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# Effect of Geometrical Parameters on Nonlinear Soil-Structure Interaction Behavior of Plane Frame-Soil System

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# EFFECT OF GEOMETRICAL PARAMETERS ON NONLINEAR SOIL-STRUCTURE INTERACTION BEHAVIOR OF PLANE FRAME-SOIL SYSTEM

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ABSTRACT

The analysis of soil-structure interaction problem is affected by various structural parameters and behavior of the soil mass. The nonlinear soil behavior plays a vital role in the redistribution of the forces in superstructure. Consequently, the forces in the frame members significantly get altered due to differential settlement of the soil mass. The study of interaction behavior due to these parameters requires the use of finite element method. The physical modeling of the interaction system is achieved by use of variety of elements. The unbounded domain of the soil mass is discretized with coupled finite-infinite elements and proper location of truncation boundary is established.

The structural parameters like relative stiffness of columns and beams, type of connections between beams and columns, bay width, storey height, number of storeys, number of bays, type of soils, loading conditions and many other factors have significant influence on interaction behaviour of building frame-soil system. The present study investigates the effect of change of bays and storeys on the linear and nonlinear interaction behaviour of plane frame-soil system and the forces in the frame members, vertical settlements and contact pressures below foundation beam have been evaluated. The constitutive law of nonlinear behaviour of the soil mass is modeled using hyperbolic model. The effect of these parameters on differential settlement of soil mass is also discussed.

## INTRODUCTION

In the conventional method of analysis, a structure is analyzed assuming fixity at the base of the foundation and ignoring the effect of supporting soil media. The structure analyzed in this way does not provide the realistic behaviour. In reality, the structure is generally supported on soil mass and there exists, the interaction between structure, foundation and soil mass. The flexibility of the foundation, the compressibility of the soil mass and other factors cause redistribution of bending moments and shear forces in the superstructure due to differential settlement of soil. Several investigators studied the influence of the phenomenon of soil-structure interaction in framed structures and investigated that the forces change significantly due to interaction effect.

Lee and Brown[1] presented an interaction analysis of a seven-storey, three-bay framed structure in which the soil mass was treated as a Wrinkler's or elastic half space medium. King and Chandrasekaran[2] provided the solution for a rafted plane frame, in which the frame and the combined footing were discretized into beam bending elements and the soil mass into plane rectangular elements.

Brown[3] examined the effect of 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. Jain et al.[4] proposed an economical iterative procedure for building frames and found significant reduction in differential settlements and consequent additional moments. Desai and Sargand[5] developed hybrid finite element procedure for nonlinear elastic and elasto-plastic analysis of soil-structure interaction including simulation of construction sequences. Aljanabi et al.[6] studied the interaction of plane frames with an elastic foundation, of Wrinkler's type, having normal and shear modulli of subgrade reaction. Viladkar et al.[7] employed a coupled finite-infinite element formulation to highlight the advantage of using the infinite elements to study the interaction behaviour of the framed structures. Noorzaei et al.[8] considered the elasto-plastic behaviour of soil mass and carried out the interaction analysis of plane frame-combined footing-soil system to study the interaction behaviour.

Dasgupta et al.[10] studied the effect of three influencing parameters on the column axial force and column moment of three-dimensional building frames. These parameters are namely, relative flexural stiffness of columns with respect to beams, number of bays and number of storeys. Stavridis[11] presented the simplified interaction analysis of layered soil-structure interaction. The stratified soil was represented by linear elastic half space model having specific geometrical and elastic properties for its layer.

Pong and Tsai[12] investigated effect of soil-structure interaction on damped structures. The study presents a rigorous time domain procedure to address the interaction effects of structures equipped with fluid viscous dampers and foundations with an unbounded medium. Quantitative results show that, during earthquakes, there are significant differences between a system with or without radiation damping.

Roy and Dutta[13] investigated the effect of differential settlements on the forces in the frame members. He studied the effect of the same on design force quantities of simple three-dimensional building frame with isolated footings. The nonlinear settlement verses stress relationship arising in case of building frames with isolated footings on clayey soils considering two alternative iterative approaches.

Doo and Chung[14] devised time domain earthquake response analysis method for two-dimensional soil- structure interaction analysis of massive structures under seismic excitations. The finite element formulation incorporates infinite elements for the far field soil region. The equivalent earthquake input forces are calculated based on the free field responses along the interface between the near and far field soil regions utilizing the fixed exterior boundary method in the frequency domain.

Sommer and Bachmann[15] investigated seismic behaviour of asymmetric RC wall buildings, which were asymmetric in plan but regular in elevation and stiffened with ductile RC structural walls. A realistic modeling of the nonlinear ductile behaviour of the RC wall is considered in combination with the characteristics of the dynamic torsional response of asymmetric buildings. The design criterion such as the determination of the system ductility taking into account the location and ductility demand of the RC wall, the storey drift demand at the softer (most displaced edge of the building under the design earthquake), the allowable ductility (ultimate limit state and the allowable storey drift (performance goals) are investigated.

The present study investigates the effect of increase in bays and storeys on the interaction behaviour of plane frame-soil system. The effect of these structural parameters on the differential settlements of the soil mass is also investigated.

## MODELLING OF PLANE FRAME - SOIL SYSTEM

### Super-structure and Foundation Beam

The finite element modelling of plane frame-foundation-soil interaction system requires use of various isoparametric finite and infinite elements. The individual components of the interaction system are discretized with appropriate elements. The floor beams, columns and the foundation beam are discretized using three noded beam elements with three degrees of freedom per node (u, v, φ). The present beam element is modified form of the beam-bending element (Hinton and Owen[16]), which includes one additional degree of freedom to take care of axial deformation in the frame members.

### Modeling of Soil Media

The modeling of unbounded domain of soil mass using coupled finite-infinite elements has proved computationally economical (Viladkar et al.[7]). However, the location of truncation boundary between finite and infinite elements is the most important aspect, especially in case of plain strain type of problem. The infinite elements with different types of decay pattern are able to model the far field behaviour quite accurately.

The unbounded domain of the soil mass is represented by conventional eight noded plane strain finite elements with two degrees of freedom per node (u, v) coupled with six noded infinite elements with 1/r type decay (Viladkar et al.[7, 17]) having two degrees of freedom per node (u, v). The distance 'r' is measured from a reference pole to a general point within an element. This reference pole must be exterior to the infinite element. In any coupled finite-infinite element formulation, the most important aspect is the location of truncation boundary (the common junction between the finite and infinite element layers), which is found by trial and error.. A three noded doubly infinite element with 1/r type decay pattern is used as corner element in the finite-infinite element mesh. The shape functions of the finite and infinite elements are available in the literature (Hora[18]).

## NONLINEAR ELASTIC HYPERBOLIC SOIL MODEL

In this study, material non-linearity of the soil mass is considered. The non-linearity of soil mass has been represented by using the Duncan and Chang [19], widely adopted for the hyperbolic model proposed by Kondner and Zelasko[20]. The tangent modulus ($E_T$), of the soil mass at any stress level is represented as:

$$E_T = \left[ 1 - \frac{R_f\,(1-\sin\phi)(\sigma_1-\sigma_3)}{2(c\cos\phi + \sigma_3\sin\phi)} \right]^2 E_i \tag{3.1}$$

where,

$$E_i = K\,P_a \left( \frac{\sigma_3}{P_a} \right)^n \tag{3.2}$$

Various parameters representing the non-linearity of soil mass are:

$E_i$ = initial tangent modulus

c = cohesion

$P_a$ = atmospheric pressure

$\sigma_1, \sigma_3$ = major and the minor principal stresses

$\phi$ = angle of internal friction

K = modulus number

n = exponent determining the variation of initial tangent modulus $E_i$, with confining pressure $\sigma_3$.

$$R_f = \text{failure ratio} = \frac{(\sigma_1 - \sigma_3)_f}{(\sigma_1 - \sigma_3)_{ult}}$$

Where,

$(\sigma_1 - \sigma_3)_f$ = compressive strength

$(\sigma_1 - \sigma_3)_{ult}$ = asymptotic value of deviatoric stress

The soil parameters (hyperbolic constants) such as K, n and $R_f$ for nonlinear analysis define the constitutive law. The numerical values of these parameters are provided in Fig. 1. These parameters have been taken from the literature (Noorzaei[8]). The Poisson's ratio has been kept constant in the analysis. A load, at which yielding just starts in a soil element is determined. Beyond this load value, the results obtained would not be reliable because the soil mass exhibits elasto-plastic behaviour. The model has been incorporated into the computer code developed for the nonlinear interaction analyses

## INTERACTION ANALYSES OF PLANE FRAME-SOIL SYSTEM

### Problems under Investigation

Mainly, there are two types of materials involved in the present problem: reinforced concrete and the soil. The stiffness of the reinforced concrete is much higher in comparison to that of soil. Therefore, in this study, material non-linearity of the soil mass is considered while the reinforced concrete is assumed to follow the linear stress-strain relationship.

The computer programs in FORTRAN 90 have been developed for the linear and nonlinear interaction analyses. The different types of analyses are carried out to study the interaction behaviour of the plane frame-soil soil system due to increase in the bays and storeys.

The non-interaction analysis (NIA) is carried out assuming the bases of the columns as fixed and the frame to behave in linear elastic manner. The linear interaction analysis (LIA) is carried out assuming that the plane frame, foundation beam and the soil mass to behave in linear elastic manner. The nonlinear elastic interaction analysis (NLIA) considers the soil mass to behave in nonlinear manner. The nonlinear elastic constitutive relationship (Duncan and Chang[19], Kondner and Zelasko[20])of the soil mass has been taken into account to study its influence on redistribution of forces in the structural members, the settlement pattern of the foundation and the contact pressure distribution below the foundation have been evaluated due to increase in bays and storeys. The effect of these parameters on the differential settlement in the soil mass is also discussed.

The interaction analyses are carried out by varying the number of bays from 2 to 4 and number of storeys from 1 to 5. The bay width and storey height are kept as 4.0 m and 3.0 meter respectively. The floor beams and the foundation beam carry uniformly distributed load of 25kN/m, which includes dead load and live load. Since the system is symmetrical with respect to geometry and loading, only half of the structural-foundation-soil system is considered and meshed for carrying out the interaction analysis.. Fig. 1 shows the discretization of the interaction system along with the geometrical details. The mixed technique (incremental-iterative) nonlinear solution algorithm is adopted for nonlinear analysis to achieve faster rate of convergence. In this analysis, the load is limited to a value, which causes local failure in some of the finite elements because the result will no longer be reliable in terms of the behaviour of the soil at and after failure, hence, a load factor of unity (which corresponds to 25 kN/m) is taken into consideration. The total vertical load of intensity 25 kN/m acting on the interaction system is applied in seven load increments (30, 15, 15, 10, 10, 10, 10% of 25 kN/m). The convergence took place after 5 to 9 iterations for each load increment. The load increments are chosen depending upon the nature of the stress-strain curve, material properties etc. of the soil mass and this requires trial and error. Initially, the behaviour of the interaction system is linear elastic up to certain load value corresponding to the first load increment of 30% of the total load. Thereafter, the curve becomes nonlinear and therefore the remaining load increments are smaller as compared to initial elastic portion of the curve. The norm of residual force for convergence is adopted for nonlinear interaction analysis. A tolerance limit of 1% is selected for residual forces.

## EFFECT OF BAYS AND STOREYS ON INTERACTION BEHAVIOR

### Effect of bays on Settlements below Foundation Beam

Table 1 shows that there is significant increase in the vertical settlements due to increase in number of bays from 2 to 4. The increase in number of bays causes significant increase of nearly 75% in the settlements due to LIA

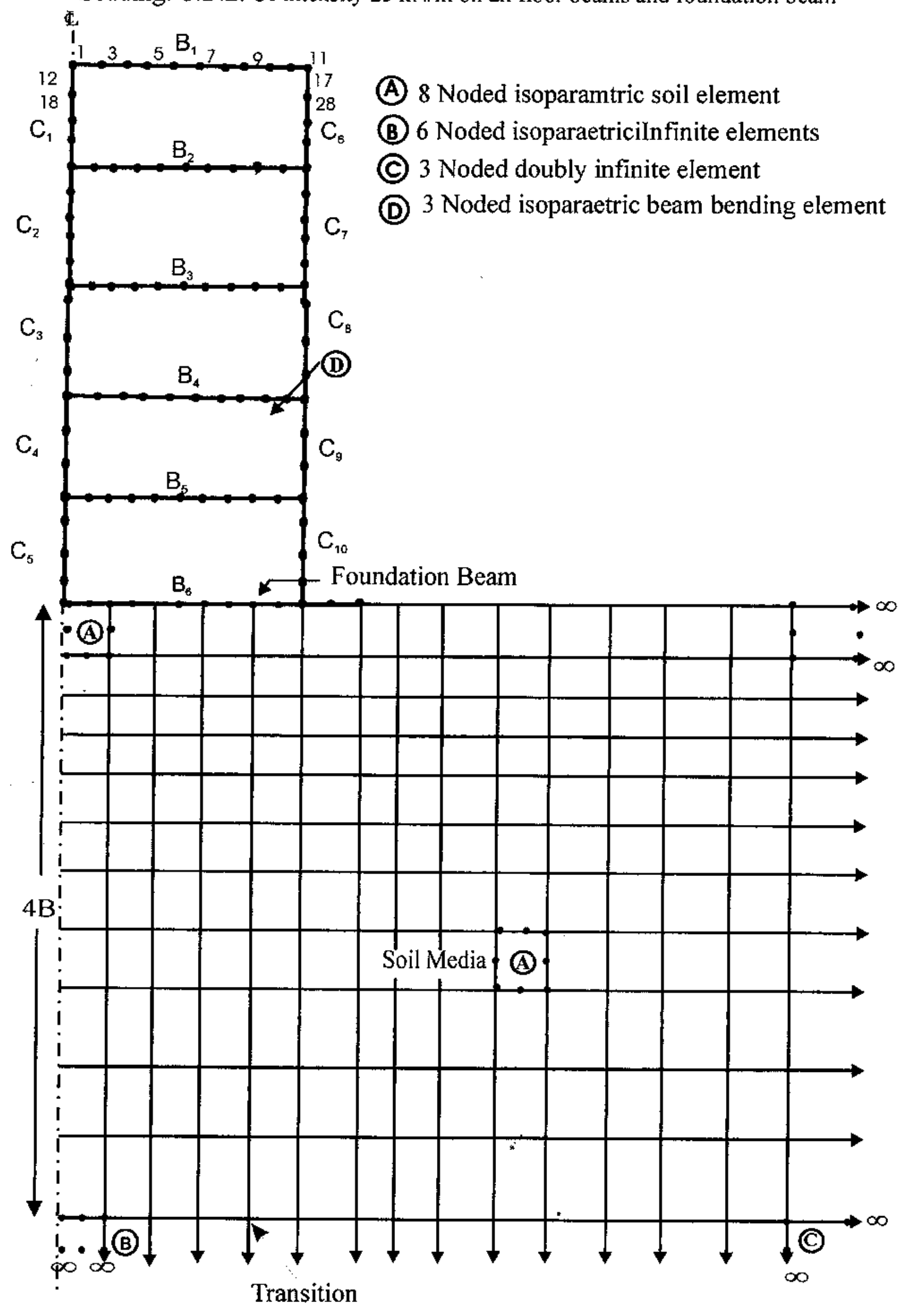
**Geometrial & material properties**

All Columns 0.4 m x 0.4 m
All beams 0.25 x 0.40 m
Foundation beam 0.35 m to 0.65 m
Storey height 3.0 m
Bay width 4..0 m
E(structure)= 2.1 X $10^7$ kN/$m^2$
Poisson's Ratio(structure) = 0.2

**Nonlinear soil properties**

Modulus number (K) = 110.0
Initial tangent modulus of soil (E) =7500.0 kN/$m^2$
Poisson's Ratio (1/m) = 0.35
Cohesion (c) =25.0 kN/$m^2$
Angle of internal friction= $30^0$
Exponent (n) = 0.9
Failure ratio ($R_f$) =0.87

Loading: U.D.L. Of intensity 25 kN/m on all floor beams and foundation beam




All nodes on the line of symmetry are restrained in x-direction

Fig.1 Finite-infinite element discretization of plane frame-soil system

Table 1. Variation of vertical settlements (mm) with number of storeys below central column of plane frame-soil system

| SN | Vertical Settlements below Central Column - Load Factor 1.0 | | | | | | | | % Diff. (2 & 6) | % Diff. (7 & 9) | % Diff. (2 & 7) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2B1S 2 | 2B2S 3 | 2B3S 4 | 2B4S 5 | 2B5S 6 | 4B1S 7 | 4B3S 8 | 4B5S 9 | 10 | 11 | 12 |
| Linear Interaction Analysis – LIA | | | | | | | | | | | |
| 1 | 8.16 | 11.68 | 15.80 | 21.17 | 25.30 | 14.57 | 27.75 | 41.20 | +204.82 | +182.19 | +75.90 |
| Nonlinear Elastic Interaction Analysis – NLIA | | | | | | | | | | | |
| 2 | 32.74 | 35.71 | 39.27 | 45.81 | 49.27 | 49.95 | 62.24 | 74.16 | +50.76 | +55.67 | +45.56 |
| Ratio | 4.01 | 3.05 | 2.49 | 2.16 | 1.95 | 3.43 | 2.24 | 1.80 | - | - | - |

2B5S – Two-bay five-storey plane frame-soil system

<u>Effect of storeys on Vertical Settlements below Foundation Beam</u>

Table 1 shows that the increase in number of storeys of two-bay plane frame-soil system causes significant increase of nearly 205% in the vertical settlements below central column due to LIA. NLIA provides significant increase of nearly 51%. Table 2 shows that the increase in storeys of two-bay plane frame-soil system causes significant increase of nearly 220% in the vertical settlements below outer column due to LIA whereas; NLIA provides significant increase of nearly 51%. The vertical settlements for the two-bay single-storey plane frame-soil system due to NLIA are nearly 4 times to those obtained due to LIA. These settlements become almost 2 times when storeys are increased to 5. Fig. 2 and Fig. 3 show the non-dimensional plot of the settlements below the entire length of the foundation beam

length of the foundation beam due to LIA and NLIA respectively.

Table 1 shows that the increase in storeys of four–bay plane frame-soil system causes significant increase of nearly 182% in the settlement below central column due to LIA and of nearly 56% due to NLIA. Table 2 shows that the increase in storeys of four-bay plane frame-soil system causes significant increase of nearly 200% in the vertical settlements below outer column due to LIA. NLIA provides significant increase of nearly 50%. The settlements obtained in case of two-bay plane frame-soil system are significantly more compared to those obtained in case of four-bay plane frame-soil system. Fig. 4 and Fig. 5 show the variation of settlements for four-bay plane frame-soil system due to LIA and NLIA respectively.

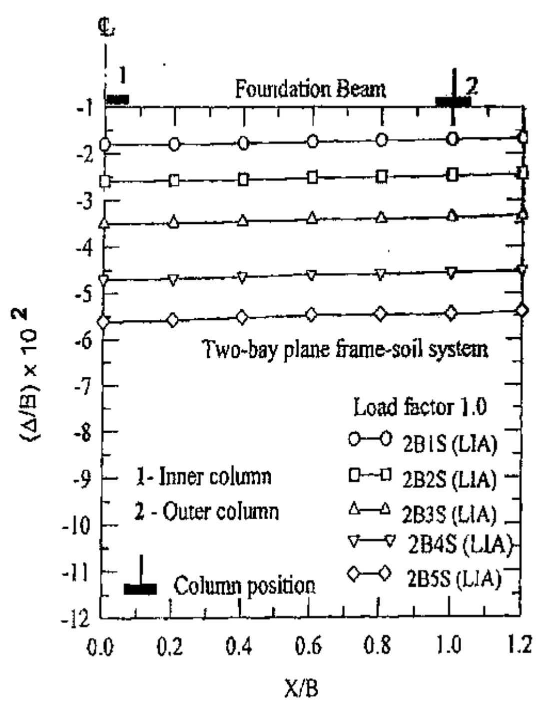



Fig 2. Variation of vertical settlements with for linear analysis

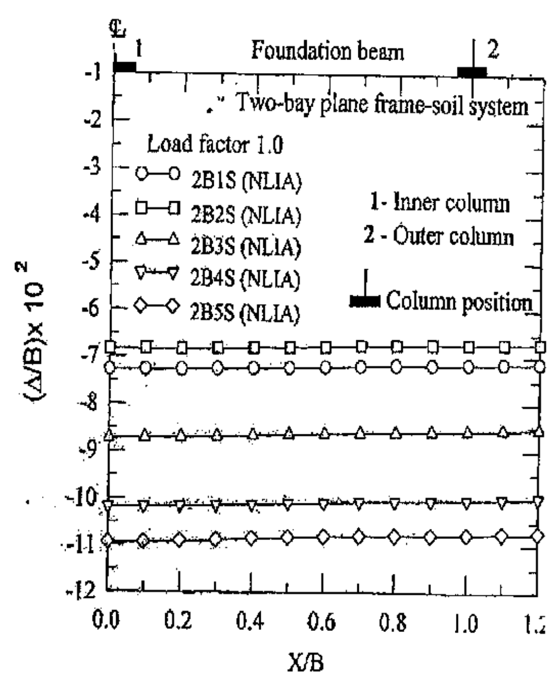



Fig 3. Variation of vertical settlements with storeys for non linear analysis

Table 2 Variation of vertical settlements (mm) with number of storeys below outer column of plane frame-soil systems

| SN | Vertical Settlements below outer Column - Load Factor 1.0 | | | | | | | | % Diff. (2 & 6) | % Diff. (7 & 9) | % Diff. (2 & 7) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2B1S 2 | 2B2S 3 | 2B3S 4 | 2B4S 5 | 2B5S 6 | 4B1S 7 | 4B3S 8 | 4B5S 9 | 10 | 11 | 12 |
| Linear Interaction Analysis – LIA | | | | | | | | | | | |
| 1 | 7.67 | 11.10 | 15.17 | 20.51 | 24.55 | 12.87 | 25.51 | 38.69 | +220.08 | +200.62 | +67.79 |
| Nonlinear Elastic Interaction Analysis – NLIA | | | | | | | | | | | |
| 2 | 32.15 | 35.05 | 38.58 | 45.11 | 48.47 | 47.56 | 59.62 | 71.42 | +50.76 | +50.17 | +47.93 |
| Ratio | 4.19 | 3.15 | 2.54 | 2.20 | 1.97 | 3.69 | 2.33 | 1.85 | - | - | - |

2B5S – Two-bay five-storey plane frame-soil system

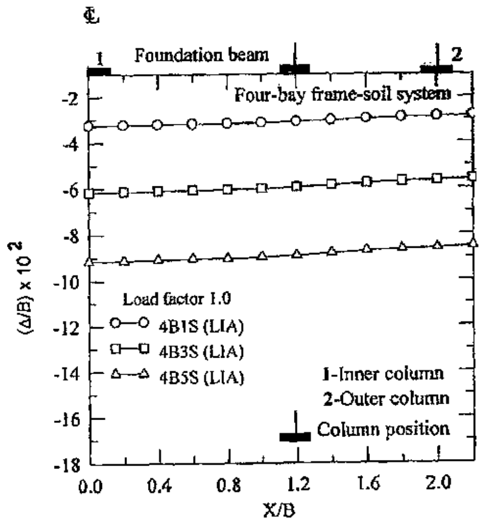



Fig 4. Variation of settlement with storeys for linear analysis

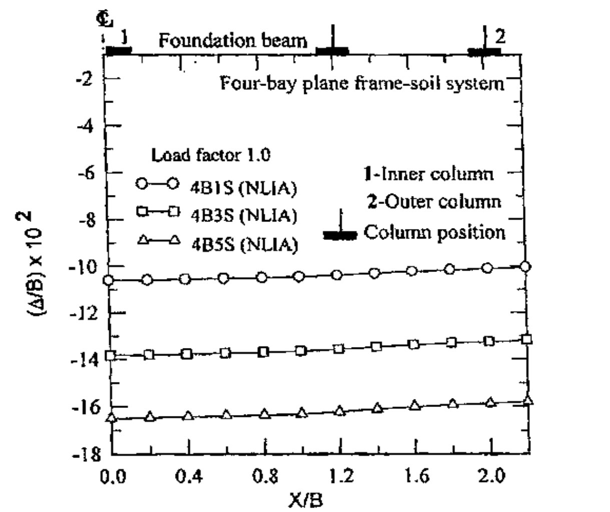



Fig 5. Variation of settlements with storeys (non linear analysis)

Effect of Bays on Contact Pressures below Foundation Beam

Fig. 6 shows the variation of contact pressure distribution below the foundation beam of the two-bay plane frame- soil system in the non-dimensional form in terms of load intensity 'q' and foundation width 'B'. It is found that the minimum pressure exists at the center of the foundation beam whereas the maximum pressure is found at the edge. This is because the central column is relieved of the moments and only the end columns transfer the moments to the foundation.

Effect of Storeys on Contact Pressures below Foundation Beam

Table 3 shows the absolute values of contact pressures at the center and at the edge of the foundation beam of two-bay plane frame-soil system due to both the interaction analyses.

It is observed that the increase in number of storeys causes significant increase in the contact pressures below the entire length of the foundation beam. The significant increase of nearly 181% is found at the center and nearly 188% at the edge of the foundation beam of two-bay plane frame-soil system due to LIA. NLIA gives the significant increase of nearly 189% at the center and nearly 166% at the edge

Table 3. Variation of contact pressures (kN/m$^2$) with number of storeys at center of foundation beam

| S | Contact Pressure at Center of Foundation Beam | | | | | | % Difference (2 & 4) | % Difference (5 & 7) | % Difference (4 & 7) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 2B1S 2 | 2B3S 3 | 2B5S 4 | 4B1S 5 | 4B3S 6 | 4B5S 7 | 8 | 9 | 10 |
| Linear Interaction Analysis – LIA | | | | | | | | | |
| 1 | 37.24 | 67.53 | 104.66 | 42.45 | 77.31 | 109.88 | +181.00 | +158.00 | +4.98 |
| Nonlinear Elastic Interaction Analysis-NLIA | | | | | | | | | |
| 2 | 31.68 | 75.50 | 91.58 | 31.34 | 78.01 | 91.81 | +189.05 | +192.42 | +0.25 |

Load Factor 1.0

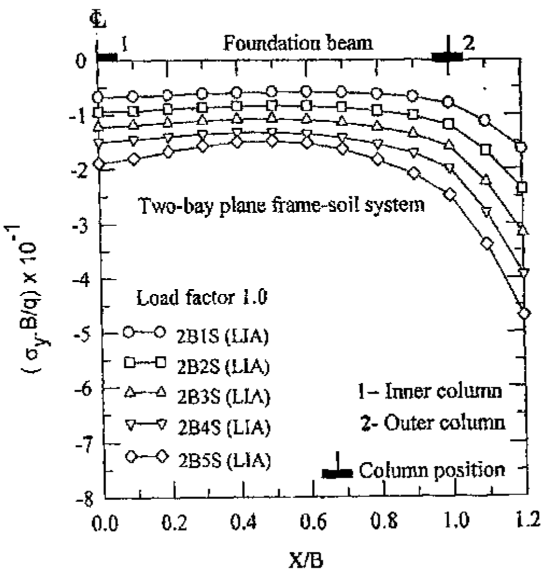



Fig 6. Variation of contact pressures for linear analysis

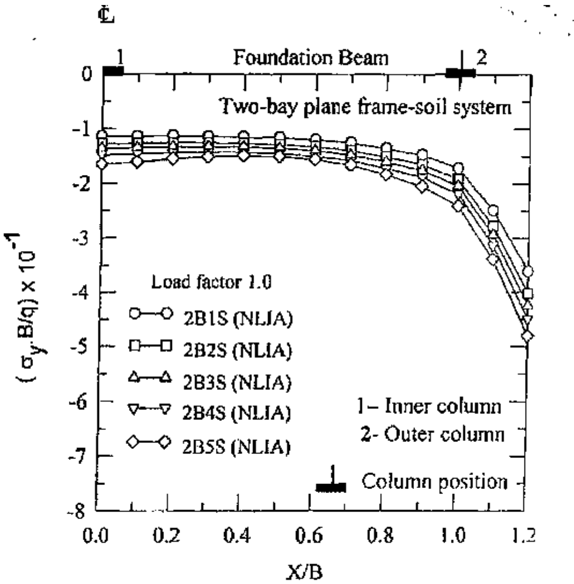



Fig 7. Variation of contact pressures for non linear analysis

Fig. 6 shows the variation of contact pressures distribution below the foundation beam of the two-bay plane frame-soil system due to LIA. Tables 3 and 4 show that a significant increase of nearly 160% in the contact pressure at the center and of nearly 230% at the edge is found in the foundation beam of four-bay plane frame-soil system due to LIA. The significant increase of nearly 192% is found at the center and of nearly 195% at the edge due to NLIA. Fig. 8 and 9 depict the contact pressure distribution for four-bay plane frame-soil system due to LIA and NLIA respectively

.

Table 4. Variation of contact pressures (kN/m$^2$) with number of storeys at edge of foundation beam

| SN | Contact Pressure at Edge of Foundation Beam | | | | | | % Diff. (2 & 4) 8 | % Diff. (5 & 7) 9 | % Diff. (4 & 7) 10 |
|---|---|---|---|---|---|---|---|---|---|
| | 2B1S 2 | 2B3S 3 | 2B5S 4 | 4B1S 5 | 4B3S 6 | 4B5S 7 | | | |
| Linear Interaction Analysis – LIA | | | | | | | | | |
| 1 | 90.58 | 176.30 | 261.14 | 106.59 | 229.56 | 350.95 | +188.29 | +229.25 | +34.39 |
| Nonlinear Elastic Interaction Analysis – NLIA | | | | | | | | | |
| 2 | 100.36 | 236.04 | 267.16 | 115.47 | 290.99 | 341.16 | +166.20 | +195.45 | +32.04 |

Load factor 1.0

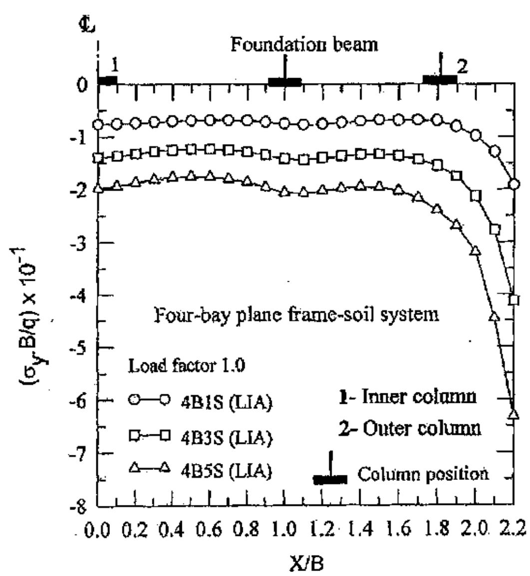



Fig 8. Variation of contact pressures with storeys for linear analysis

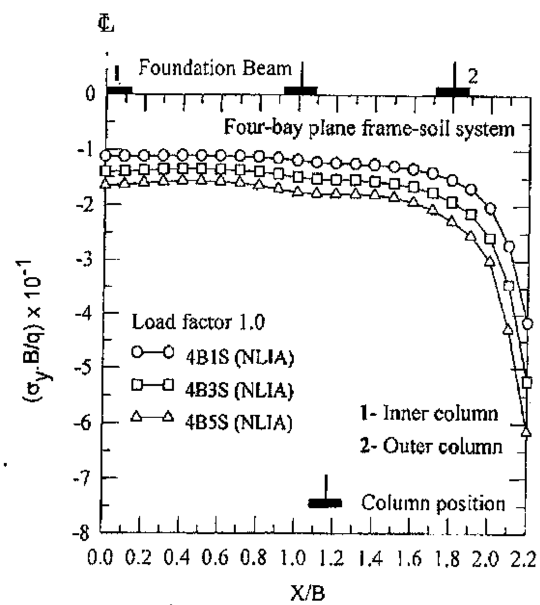



Fig 9. Variation of contact pressures with storeys for nonlinear analysis

<u>Effect of Bays on Axial Force in Outer Column of First Storey</u>

The variation in the axial force and bending moment of the outer column of first storey is investigated due to increase in bays and storeys. The investigation is focused on the outer column because this column is subjected to maximum axial force and the interaction effect will be significant due to differential settlements of the soil mass.

Table 5 shows that the increase in number of bays causes significant increase of nearly 38% in the axial force of outer column of the first storey due to LIA. The axial forces due to interaction effect in four-bay plane frame-soil system are significantly more than those in case of two-bay plane frame-soil system. This clearly suggests that the frames with four-bays always have stronger effect of soil-structure interaction than the two-bay frames due to stronger framing action. NLIA provides marginally higher variation of nearly 42%.

<u>Effect of Storeys on Axial Force in the Outer Column of the First Storey</u>

Table 5 shows the values of axial force in the outer column of the first storey of two-bay plane frame-soil system for both interaction analyses. It is observed that the increase in number of storeys from 1 to 5 causes significant increase of nearly 455% in the axial force of the outer column of the first storey due to LIA. NLIA provides significant increase of nearly 431%. Fig. 10 depicts the variation of axial force in the outer column of the first storey of two-bay plane frame with increase in storeys due to LIA and NLIA

Table 5 Variation of axial force (kN) with number of storeys in outer column of first storey of plane frame-soil system

| Problem Type<br>1 | 2B5S<br>2 | 2B4S<br>3 | 2B3S<br>4 | 2B2S<br>5 | 2B1S<br>6 | % Diff. (2 & 6)<br>7 |
|---|---|---|---|---|---|---|
| Linear Interaction Analysis – LIA | | | | | | |
| NIA | 279.34 | 220.94 | 63.81 | 107.86 | 52.17 | +435.44 |
| FS | 376.47 | 301.46 | 222.47 | 144.41 | 67.84 | +454.93 |
| % Difference (NIA Vs FS) | +34.77 | +36.44 | +35.80 | +33.96 | +30.03 | - |
| Nonlinear Elastic Interaction Analysis – NLIA | | | | | | |
| FS | 380.56 | 307.27 | 228.89 | 150.05 | 71.64 | +431.21 |
| % Difference (NIA Vs FS) | +36.24 | +39.07 | +39.72 | +39.11 | +39.11 | - |

FS – Plane frame-soil system 2B5S -means two-bay five-storey plane frame-soil system LF – Load factor 1.0

Table 6 shows the values of the axial force in the outer column of the first storey of four-bay plane frame-soil system due to both the interaction analysis. The significant increase of nearly 526% is found due to LIA. NLIA gives significant increase of nearly 466%. It is observed that the increase in the axial force in the outer column of the first storey of four-bay plane frame-soil system is significantly more compared to the axial force in the outer column of two-bay plane frame-soil system. Fig. 11 depicts the variation of axial force in the outer column of the first storey of four-bay plane frame with increase in storeys due to LIA and NLIA.

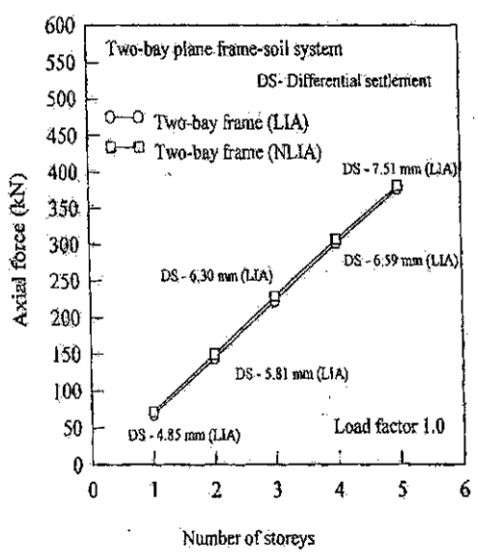



Fig.10 Variation of axial force in the outer column of first storey

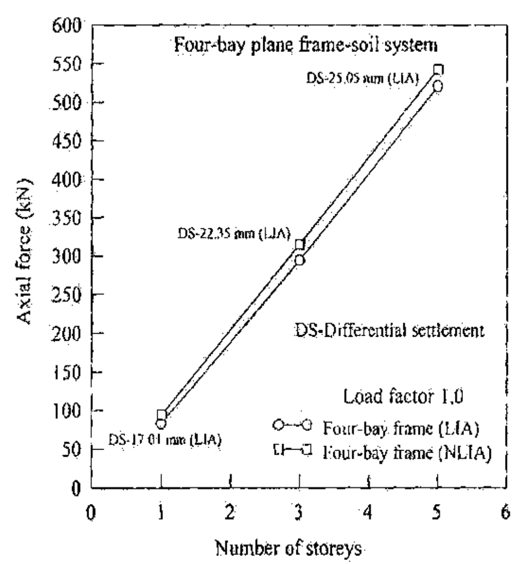



Fig.11. Variation of axial force in the outer column of first storey

Table 6. Variation of axial force (kN) with number of storeys in outer column of first storey of plane frame-soil system

| Problem Type<br>1 | Axial Force in Outer Column of First Storey | | | | | | % Diff.<br>5 & 7<br>8 | % Diff.<br>2 & 5<br>9 | % Diff.<br>4 & 7<br>10 |
|---|---|---|---|---|---|---|---|---|---|
| | 2B5S<br>2 | 2B3S<br>3 | 2B1S<br>4 | 4B5S<br>5 | 4B3S<br>6 | 4B1S<br>7 | | | |
| Linear Interaction Analysis – LIA | | | | | | | | | |
| NIA | 279.34 | 163.81 | 52.17 | 278.90 | 163.80 | 52.43 | * | * | * |
| FS | 376.47 | 222.47 | 67.84 | 520.02 | 293.75 | 83.04 | +526.0 | +38.13 | +22.40 |
| % Diff. (NIA Vs FS) | +34.77 | +35.80 | +30.03 | +86.45 | +79.33 | +58.38 | - | - | - |
| Nonlinear Elastic Interaction Analysis-NLIA | | | | | | | | | |
| FS | 380.56 | 228.89 | 71.64 | 542.02 | 314.49 | 93.83 | +465.6 | +42.42 | +30.97 |
| % Diff. (NIA Vs FS) | +36.24 | +39.72 | +39.11 | +94.34 | +91.99 | +78.96 | - | - | - |

*Negligible percentage difference 4B5S –means four-bay five-storey plane frame-soil system LF – Load factor 1.0

<u>Effect of Bays on Bending Moment in the Outer Column of First Storey</u>

Table 7 and Table 8 show that the increase in bays causes significant increase in the bending moment at roof level of the first storey outer column. It is observed that the increase in number of bays causes the significant variation of nearly 203 to 517% in the bending moment in the outer column of first storey due to LIA. NLIA gives significant variation of nearly 215 to 561%. The bending moment in the outer columns at the roof level of four-bay plane frame-soil system is significantly more compared to two-bay plane frame-soil system.

Table 7. Variation of B.M.'s (kN-m) with number of storeys at roof level in outer column of first storey

| Problem Type<br>1 | 2B5S<br>2 | 2B4S<br>3 | 2B3S<br>4 | 2B2S<br>5 | 2B1S<br>6 | % Diff. (2 & 6)<br>7 |
|---|---|---|---|---|---|---|
| Linear Interaction Analysis (LIA) | | | | | | |
| NIA | 16.02 | 15.86 | 16.13 | 13.48 | 29.72 | -46.09 |
| FS | 48.65 | 53.48 | 52.51 | 44.37 | 63.64 | -23.55 |
| % Diff. NIA & FS | +202.55 | +237.20 | +225.54 | +229.15 | +114.13 | - |
| Nonlinear Elastic Interaction Analysis (NLIA) | | | | | | |
| FS | 50.46 | 56.31 | 56.08 | 49.03 | 70.93 | -28.85 |
| % Diff. NIA & FS | +214.98 | +255.0 | +247.67 | +263.72 | +138.67 | - |

** Indicates very high difference in values. LF – Load factor 1.0

<u>Effect of Storeys on Bending Moment in the Outer Column of First Storey</u>

Table 7 shows the values of bending moment in the outer column at roof level of the first storey of the two-bay plane frame-soil system for LIA and NLIA. The increase in storeys causes significant variation of nearly 114 to 237% due to LIA. The minimum increase of nearly 114% is observed in the outer column of the first storey of the two-bay single storey plane frame-soil system whereas the maximum increase of nearly 237% is found in the outer column of the first storey of two-bay four-storey plane frame-soil system. A significant increase of nearly 138 to 264% is found due to NLIA. Fig. 12 shows the variation of bending moment at roof level in the outer column of the first storey of two-bay plane frame-soil system due to increase in number of storeys for LIA and NLIA.

Table 8. Variation of BM's (kN-m) in outer column offirst storey at roof level with number of storeys

| AnalysisType<br>1 | 4B5S<br>2 | 4B3S<br>3 | 4B1S<br>4 | % Diff.<br>5=(2 & 4) |
|---|---|---|---|---|
| Linear Interaction Analysis (LIA) | | | | |
| NIA | 16.35 | 16.33 | 29.90 | -45.31 |
| FS | 100.87 | 89.85 | 101.52 | * |
| % Diff. | +516.9 | +450.0 | +239.5 | - |
| Nonlinear Interaction Analysis (NLIA) | | | | |
| FS | 108.01 | 100.86 | 127.79 | -15.47 |
| % Diff. | +560.6 | +517.6 | +327.4 | - |

** Indicates very high difference in values. Load factor 1.0

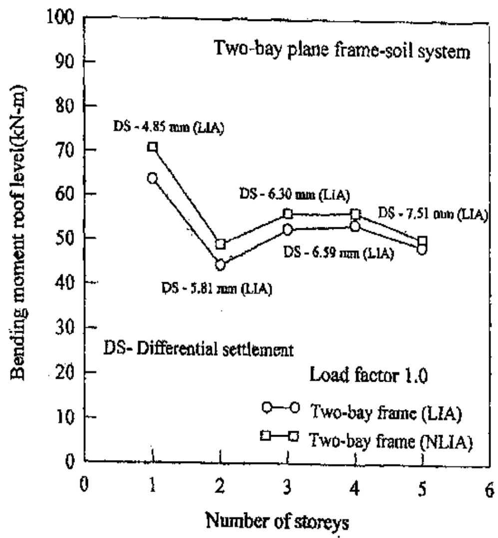
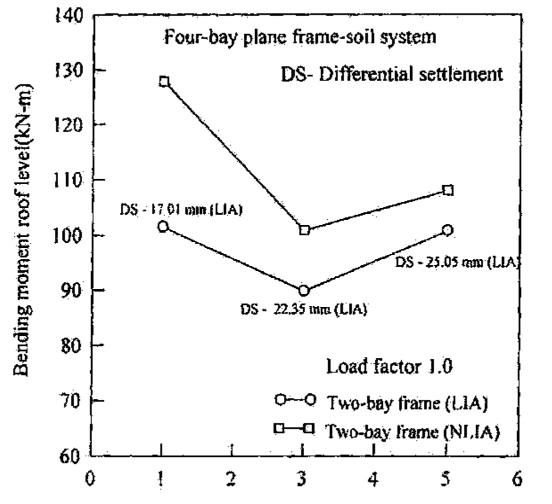



Fig 12. Variation of B.M. In the outer column of first storey with storeys




Number of storeys

Fig.13. Variation of B.M. in the outer column of first storey

Table 8 shows that the increase in storeys of four-bay plane frame-soil system causes significant variation of nearly 240 to 517% due to LIA. The maximum significant increase of nearly 517% is found in the outer column of the first storey of four-bay five-storey plane frame-soil system whereas the minimum significant increase of nearly 240% is found in the outer column of the first storey of four-bay single storey plane frame-soil system. NLIA suggests increase of nearly 327 to 561%. The bending moment in the outer columns due to increase in number of storeys is significantly more in case of four-bay plane frame-soil system in comparison to two-bay plane frame-soil system. Fig. 13 shows the variation of bending moment at roof level in the outer column of the first storey of four-bay plane frame-soil system due to increase in number of storeys for LIA and NLIA.

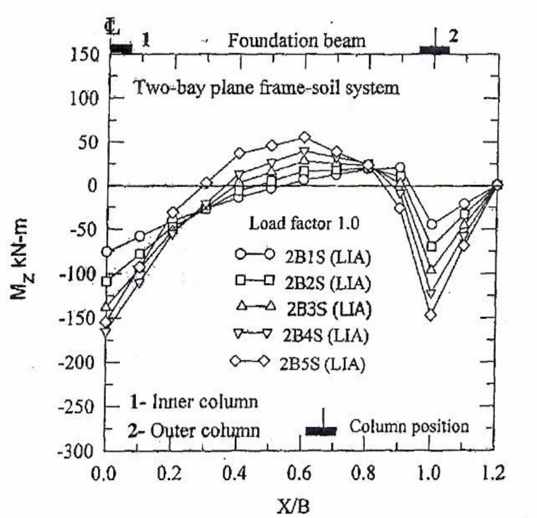



Fig 14. Variation of Bm's in foundation beam with storeys

Effect of Storeys on Bending Moments in Foundation Beam

Fig. 14 shows the distribution of bending moment along the length of foundation beam of two-bay plane frame-soil system due to LIA. The increase in storeys causes significant increase of nearly 170% in the maximum positive bending moment and of nearly 105% in the maximum negative bending moment due to LIA. The points of contrafluxtures are found to exist at the same location. NLIA also provides almost the same variation. Fig. 15 depicts the variation of bending moments in the foundation beam of two-bay plane frame-soil system due to 7$^{th}$ load increment (load factor 1.0) of NLIA.

Effect of Bays on Bending Moments in Foundation Beam

Fig 16.shows the variation of BM's in the foundation beam of four-bay plane frame-soil system due to LIA. It is observed that the maximum positive bending moment in the inner bay is less as compared to the outer bay. The significant increase in the maximum positive bending moment in the inner bay is nearly 120% whereas the increase of nearly 176% is found in the maximum negative bending moment. The outer bay undergoes significant increase of nearly 72% in the maximum bending moment and of nearly 131% in the maximum negative bending moment due to LIA. Both the interaction analyses provide almost the same results. The increase in maximum positive bending moment in the foundation beam of two-bay frame-soil system is significantly more compared to four-bay frame-soil system. The increase in maximum negative bending moment is more significant in case of four-bay frame-soil system compared to two-bay frame-soil.

Fig. 17 depicts the variation of bending moments in the foundation beam of four-bay plane frame-soil system due to 7$^{th}$ load increment of NLIA

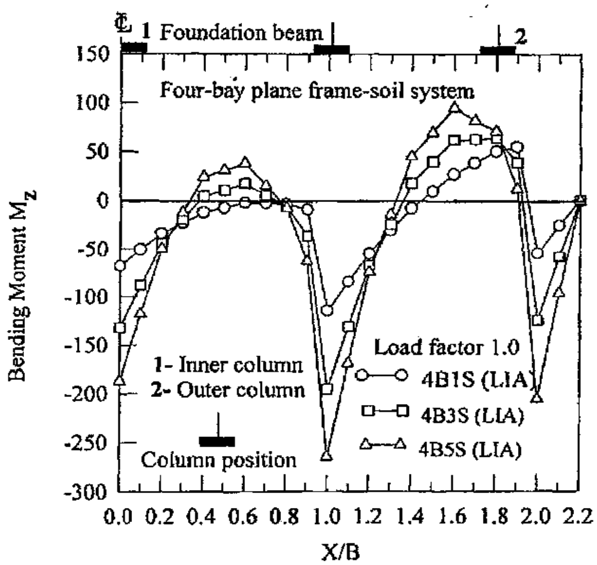



Fig 15. Variation of BM's in foundation beam with storeys

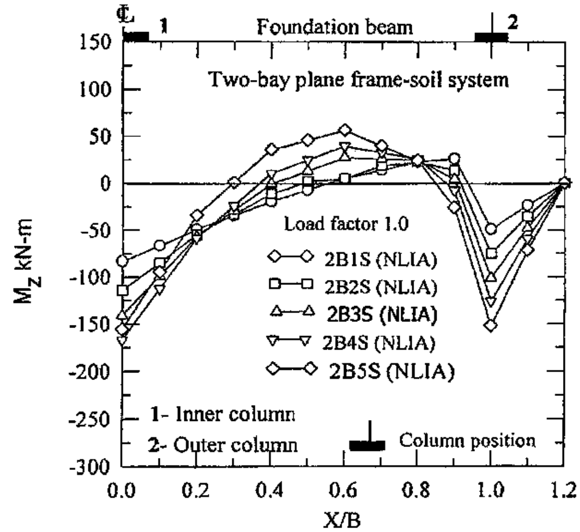



Fig 16. Variation of BM's in foundation beam with storeys

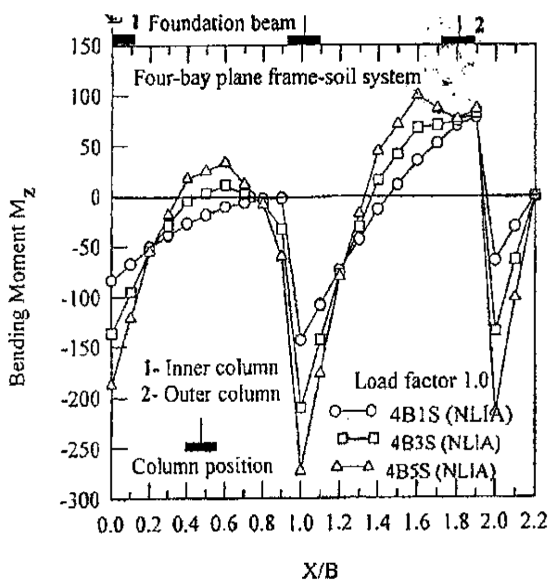



Fig 17. Variation of BM's in foundation beam with store;

SUMMARY AND CONCLUSIONS

In the present work, the linear and nonlinear analyses of two-bay plane frame-soil and four-bay plane frame-soil systems have been carried out to investigate the effect of bays and storeys on the interaction behaviour. The parametric studies have been made and trends are observed for the variation in the vertical settlements and contact pressures in the soil mass below the foundation beam and the forces in the frame members. The increase in bays and storeys causes significant increase in the vertical settlements, differential settlements, contact pressures and forces in the frame members and the foundation beam. The nonlinear soil behaviour also has significant influence on the interaction behavior.

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