plane frame foundation beam soil system. It was due to the fact that the inclusions of in-filled panels significantly increased the stiffness of superstructure, that has reduced the differential settlement of the foundation beam.

Chore *et al*. (2009) carried out interaction analyses between building frame-pile foundation and supporting soil to evaluate the influence of various parameters of pile and pile cap on the response of super structure. Three dimensional finite element models were simulated for the problem considered and analysed for two conditions. Initially the analysis was performed for the conditions of fixed columns and later analyses were carried out separately for the pile foundation alone. Finally uncoupled analysis was performed for the frame utilizing the stiffness obtained separately for the pile foundation.

3. Interaction analysis of the Soil-Mat-Space frame

In the interaction analysis of foundation-soil system both the deformation of the mat and the deformation of the soil must fulfill the requirements of equilibrium and compatibility.

Meyerhof (1947) showed the importance of the rigidity of the superstructure in the design of the foundation through a simple interaction analysis. An approximate method was proposed to estimate the stiffness of the superstructure and to relate it to the deformation of the soil. Applicability of the proposed method was demonstrated through an analysis of a frame on London clay which showed that a relatively small differential settlement of footing induced large forces and moments on all structural members, particularly at external joints in the lower storey. The secondary moments due to the settlement of the footing were evaluated by the slope deflection method and distributed them using Hardy Cross method. Further a method for estimation of moments in members of the frame supported on isolated footings was also suggested. Sommer (1957) studied the effect of the rigidity of the superstructure in the analysis of foundation in the homogenous, isotropic and elastic half-space. The structures with different degrees of rigidity including perfectly flexible and perfectly rigid cases were analysed. The foundation slab was divided into a number of parts and it was assumed that there was a rigid support at the center of each part. The reaction at these supports was determined from the superstructure loads using the laws of statics. Unit settlement was induced at each of these supports and the reaction forces were found at all these supports. These reaction forces due to unit settlement were then used to find out the reaction forces at the supports. Equilibrium equations were then formed, from the forces obtained for the structure considered to be supported on an unyielding base and the reaction forces due to sub-soil settlement. Assuming deformation and compressibility of the soil in one direction, the settlement at the imaginary supports were determined in terms of the unknown reactions, and then substituted in the equilibrium equations to determine the support reactions. The study concluded that the bending moment in the slab increases with an increase in the rigidity of the foundation and decreases with an increase in the rigidity of the superstructure. Hence, the design of the mat, without taking into account the rigidity of the superstructure, will result in greater dimensions of the mat than necessary.

Lee and Harrison (1970) analysed the superstructure-foundation system supported on the Winkler's springs by taking sways and rotations at the column bases as unknowns. These rotations and sways obtained from the independent analysis of the superstructure were then equated to the corresponding values obtained by considering the foundation to be a beam on a Winkler medium subjected to forces and moments. In another method, successive modification of the contact pressure distribution was advocated. In this method, the contact pressure corresponding to a rigid foundation was assumed and treating the superstructure and foundation as a single compatible unit, a conventional structural analysis was carried out to evaluate the column forces and the moments. Then isolating the foundation from the superstructure the new contact pressure distribution was evaluated using these column forces and moments. This process was repeated with the new contact pressures until the required accuracy was reached. Very recently Swamy *et al*. (2011) carried out uncoupled and coupled FE analyses to study the interface characteristics between the soil and isolated footing on structure. In this study two independent cases were considered to represent smooth and rough interface. In the first case the smooth interface was modeled as a complete slip and in the second case rough interface was modeled by assigning complete welding between the joints and foundation and soil elements. The FE code developed for thses two conditions were applied to evaluate the influence of interface elements in soil structure interaction analysis of structures supported by isolated footings.

From the above discussion, it is clear that most of the previous investigators have analysed the mat either founded on an elastic half-space or wherein the soil was treated as a linear elastic solid. The settlement, the bending moment and the contact pressure on the mat were analysed in detail but the modulus of the soil and thickness of the mat was not discussed in most of the cases. Hence in this paper to find the effect of modulus of the soil and thickness of the mat on the behavior of mat and frame are studied.

4. Method of study and relative stiffness

In the proposed study both interaction (INT) and non-interaction (N-INT) analyses were carried out. In the non-interaction analysis, the forces and moments obtained for the structure on an unyielding base are applied on the mat-soil system, and analysed independently. In the interaction analysis, all the three components namely soil, mat and superstructure are analysed as a single compatible unit and compared with non-interaction analysis. A detailed parametric study was conducted by varying the relative stiffness of superstructure, k_{sb} and the mat, $k_{rs.}$ The relative stiffness k_{sb} and k_{rs} are determined based on the recommendation of Brown *et al*. (1986) which are as follows.

$$k_{sb} = \frac{E_s l^4}{mE_b I_b (1-\upsilon_s^2)}$$

$$k_{rs} = \frac{16 E_r I_r (1-\upsilon_s^2)}{\pi E_s L^4}$$

where, m = Number of storeys, E_b = Elastic modulus of beam, E_s = modulus of soil, E_r = Young's modulus of mat, I_b = Moment of Inertia of beam, I_r = Moment of Inertia of mat, L = Length of the mat, l = Span of the beam and υ_s = Poisson's ratio of soil.

The influence of these two parameters on the forces and moments in superstructure and the mat were studied. Analyses were carried out for the following values: k_{rs} = 0.001, 0.005 and 0.01 and k_{sb} = 15, 20, 30, 60 and 100.

These values were selected as they are of practical interest. The lower limit of k_{sb} represents a building on the very soft or loose deposit and the upper limit of k_{sb} is a point beyond which there is a little interaction effect. The lower limit of k_{rs} corresponds to a foundation of a minimum feasible relative stiffness and the upper limit of k_{rs} represents a semi rigid foundation. Thus, this analysis covers mostly the semi flexible behaviour of the foundation system. The various relative stiffness were obtained for a constant building stiffness k_b, ($k_b = mE_bI_b/l$, where m = number of stories, E_b = modulus of beam, $I_b/$ = Moment of Inertia of beam and l = span of the beam) then selecting k_s (k_s = $Es/$ 1-υ_s, Es = modulus of soil, υ_s = Poisson's ratio of soil) to give the desired value of k_{sb} and finally

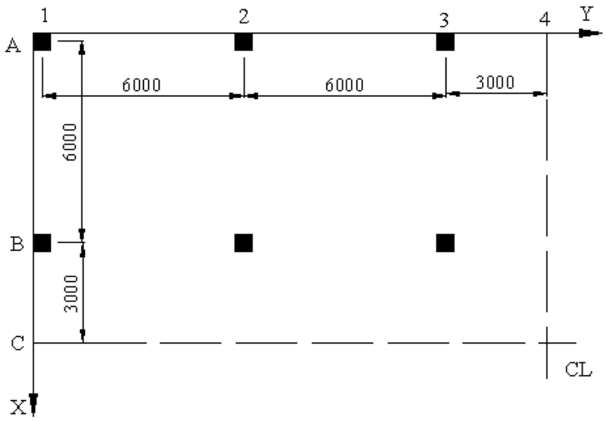

Fig. 1 Plan of quarter mat and column position (All dimension are in mm)

Table 1 Geometric and elastic properties of frame, mat and soil

Column size, *m*	Storey- 1, 2, 3	0.5×0.5
	Storey- 4, 5	0.4×0.4
Beam size, *m*		0.3×0.6
Modulus of concrete, kPa		2.5×10^7
Load on inner beams		35 kN/m
Load on outer beams		28 kN/m
Poisson's ratio of concrete		0.15
Poisson's ratio of soil		0.35
Modulus of soil, MPa		20 to 134

using the selected value of k_s to determine k_r such that the desired value of k_{rs} is obtained.

5. Details of the problem

The plan of the quarter mat and the position of the columns of 3 bay × 5 bay frame are shown in Fig. 1. The spacing between the columns is 6 m and the column height between the floors is 3.5 m. An analysis is carried out by assuming that the mat is placed directly on the sand bed. In general, sand is a non-homogeneous material, whose modulus varies with depth. However the trial analysis on the frame-mat-soil system by including non-homogeneity showed some influence on the total settlement but only marginal difference on the differential settlement as well as on the member forces. Therefore, the elastic property of sand are assumed to be uniform with depth. In the analysis, the stiffness of the wall and the slab are not included. The load on the slab including self-weight and weight of the wall are considered and applied as uniformly distributed loads on the beams. The geometric properties of the frame and the material properties adopted in the analysis are presented in Table 1.

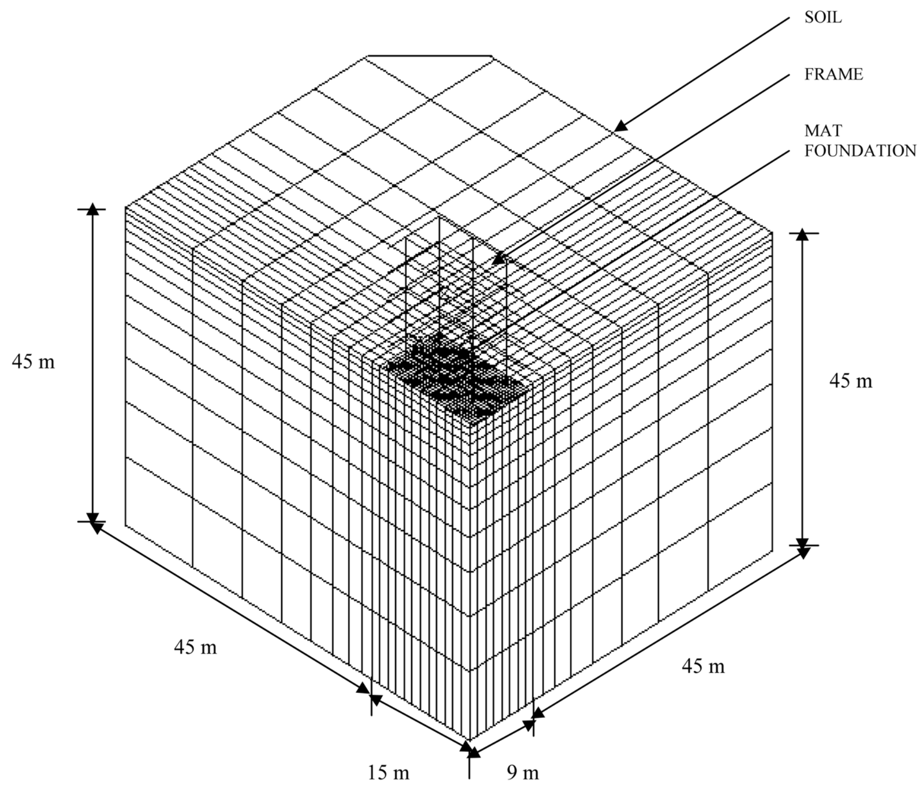

Fig. 2 Frame-mat-soil and element discretization (Quarter model) of FE model

6. Finite element model

The complexities involved in the interaction analysis of the mat and the superstructure can be simplified to a larger extent if the finite element technique is used. The finite element discretization of frame-mat-soil is shown in Fig. 2.

6.1 Frame model

The frame is modelled as an assemblage of beam elements (Beam 4, ANSYS). Beam 4 is a uniaxial element which has the capabilities of tension, compression, torsion and bending capabilities. This element has two nodes and six degrees of freedom at each node and it is treated as Timoshenko beam elements. They are translations in the nodal x, y and z directions and rotations about the nodal x, y and z directions. The joints between the columns and beams are assumed to be rigid.

6.2 Mat foundation and contact element

The mat is modelled as a plate-bending element (Shell 93) with eight nodes having six degrees of freedom at each node. The shell 93 element of ANSYS is considered as Mindlin plate bending elements and the moment per unit length of the mat is calculated in the element co-ordinate system.

The interface characteristics between the mat and the soil are represented by the combination of element Targe 170 and Conta 174. These interface elements are adopted to represent contact of dissimilar materials of soil and concrete mat as adopted by other researchers (Zeghal *et al*. 2002, Swamy *et al*. 2011, etc). The interface adopted in this study represent no slip between soil and foundation.

6.3 Soil model

The soil is treated as an isotropic, homogenous and elastic half space medium. For the linear analysis, the initial tangent modulus (E_s) and Poisson's ratio (υ_s) are the inputs. The soil medium below the mat is modelled using the eight-node brick element (SOLID 45) having three degrees of freedom of translation in the x, y and z directions at each node. In order to find the extent of the soil region to be used in the study, many trial analyses were carried out and was found that for the width and the thickness of the soil medium more than 2.5 times the least width of the mat foundation the variation in settlement and the contact pressure was negligible, thus the region of soil medium considered was 2.5 time the width in all three direction by arresting vertical translation at the bottom boundary and arresting lateral translation on the vertical boundaries. Fine meshes with aspect ratio 1 are generated close to the mat while meshes generated away from the mat area are made coarser gradually.

7. Results and discussion

A rectangular mat of 18 m × 30 m supporting 24 columns spaced at 6 m centre to centre on both the directions was analysed for the linear behaviour of the soil. The results of the analyses are presented and discussed below.

7.1 Settlement of mat foundation

In order to understand the effect of k_{rs} on the settlement, the variation of the normalized settlement along the section A1-A4 is presented in Fig. 3 for a set of k_{rs} and k_{sb} values. The settlement of the mat is higher for lower k_{sb} value, irrespective of the k_{rs} values. For the k_{sb} value of 15, the maximum settlement along the section A1-A4 is around 0.70% of the span (l). Though there is not much difference in the settlement between the k_{rs} values of 0.001 and 0.01, the differential settlement is less by 16% for the k_{rs} value of 0.01. This indicates that the increase in the mat thickness has only a marginal influence on the settlement. However, the increase in the k_{sb} has a significant influence on the settlement which is evident from the appreciable decrease in the settlement. The reduction in the differential settlement is 20%, which again indicates that the modulus of the soil has more influence than the thickness of the mat in reducing both the total and the differential settlement of the foundation soil system. Fig. 4 depicts the variation of the total settlement with k_{sb} at the column points. The settlement at the column point is reduced appreciably for the k_{sb} values between 15 and 60 and for the k_{sb} values more than 60, the reduction in the settlement is negligible. Moreover, the magnitude of the settlement was very less (< 10 mm) for higher k_{sb} values (> 60) irrespective of the column locations for the intensity of the load considered in this analysis.

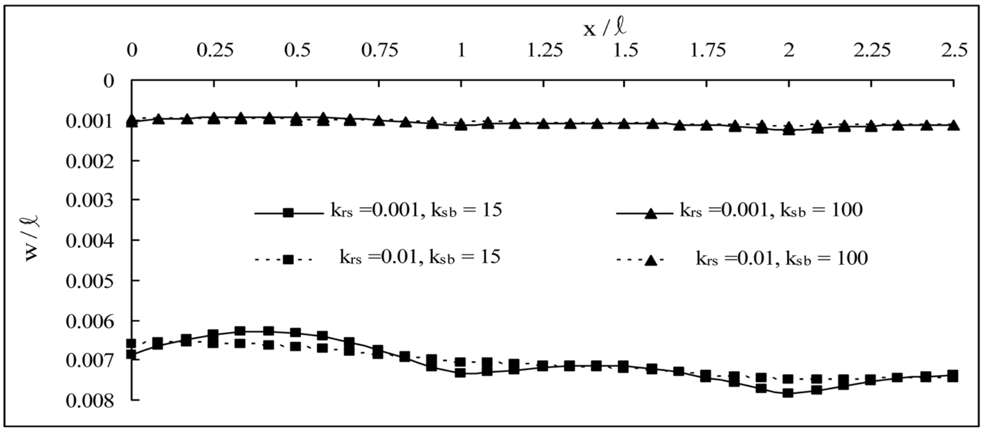

Fig. 3 Normalized settlement along the section A1-A4 of the mat

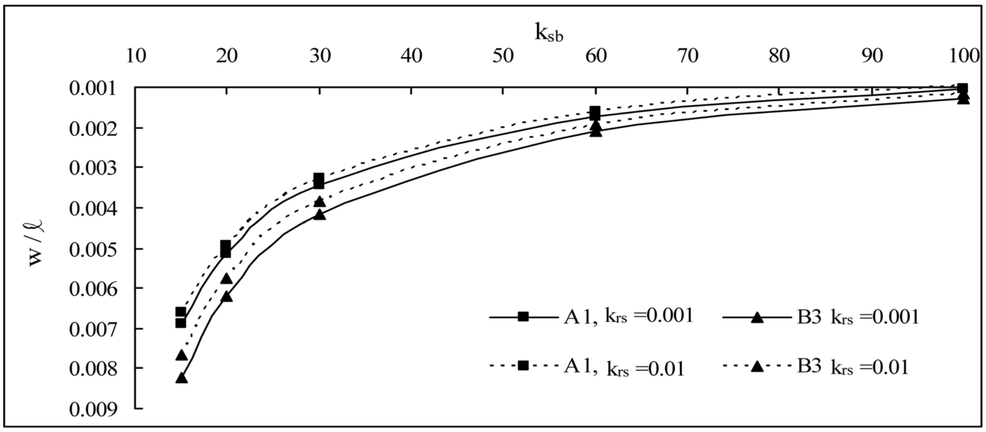

Fig. 4 Variation of total settlement with k_{sb} in the mat at the column points

7.2 Bending moment in the columns

The bending moment in column A1 about x and y axes between the conventional and the interaction analyses are compared in Table 2. In the case of the conventional analysis, the moment in the column A1 about x and y axes (i.e., Mx and My) are the same whereas in the interaction analysis they are not the same. The difference is more for the $k_{sb} = 15$ and $k_{rs} = 0.001$. The moments M_x and M_y in the column A1 at all the storey levels are higher in the case of the interaction analysis than in the conventional analysis. The increase is significantly higher in the ground floor column and to some extent at the bottom level of the first floor column for a given k_{sb}. This effect is decreased with the increase in k_{rs} value irrespective of k_{sb} and in particular for the $k_{sb} = 100$. The maximum increase in M_x or M_y is 8 and 2 times the moment of the conventional analysis for $k_{sb} = 15$ and 100 respectively. But the moment in this column due to interaction is almost the same as that of the moment of the conventional analysis for the k_{rs} and k_{sb} values of 0.01 and 100 respectively. This indicates that for the thicker mat and stiffer the soil the interaction between the

Table 2 Variation of moment in the column A1

Storey	Conv.	Moment (M_x), kNm					
		k_{sb} = 15			k_{sb} = 100		
		k_{rs}			k_{rs}		
		0.001	0.005	0.01	0.001	0.005	0.01
*S*1	-17	141	14	-22	31	-15	-22
*S*2	-42	-92	-76	-70	-54	-48	-47
*S*3	-42	-62	-64	-64	-45	-47	-46
*S*4	-29	-44	-44	-44	-31	-32	-32
*S*5	-42	-57	-58	-58	-43	-44	-44
		Moment (M_y), kNm					
*S*1	-16	149	38	9	35	-7	-13
*S*2	-42	-83	-62	-55	-53	-46	-44
*S*3	-42	-51	-50	-49	-43	-44	-44
*S*4	-28	-35	-34	-32	-29	-29	-29
*S*5	-41	-50	-48	-47	-43	-42	-42

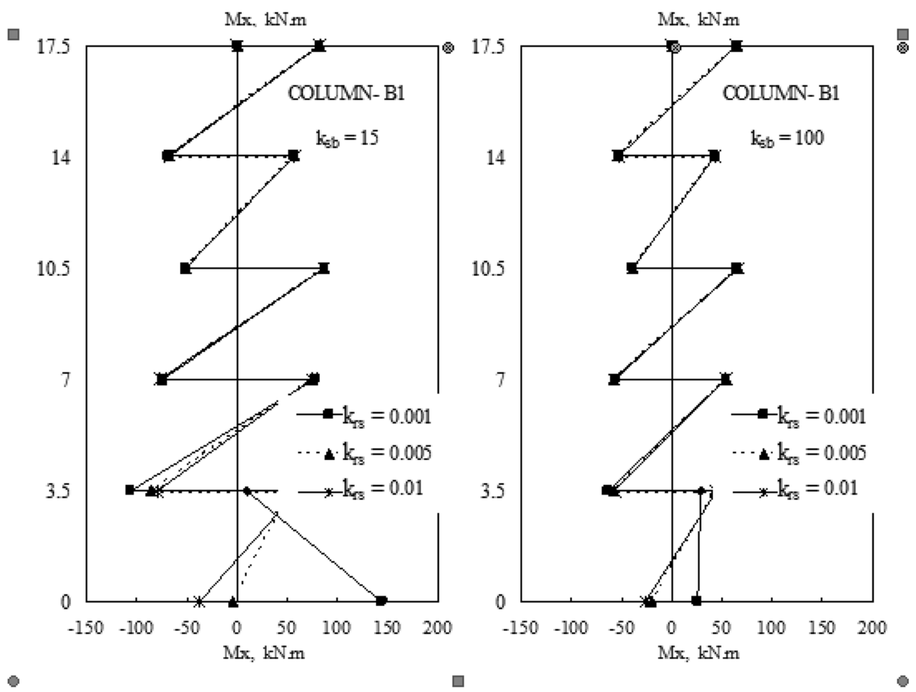

Fig. 5 Moment about *x* axis in column B1 at different storey level

mat and the frame is not significant, which shows that the interaction behaviour is tending towards the behaviour of the frame on unyielding supports.

Fig. 5 depict the variation of column moments (*Mx*) for various k_{rs} for a given $k_{sb.}$ The moment

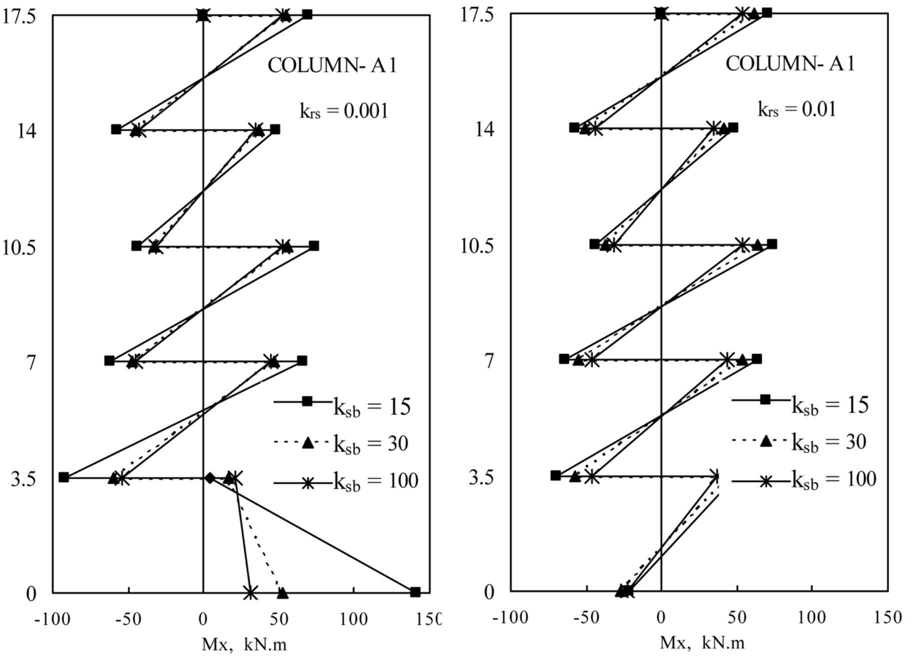

Fig. 6 Moment about x axis in column A1 at different storey level for various k_{sb} values

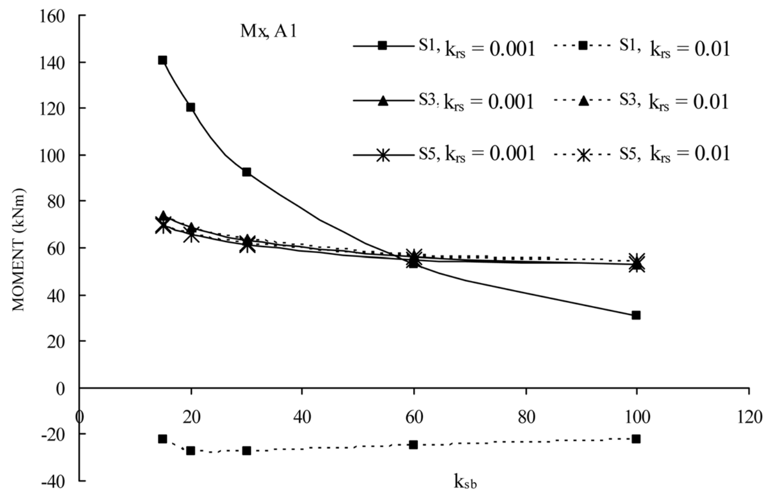

Fig. 7 Variation of column moment A1 for various k_{sb} and k_{rs}

varied mainly in the ground floor column with the increase in k_{rs}. Further, the effect of k_{rs} is more when k_{sb} is less. But for the higher k_{sb} (i.e., 100) the moment in the column is less and the difference in the moment between the different k_{rs} is also not much. The effect of k_{sb} for a given k_{rs} on the column moment can be seen from the Fig. 6. For a given k_{rs}, the change in k_{sb} varied the moment in columns at all the floor levels. However, the moment is higher for lower k_{sb} (15) irrespective of k_{rs} , the location of the column and the floor level of the column. The difference in the moment between the k_{sb} values is significant only in the ground floor part of the column that too for the lowest k_{rs} value (0.001). The effect of the relative stiffness of the frame and the mat are represented in Fig. 7 for the corner column since the variation in the moment among the interaction parameters analysed is appreciable in this column. The moment in the columns of the different floors with mat relative stiffness (k_{rs}) values of 0.001 and 0.01 decreases with increase in super structure stiffness (k_{rs}). The effect of k_{sb} on the moment is almost negligible for k_{sb} values more than 60 and is true for all the values of k_{rs} considered in the analyses. Between the two k_{rs} values, both the moments M_x and M_y in the column are lesser for higher k_{rs} values, which shows that when the mat becomes rigid and the moment in the column decreases and the moment in the mat increases.

7.3 Axial force in the columns

In Table 3 the axial force on the columns is compared for the k_{sb} values of 15 and 100. The influence of k_{rs} is also shown in the table for all the columns of the frame. For a given k_{sb} value the least loaded and heavily loaded columns are the corner column (A1) and the intermediate column (B2) respectively. This is true for all the values of k_{rs} analysed. Further, the axial forces in the inner row columns (row B, along length of mat) are higher than the axial forces in the corresponding columns of the outer row (row A- edge columns along the length of the mat). In a given row, the axial force on the column adjacent to the end column is higher. However, the column B2 shares the maximum load irrespective of k_{rs} and k_{sb} values. For a given k_{sb}, the increase in k_{rs} showed a marginal variation in the column loads and the maximum variation is 3% for the variation of k_{rs} from 0.001 to 0.01.

Further for a given k_{sb} the increase in the rigidity of the mat (k_{rs}) distributes higher load to the columns B2 and B3 and to that extent other columns are relieved. But for a given k_{rs}, the increase in k_{sb} from 15 to 100 showed a reduction in the axial force in the corner column (A1) and the column adjacent to the corner column on either direction (A2 and B2) and the increase in the axial force is on the remaining columns (A3, B2 and B3). The maximum variation in the column forces is for $k_{rs} = 0.001$. The maximum reduction is in the column A1 which is about 8% whereas the maximum increase is 5% in the column B3.

An interaction factor (I_f) is introduced to study the effect of k_{rs} and $k_{sb,}$ on sharing the load

Table 3 Axial force in columns

Column	Axial force, kN					
	k_{sb}=15			k_{sb}=100		
	k_{rs}			k_{rs}		
	0.001	0.005	0.01	0.001	0.005	0.01
A1	898	900	896	830	835	834
B1	1393	1404	1407	1369	1372	1373
A2	1408	1392	1379	1374	1368	1366
B2	2112	2097	2095	2125	2116	2115
A3	1336	1323	1321	1347	1348	1348
B3	1988	2019	2037	2090	2096	2099
Total	9135	9135	9135	9135	9135	9135

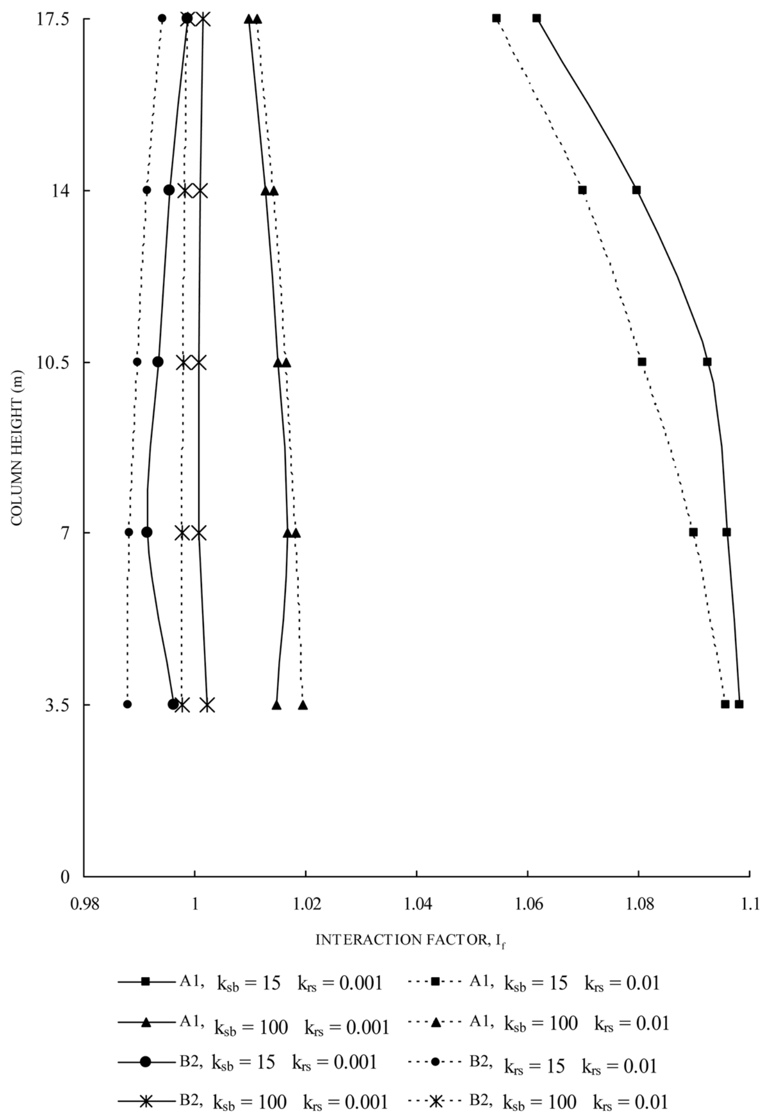

Fig. 8 Interaction factor (I_f) for axial force of columns A1 and B2

between the columns. It is expressed as a ratio of the axial force of a column in the interaction analysis to the axial force of the same column in the conventional analysis. Fig. 8 presents the interaction factor for the minimum and the maximum loaded columns A1 and B2 respectively. For a given k_{sb}, I_f of the column A1 is greater than that of B2 and is also more than unity irrespective of the k_{rs} value. The influence factor for the B2 column increases with the increase in k_{rs}, whereas it decreases for the outer column irrespective of the k_{sb}. This is due to the reduction in the differential settlement with the increase in k_{rs} value. Further, the I_f factors are very close to unity for the higher k_{rs} and k_{sb} values which is a clear indication for the marginal interaction between the structure and the foundation (just like frame is on the unyielding supports). The discussion presented above on

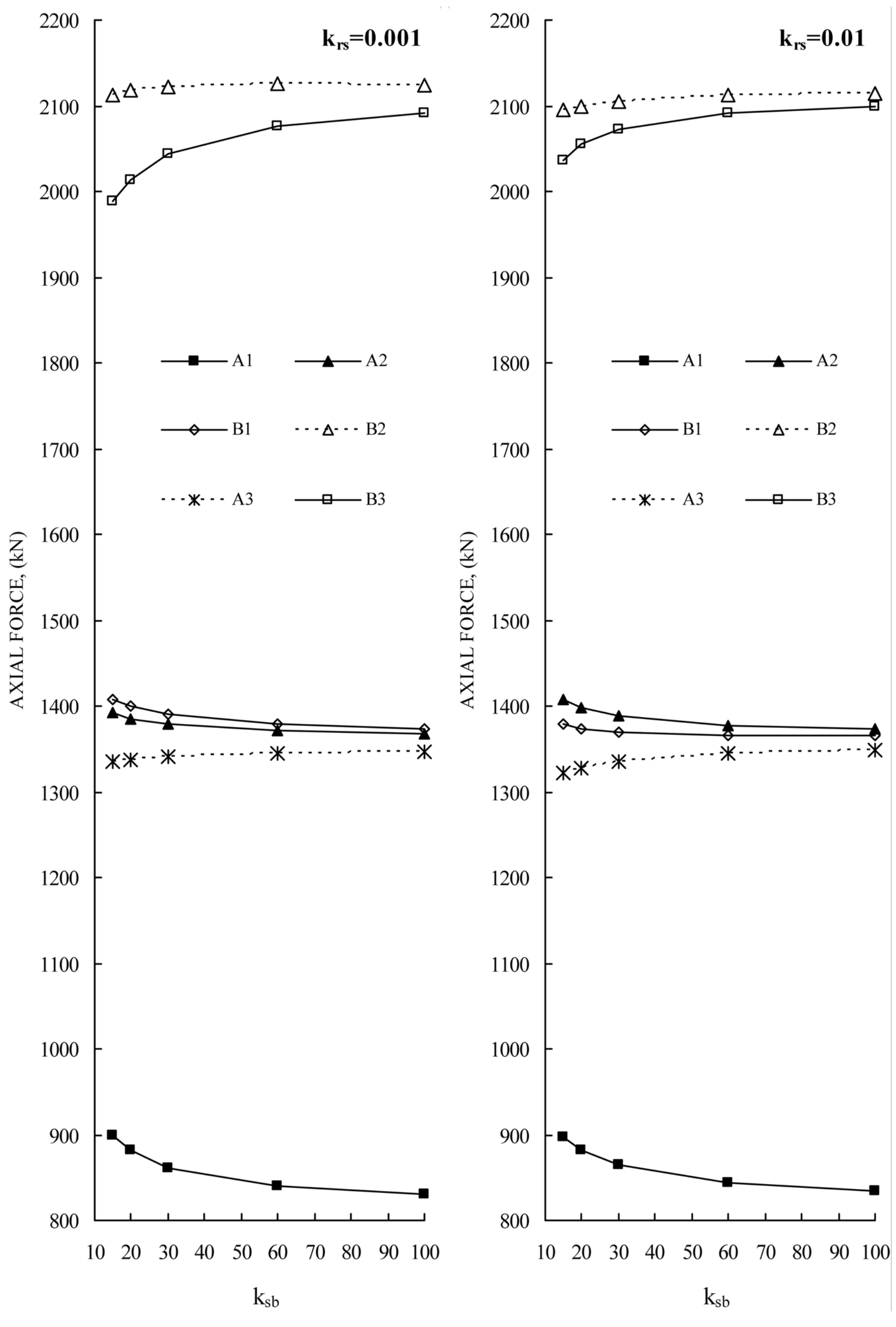

Fig. 9 Variation of axial force below the columns for various k_{sb} values

the axial force on the column is for the extreme values of k_{sb}. In order to have more details on the axial force variation with k_{sb}, the axial forces on the various columns obtained from the interaction analysis are compared in Fig. 9. From the figure it is clear that the axial force in the columns A1,

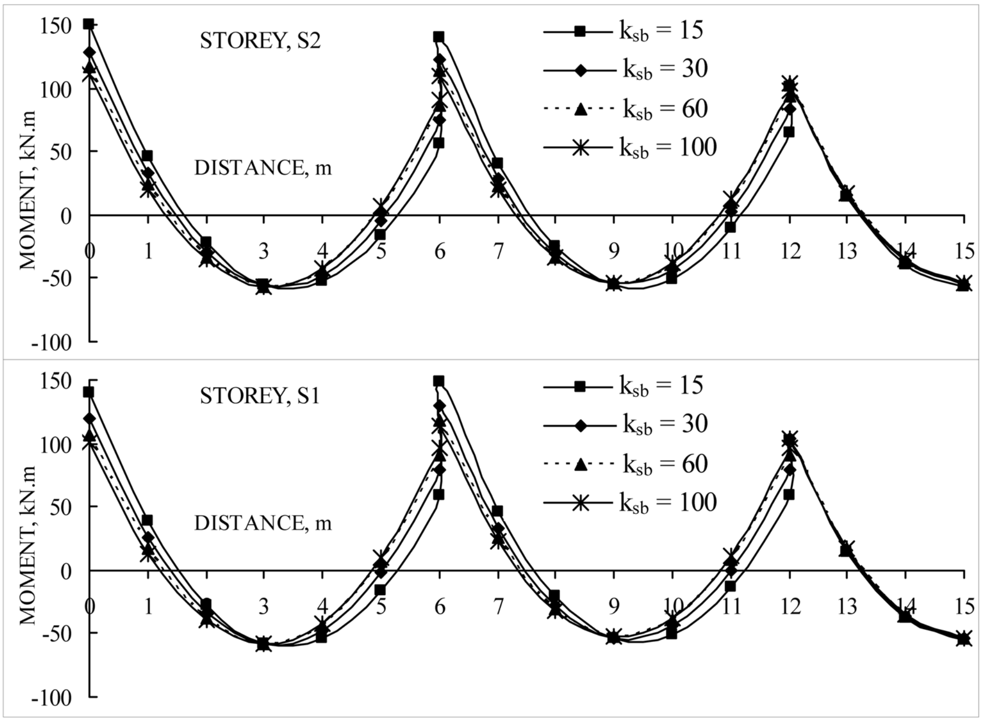

Fig. 10 Variation of bending moment along B1-B4, $k_{rs} = 0.001$

B1 and A2 decreases with the increase in k_{sb} whereas in the remaining columns the axial force increases with k_{sb} values and this trend is almost identical to that of the variation of axial force with k_{rs} value of the mat. However, the variation in the axial force with k_{sb} is negligibly small for the k_{sb} values higher than 60 irrespective of k_{rs} values which is almost similar to the response seen in the case of the settlement of the mat with k_{sb} values.

7.4 Variation of bending moments in the beams

A typical variation of the bending moment on the beams of the different floors for the beam section B1-B4 is presented in Fig. 10 for $k_{rs} = 0.001$. The influence of k_{sb} is also examined in this figure. In the beams of all the floors, the support moment is higher than the span moment irrespective of the k_{sb} values. For the different k_{sb} values of the frame the support moment is higher for lower k_{sb} values in the beams of all the floor levels. For example, the support moment at B1(column B1) of the first floor beam (*S*2) decreases by 27% for an increase in value of k_{sb} from 15 to 100. But the magnitude of the span moment at the centre of the beam is almost constant for all the values of k_{sb}. In Fig. 11 the variation of the moment at the support A1 with k_{sb} for the beam A1-A4 is presented. The figure shows the moment variation in the beams of all the five floors and also for the different k_{rs} values. For a given k_{rs}, the moment at the supports decreases with the increase in the k_{sb}. The reduction in the moment is gradual or almost nil for the values more than 60 in the beams of all the floors. For the change in the value of k_{sb} from 15 to 100 the reduction in the moment is 30% and 25% in the beams *S*2 and *S*5 respectively. Among the beams the support

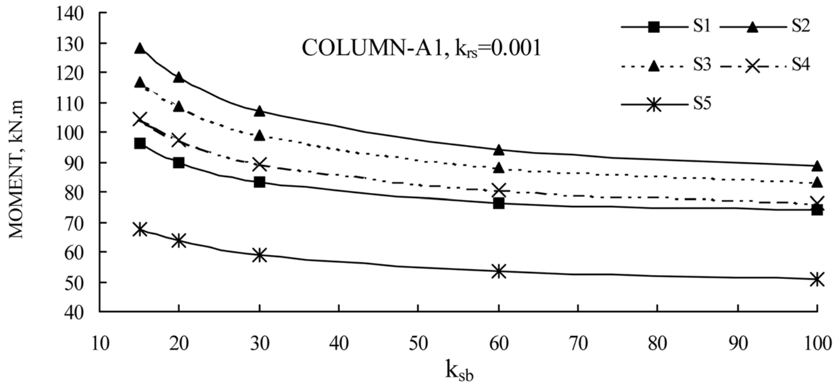

Fig. 11 Variation of moment at the support A1 of beam A1-A4

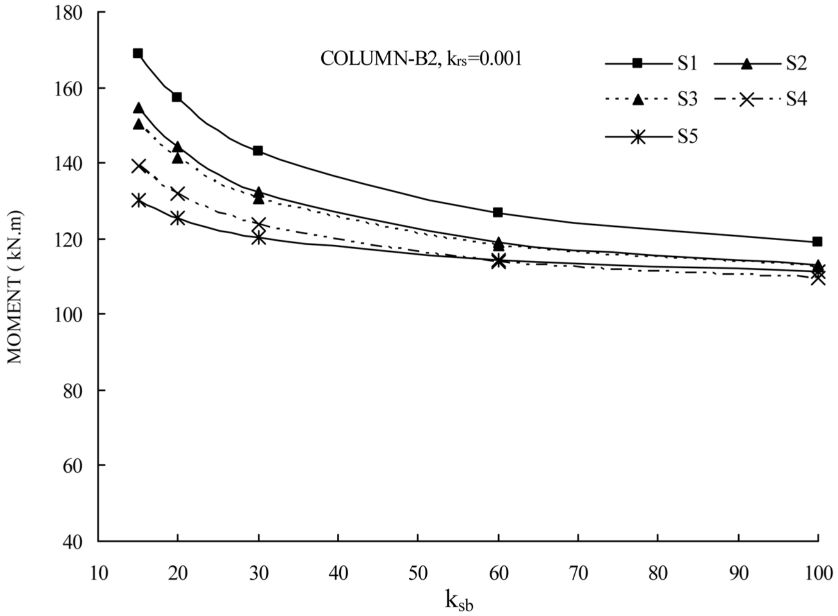

Fig. 12 Variation of moment at the support B2 of beam B1-B4

moment is maximum in the first floor beam ($S2$), minimum in the fourth floor beam ($S5$) and the moment of beams in other floors lies between these two values. Further, the difference in the support moments of beam $S1$ and $S3$ is the least when compared to other beams. The support moment is reduced marginally in all the beams with the increase in k_{rs} value. The difference in the bending moment between the beams also reduces and particularly between the beams $S1$ and $S3$ it is almost negligible when $k_{rs} = 0.01$. Fig. 12 shows the relation between the support moment and k_{sb} for the column beam junctions at B2.

The maximum variation in bending moment is seen in the $S1$ level. At the junctions, the support moment decreases with increase of k_{sb}. The modulus of the soil affects the differential settlement and hence the moment.

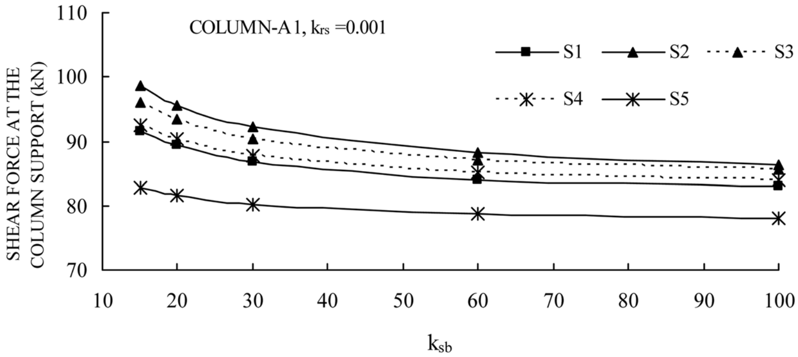

Fig. 13 Variation of shear force at the support A1 of beam A1-A4

7.5 Shear force in the beams

Fig. 13 shows the shear force at the support A1 of beams spanning between A1-A4 at different floor levels for various k_{sb} values. In the interaction analysis, the shear force in the beam is reduced for the increase in k_{sb}. For the variation of k_{sb} from 15 to 100 the maximum reduction in the shear force is in the first floor beam *S*2 which is around 13% and the minimum shear force is in the beam *S*5. The effects of k_{rs} on the shear force are almost identical to those of its effects on the support bending moment.

8. Conclusions

Based on the interaction and the non-interaction analyses of the soil-mat-space frame system, the following important conclusions are drawn.

By frame-mat-soil interaction the anticipated behaivour of a structure can be predicted even more reliably which significantly increases the safety and stability of the building.

The interaction analysis showed less total and differential settlements than the non-interaction analysis. Between the two parameters, k_{rs} and k_{sb}, k_{sb} has a significant influence on both the settlements indicating that the modulus of the soil plays major role in the performance of the mat.

The column moment at different floor levels decreases with the increase in k_{sb} and remains almost constant for different k_{rs} values. However, the increase in k_{rs} value reduces the column moments, particularly in the edge column.

The axial forces in the peripheral columns increase and to that extent the inner column axial loads are reduced. For a given k_{sb}, I_f of the column A1 is greater than that of B2 and is also more than unity irrespective of the k_{rs} value. The I_f factors are very close to unity for the higher k_{rs} and k_{sb} values which is a clear indication for the marginal interaction between the frame and the foundation.

In the beam, more variation occurs in the support moments than in the span moments. The centre of the span moment is shifted away from the centre and magnitude is also increased for the low k_{rs} values.

The above conclusion drawn on from this study are valid for the 3 bay × 5 bay structure with *L*/*B* ratio of 1.67 and *H*/*B* ratio of 0.97.

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