A PARAMETRIC STUDY OF THE INFLUENCE OF SHORT-TERM SOIL DEFORMABILITY ON THE STATIC RESPONSE OF BUILDING STRUCTURES

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ABSTRACT

A parametric study conducted on the influence of flexible bases on the response of building structures subjected to both gravity and lateral static loads is presented. The most important parameters that are varied include the type of structural system, the type of the soil, and the embedment depth of the foundation. Both framed and dual structural systems are studied with height varying from six to twenty one stories. Base springs are established in accordance with relations available in pertinent literature and presented in a companion paper. Analyses of three-dimensional models using ETABS V 8.00 are carried out. The results presented show that all three factors have strong influence on the responses. The differences in internal forces of essential lateral-force resisting structural elements like columns and shear walls between the fixed-base and the flexible-base models are found to be significant. The fixed-base model underestimates both axial forces and moments in some columns of the dual system. The fixed-base model tends to underestimate the shear wall bending moments and axial forces, whereas it consistently overestimates the shear forces. Significant differences in the reaction moments at the foundation level are also noted between the fixed-base and flexible-base models.

INTRODUCTION

Building structures are traditionally modeled as if they were perfectly fixed at their bases irrespective of the nature of the foundation soil. This is tantamount to assuming that the soil deformations have no influence at all on the structural response. In other words, the effects of soil-structure interaction (SSI) are entirely neglected. Such a modeling approach can yield correct results, only if the foundations are firmly embedded in competent formations like rocks. If the foundations are laid on compressible materials like clayey or sandy formations, the soil deformation can have a significant influence on the structural response.

Accounting for SSI effects demands knowledge of the relationship between foundation forces and the ensuing deformations. Particularly, the ratio of a foundation force to the corresponding displacement of the foundation in the direction of the force provides a key quantity dimensionally equivalent to the coefficient of a linear spring. This observation suggests the use of simple mechanical models consisting of the massless rigid foundation supported by simple linear springs, whose coefficients are established from the force-displacement relationships of the actual foundation-soil system.

The subject of SSI has been studied since the 1930s, and a valuable wealth of such relations has been accumulated since then [1]. The theoretical background of these relationships together with selected spring formulas are provided in a companion paper [2].

A good understanding of the influence of SSI on the response of structures to different loads can be obtained if systematic parametric studies are conducted by employing such springs at the bases of structures. This paper has the objective of undertaking such a study on building structures of different heights that are subjected to both gravity and lateral quasi-static earthquake forces and identifying the importance of SSI effects.

The parameters varied include three types of structural systems, three different depths of foundation embedment, and three different soil types as stipulated in the Ethiopian Building Code Standard, EBCS 8 [3]. The internal forces studied include axial forces, shear forces, and bending moments in frame elements and in shear walls. Foundation reaction forces and moments are also included in the study. The differences observed in magnitudes of these quantities between the fixed-base and the flexible-base models are so significant that they cannot be overemphasized. A more detailed account of this work is available in [4].

MODELING OF THE SOIL-STRUCTURE SYSTEM

In this work, the building structure is considered as composed of two different parts: the soil-foundation system and the superstructure system. The soil-foundation system includes the foundation itself and the surrounding soil and is used to establish relations between foundation forces and the respective displacements and thus to obtain expressions for spring coefficients. The superstructure model consists of the superstructure and the foundation elements, to which springs are attached to account for soil deformability.

The general case of a framed or a dual frame-wall system of a building structure, whose foundations are embedded in a flexible soil layer of mass density ρ_1, shear modulus of rigidity G_1, and Poisson's ratio ρ_1 overlying a half space of corresponding parameters ρ_2, G_2, ρ_2 is considered as shown in Fig. 1. Each foundation element is provided with a set of springs responsible for each of its six degrees of freedom in three dimensions. The three springs in two-dimensional representation are shown in Fig. 1(b). This model is subjected to gravity and lateral loads. Even though lateral loads are generally of dynamic nature like earthquake and wind loads, they are treated here as quasi-static in accordance with code provisions applicable to quite a large class of building structures [3].

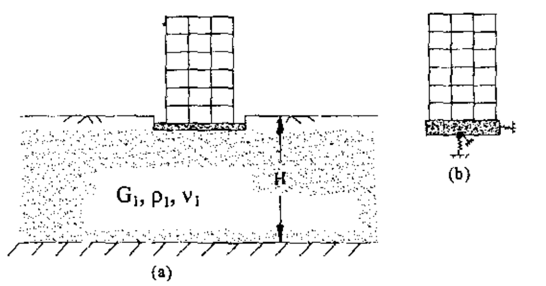


Figure 1 a) The building embedded in a layered formation; b) The building model with base springs

PARAMETRIC STUDY

The parametric study carried out in this work aims at investigating the effect of the soil flexibility on the internal force distribution of selected structural systems of buildings that are founded on soil formations.

Some of the major factors expected to influence the internal force distribution of the structures, include the type and stratification of the soil, the shape and the size of the foundation, the embedment depth of the foundation, and the type of the structural system. These parameters are varied systematically. All buildings are subjected to gravity and lateral quasi-static earthquakes forces quantified in accordance with EBCS 8 [3].

In order to avoid unnecessary complications due to torsion that would obscure the influence of the major factors mentioned above, the buildings considered are symmetric with respect to both rigidity and geometry and possess the same plan shape.

The maximum height of the buildings studied is limited to 21 stories. This is conformant with the approximate height limit for the pseudo-static method of analysis for lateral earthquake loads according to current seismic codes including EBCS 8 [3].

DESCRIPTION OF THE STRUCTURAL SYSTEMS STUDIED

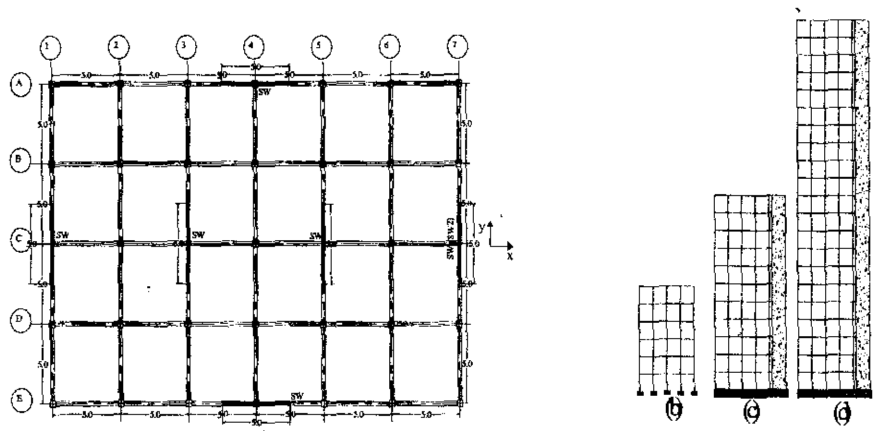
Three types of building structures are considered having the same plan area, but with different lateral force resisting systems including frame and dual systems. The plan view of all three building systems is as shown in Fig. 2. The size of the columns and the number of concrete shear walls are increased realistically as the number of stories is increased. The pertinent details of each of the three structural systems treated are as described below.

a) Structural System 1

The first structural system is a six-story regular reinforced concrete building frame. All the columns are of square cross section with a side length of 400 mm. The slabs are two-way type. All beams are 250mm wide and 300mm deep. No concrete shear walls are employed as part of the lateral force resisting system. Figure 2(a) without the shear walls represents the plan of this model. The floor height is 3m throughout. A typical frame in the *y*-direction is shown in Fig. 2(b). However, the analysis is made on the three-dimensional model of the building. The foundation elements are isolated footings.

b) Structural System 2

Structural System 2 is an eleven-story reinforced concrete building. All the columns are of square cross section with a side length of 650 mm. The slabs are two-way type with beams of 250 mm width and 300 mm depth. Four 200 mm-thick and 5m-long concrete shear walls are introduced into this system and are located symmetrically along the four external frames to resist lateral loads. Figure 2(a) represents the plan with only the external shear walls included. The floor height remains unaltered. A typical frame linked with a shear wall in the *y*-direction is shown in Fig. 2(c), though the analysis is conducted on the three-dimensional model of the building. Mat foundation is employed for this structural system.



(a)

Figure 2 (a) Floor plan of all buildings studied; (b) Structural System 1 (6-stories); (c) Structural System 2 (11-stories); (d) Structural System 3 (21-stories)

c) Structural System 3

Structural System 3 is a twenty-one-story reinforced concrete building, the plan of which is given in Fig. 2 (a) with all six shear walls included. The uniform square column size used is 900mm by 900mm. The floor height remains the same 3 meters throughout. A typical frame linked with a concrete shear wall in the y-direction is shown in Fig. 2(d). As in the previous cases, the analysis is conducted on the three-dimensional building model. Mat foundation is employed for this system as well. Two-way slabs with beams of 250 mm width and 300 mm depth are used for the floors. Pseudo-static lateral earthquake loads for all structural systems are computed in accordance with EBCS 8 [3].

FOUNDATION CONDITIONS CONSIDERED

The soil categorization in the seismic provisions of the Ethiopian Building Code Standard (EBCS 8) - soil classes *A*, *B*, and *C* - is employed [3]. It is worth reminding that this rough categorization has been replaced in recent seismic codes by a more refined one including larger number of soil classes established in more rational ways [5]. In addition to the three-soil types, foundation embedment depths of 1m, 3m, and 5m are included in the parametric study together with the fixed-base condition.

The coefficients of the static springs are determined using assumed mass density of 1800 kg/m^3 and Poisson's ratio of 0.35 for all soil types, whereas the shear wave velocity is taken as 400m/s, 200m/s, 100m/s for soil type *A*, *B*, and *C*, respectively. Thus, the shear wave velocities reflect the difference in the soil categories.

The static spring coefficients are calculated using formulas provided in a companion paper [2]. In order to provide an impression on the forms of such relations to the reader, formulas for rigid circular foundations embedded in an elastic stratum that overlies a rigid formation are presented in Table 1. In this table, G_1 and ν_1 are the shear modulus and Poison's ratio of the upper layer; *R* is the foundation radius; *D* is the embedment depth; and H is the thickness of the upper layer.

Table 1: Static spring coefficients for a rigid circular foundation embedded in an elastic stratum overlying a rigid half space [6]

Direction	Spring coefficient for H/R<2 and H/D≤0.5
Vertical	$(K_v)_e = \frac{4G_1R}{(1-\nu_1)}[1+1.28(R/D)]\left(1+\frac{H}{2R}\right)\left[1.85-0.28\frac{H}{R}\frac{H}{D}\frac{1}{(1-H/D)}\right]$
Horizontal	$(K_h)_e = \frac{8G_1R}{2-\nu_1}\left(1+\frac{R}{2D}\right)\left(1+\frac{2H}{3R}\right)\left(1+\frac{5H}{4D}\right)$
Rocking	$(K_r)_e = \frac{8G_1R^3}{3(1-\nu_1)}\left(1+\frac{R}{6D}\right)\left(1+\frac{2H}{R}\right)\left(1+\frac{0.7H}{D}\right)$
Torsional	$(K_t)_e = \frac{16G_1R^3}{3}\left(1+\frac{2.67H}{R}\right)$
Coupled horizontal-rocking	$(K_{kh})_e = 0.4H(K_h)_{emb}$

The springs are assigned at the bases of the columns and shear walls in the respective directions of freedom of movement. Three-dimensional analyses of the building models are conducted using the commercial software, ETABS

Non linear *V* 8.00, which has features to incorporate base springs. The results of the analyses are presented and discussed in the following sections.

Results for Structural System 1

The responses studied include bending moments, shear forces, axial forces, foundation reactions, and story drifts. For the purpose of this discussion, only the internal forces in the frame along Axis 4 of Fig. 2(a) are considered as obtained by analyzing the 3D-model of the system. The results are presented in two parts by treating the influence of foundation embedment and soil type separately.

i) Influence of foundation embedment depth

The flexible-base model was analyzed for foundation embedment depths of 1m, 3m, and 5m in Soil Type *C*. This is in addition to the fixed-base model. In employing Soil Type *C*, extreme differences in internal forces are anticipated. Diagrams of bending moments, shear forces, and axial forces were output for the frame along axis 4 but not presented here for brevity reasons. The results for embedment depths of 3m and 5m fell in between the two extreme cases of the fixed-base and the flexible-base model with a foundation embedment depth of 1 m. Notable differences are observed in the internal forces of these two extreme cases.

In the beams located at the end bays (between Axes *A* & *B* and *D* & *E*), an average difference of about 39% in moments at the connections with the columns is observed between the fixed-base and the flexible-base models. In the beams located in the interior bays (between Axes *B* & *D*), the average difference in moments is about 9 % at the supports. There is no significant difference in the span moments in the entire frame.

Figure 3(a) shows the difference in end-bay beam moments of the fixed-base and the flexible-base models with foundation embedment depth of 1m in Soil Type *C* for all the floors between Axes *A* and *B*, where the largest difference in moments is observed. It can be seen that the differences at the supports are significant, whereas they are much smaller away from the supports, and even zero at mid span. As a general trend, the deviations become larger when one goes down from the upper stories to the lowest.

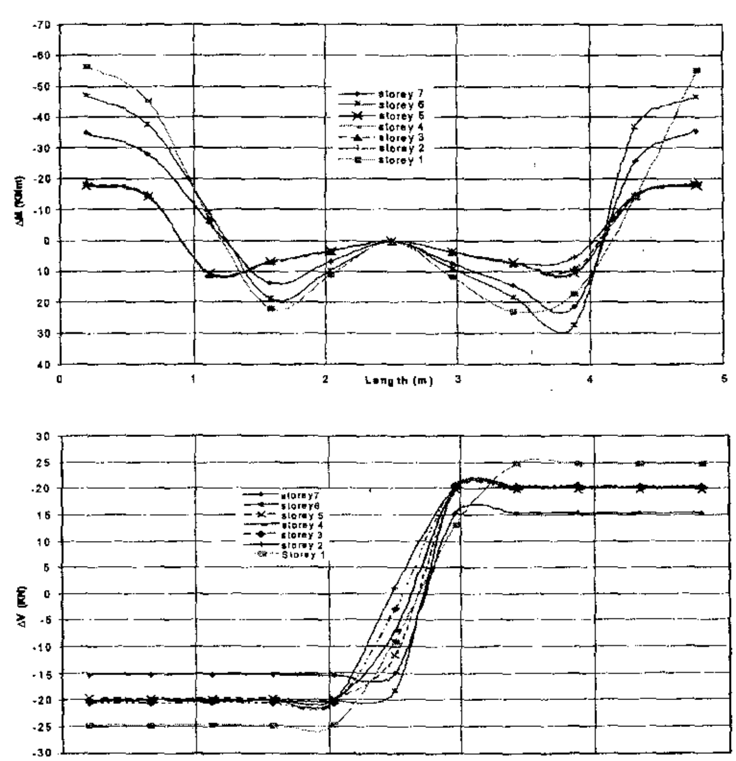


Figure 3 Plots showing difference in bending moment (upper) and in shear force (lower) along the length of end-bay beams in all floors of Structural System 1 for embedment depth of 1 m in Soil Type *C*.

A study of the shear-force diagrams of the beams showed an average difference of about 16 % around the supports of the end bays. The differences elsewhere are insignificant. The 3m- and 5m-embedment cases fell between the extreme cases of the fixed-base and the 1m-embedment cases. Figure 3(b) shows differences in shear along the span of the end-bay beams in all the floors between Axes A and B. It exhibits notable differences around the supports. Once again, as in the case of the moments, the differences in shear increase as one goes down from the top stories to the lowest.

The column moments showed significant differences between the fixed-base and the flexible-base models, especially in those columns at the edges and corners of the building. The axial forces in the columns for the fixed- and flexible-base models are also influenced by embedment depth. The observed differences at the lowest story, where they are most significant, are 12, 9, and 3% in the columns of Axes A and E, B and D, and C, respectively. By in large, the effects on the column internal forces are not as large as in the beam moments and shears.

ii) Influence of soil type

The effects of soil type on the internal force distribution were also studied keeping the foundation embedment constant. An embedment depth of 3 meters was selected as reasonably representative for shallow foundations.

The plots of the beam bending moments, which are not presented here, showed that there is a trend of increase in moments with decreasing soil stiffness. Average differences of 13, 22, and 25 % are observed between Soil Types *A* and *B*, *B* and *C*, and *A* and *C*. Differences in shear of 8, 18, and 20 % are also observed between the respective soil types. A trend in increase of axial forces is seen with decreasing soil stiffness for the external columns, whereas a decrease is observed in the internal columns. The difference in axial force between Soil Types *A* and *C* is on the average 10 and 4 % in the exterior and the inner most columns, respectively.

The differences in reaction forces and moments at the foundation level in the fixed-base and flexible-base models are also of interest, as they have a direct bearing on the design of the foundation elements and the base columns. Thus, reactions at the bases of the columns along Axis 4 of Fig. 2(a) were plotted for Soil Types *A*, *B* & *C* and for embedment depths of 1m and 3m. Whereas a maximum difference of 10% is observed in the vertical foundation reaction forces, differences up to 20% are seen in the base column moments.

The story drifts in the direction of the application of the lateral loads are also studied. They are in an order of few millimeters only.

Results for Structural System 2

In studying the influence of soil flexibility on the responses of Structural System 2, global static stiffnesses are first calculated for the mat foundation and the spring stiffnesses at the base of each column and shear wall are determined according to their tributary areas. The static springs so established are assigned at the bases of the columns and shear walls in the directions of the respective degrees of freedom. The results obtained from the analysis of the flexible-base three-dimensional model of the building are presented next.

i) Influence of embedment

The results of the flexible-base model for an embedment depth of 1m in Soil Type C together with that of the fixed-base model are presented. The results for embedment depths of 3m and 5m fell in between those of the two models.

With regard to beam moments, average differences of about 57 % at the supports and 21 % in the spans of the end bays of the frames are observed. The differences observed in some of the end-bay beams are more than 100 % in excess of the moments of the fixed-base model. It is worth noting that these large differences occurred in locations where the moments in the fixed-base model are also maximum. This is an indication that the conventional design at such critical sections may be seriously on the unsafe side. In the beams located in the interior of the frame (i.e. between Axes *B* and *D*), an average difference is about 49 % at the supports and 10 % in the spans. As a general trend, the relative differences are much larger in Structural System 2 than in Structural System 1.

Figure 4(a) shows differences in beam moments of the fixed-base and flexible-base models for foundation embedment depth of 1 m in Soil Type *C* for the beams in selected floors of the end bay between Axes *A* and *B*. It can be observed that the differences at the supports are significant, whereas they are much smaller away from the supports, and zero at mid span. Generally, the deviations become larger when one goes down from the upper stories to the lowest.

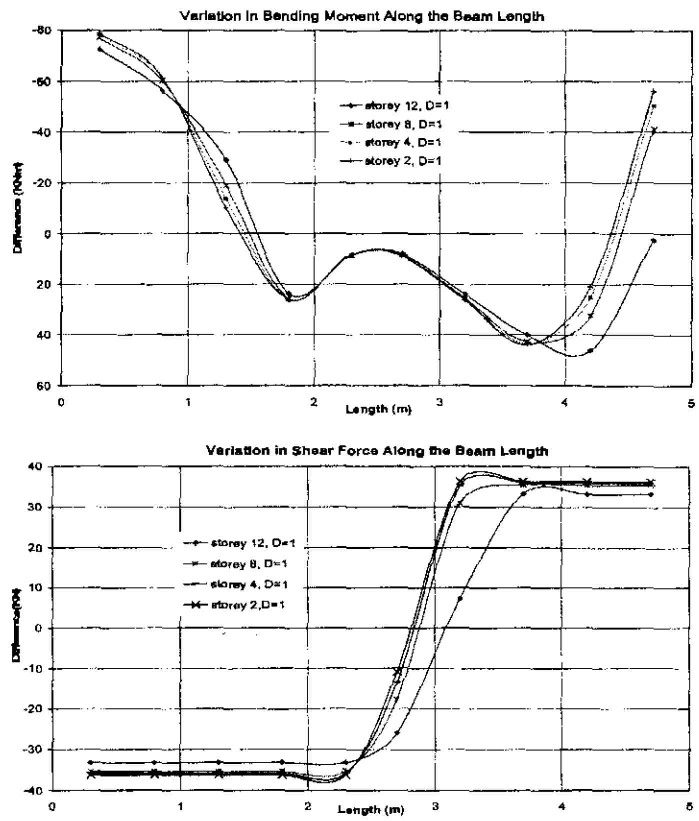


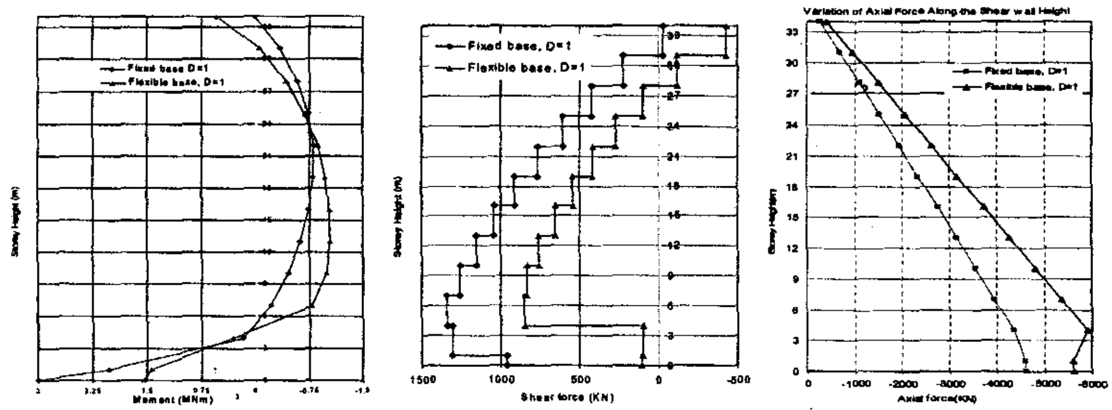
Figure 4 Plots showing differences in bending moment and shear force along the length of selected end-bay beams of Structural system 2 for a foundation embedment depth of 1 m in Soil Type C

In the end-bay beams, average differences in beam shear of about 41 % around the supports are observed. In the beams located in the interior of the frame (between Axes *B* & *D*) an average difference of about 29 % at the supports are seen.

The differences in shear force of all end-bay beams (between Axes *A* and *B*) are plotted in Fig. 4(b) for selected stories. The same trends observed in Structural System 1 are observed, except that the discrepancies are larger in this system.

The column moments showed also significant differences between the fixed-base and the flexible-base models, especially in those columns at the edges and corners of the building. The differences are larger in the edge columns and increase as one goes down with the stories. The column axial forces in the fixed-base and flexible-base models were also plotted. They showed that the axial forces in the flexible-base system are consistently larger than those of the fixed-base system in the exterior columns, and this trend is reversed in the interior columns. The average differences in axial forces in the lowest story are 31 and 25 % for the exterior and internal columns, respectively.

The moments, shears, and axial forces in the shear wall for the fixed-base and the flexible-base models (1m-embedment depth in Soil Type *C*) are presented in Fig. 5.



(*a*) (*b*) (*c*)

Figure 5 Variation of internal forces with height in Shear Wall SW2 for fixed- and flexible-base models of Structural System 2 for an embedment depth of 1 m in Soil Type *C*: (*a*) bending moment; (*b*) shear; (*c*) axial force

Figure 5(*a*) shows that the shear wall moments of the flexible-base model are larger than those of the fixed-base model for about the middle half of the wall height. A reversal of this trend with significant difference in magnitude of the moments is observed around the bottom of the shear wall. The shear forces in the shear wall are plotted in Fig. 5(b) against the height. The plots show significantly larger shears in the fixed-base model than in the flexible-base model almost throughout the height of the building. Since the base moment and shear are governing in design, one can note the potential saving in material with proper modeling.

The shear wall axial forces are plotted against height in Fig. 5(c). The axial forces in the flexible-base model are consistently larger than those of the fixed-base model. This trend is in clear contrast to the trend observed in the moments and shears.

ii) Influence of soil type

Keeping a depth of embedment of 3m in all cases constant, soil types were varied and plots of the internal forces of the frame and the shear wall prepared.

Average differences in beam support moments of 51, 40, and 27 % and in beam shears of 43, 34, and 19 % are observed between Soil Types *A* and *C*, *B* and *C*, and *A* and *B*, respectively. These discrepancies are consistently larger than those in Structural System 1.The differences in the shear forces, however, are not as large as those in the bending moments.

The column axial forces tend to increase with decreasing soil stiffness in the end columns and to decrease in the interior columns. Average differences of 26 and 16% are observed in the exterior and interior columns, respectively. Overall, the differences are larger than those observed in Structural System 1.

Bending-moment differences in one of the central edge columns at two different floors of the fixed- and flexible-base models are compared in Fig. 6 for selected soil types and a foundation embedment depth of 1 meter.

The differences are significant at the lower stories. For instance, the bending moment at the upper end of the column in Story 2 (for the flexible-base model founded at a depth of 1 meter in Soil Type C) is more than 3-fold of that in the fixed-base model. The axial force is found to be about 70 % larger. Such discrepancies are too large to neglect.

The moments, shear and axial forces in the shear walls are given in Fig. 7 for the three soil classes.

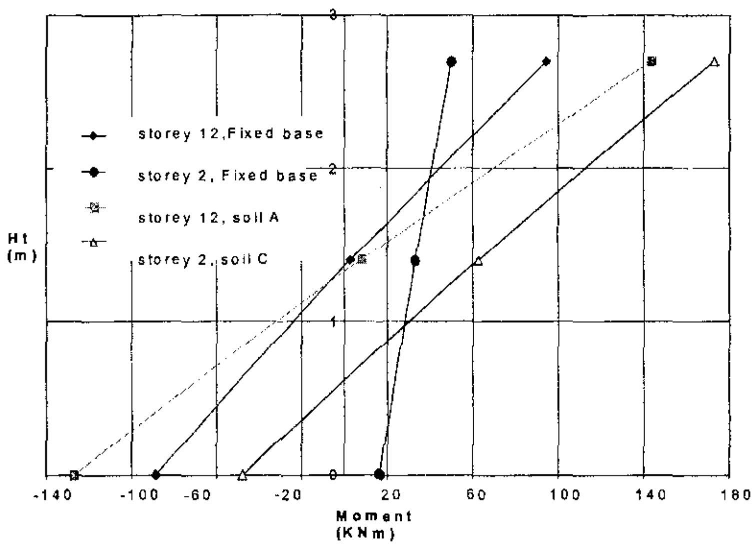
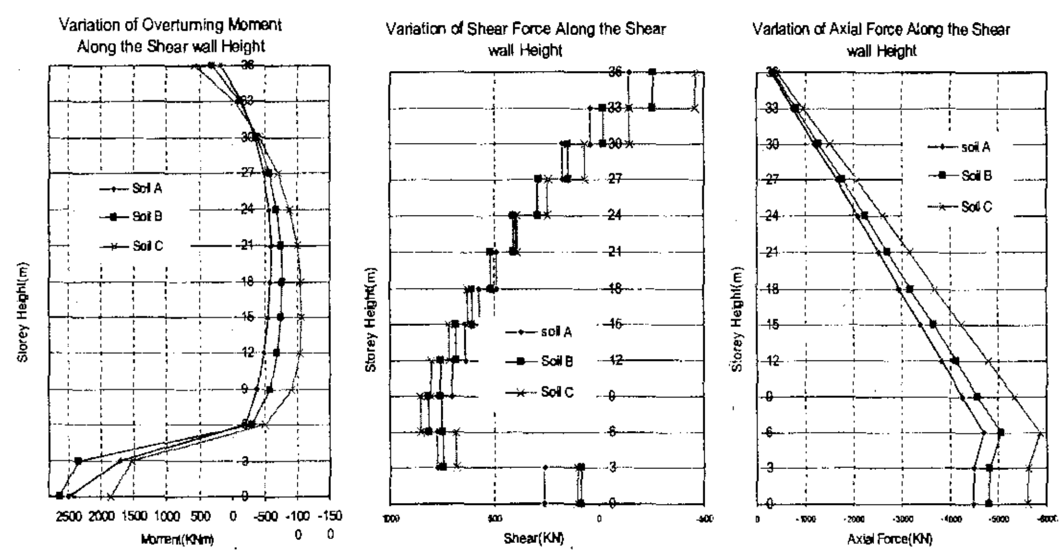


Figure 6 Bending moment variations in a column for selected cases of the fixed- and flexible-base models



(*a*) (*b*) (c)

Figure 7 Variation of internal forces in Shear Wall SW2 for fixed- and flexible-base models of Structural System 2 for an embedment depth of 3 m in different soil types: (*a*) bending moment; (*b*) shear; (*c*) axial force

The wall moments in Fig. 7(a) increase with decreasing stiffness of the soil for the majority of the height of the wall, but the trend reverses around the base of the building.

The shear forces in the shear wall are presented in Fig. 7(b) for the three types of soils. It can be seen that the influence of the soil type in the variation of the shear force is insignificant except at the base. However, it is to be recalled that the flexibly supported system exhibited consistently much smaller values of shear forces for the majority of the stories than the fixed-base system (compare with Fig. 5(b)).

The axial force variation in the shear wall is given in Fig. 7(c). There is a consistent trend of increase in the axial force with decreasing stiffness of the soil, the difference being largest at the base.

The reaction forces and moments at foundation level along Axis 4 were compared for the fixed-base and flexible-base models with various combinations of foundation embedment depth and soil types. The plots showed significant differences in bending moments and axial forces of the fixed-base and flexible-base models. In some cases, moments in the flexible-base system are significantly higher than those in the fixed-base model. These discrepancies are excessively large compared with those in Structural System 1. The differences can result in substantial changes of both the foundation and column design.

Results for Structural System 3

Three soil types and three different foundation embedment depths are considered as in the previous systems, and spring coefficients for each combination case are calculated similar to Structural System 2.

i) Influence of embedment

The effects of embedment depth on the internal force distribution are studied for Soil Type *C*. Results for an embedment depth of 1m together with that of the fixed-base model are presented.

Average differences in beam moments of about 51 % at the supports and 22 % in the spans of the end bays are observed. In the beams of the interior bays, an average difference is about 38 % at the supports and only 1 % in the spans.

Figure 8(a) shows differences in beam moments of the fixed-base and flexible-base models for foundation embedment depth of 1 m in Soil Type *C* for the beams in all the floors of the end bay between Axes *A* and *B*. One can see that these differences are on the average greater than those in Structural System 2.

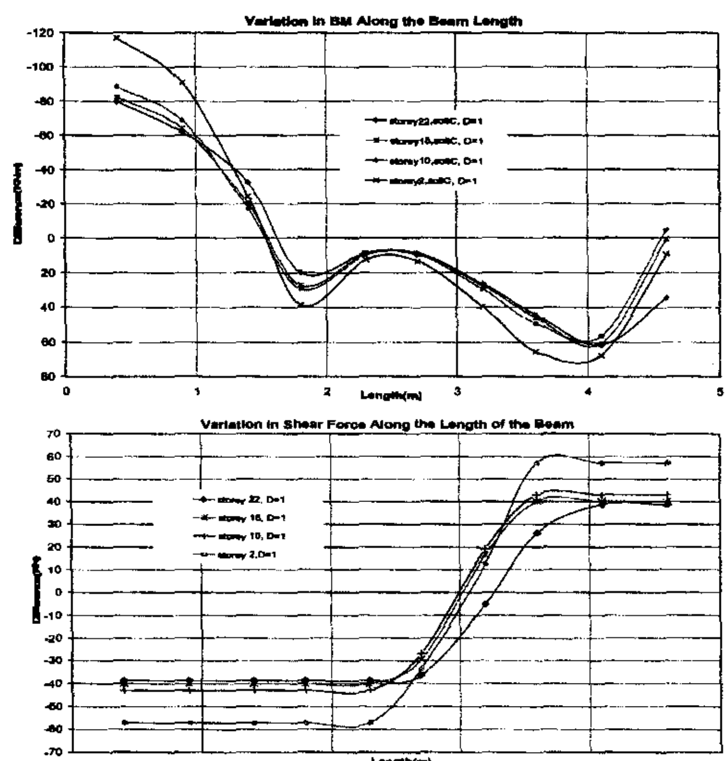


Figure 8 Plots showing differences in bending moment, and shear force along the length of selected end-bay beams of Structural system 3 for embedment depth of 1 m in Soil Type *C*

Average differences in beam shear of about 42 % around the supports are observed in the beams of the end bays. In beams located at the interior of the frame, an average difference of about 34 % at the supports are seen.

Differences in shear force of selected end-bay beams are plotted in Fig. 8(b). As in Structural Systems 1 and 2, maximum differences are observed at the supports, the absolute differences being larger when compared with those of Structural System 2.

The column axial forces in the fixed-base and flexible-base models were also plotted. They showed that the axial forces in the flexible-base system are consistently larger than those of the fixed-base system in the exterior columns, and this trend is reversed in the interior columns. The average differences in axial forces in the lowest story are 34 and 40 % for the exterior and internal columns, respectively. Contrary to the other two structural systems considered above, the maximum difference is found in the interior columns. Besides, the relative differences are larger than those of Structural System 2.

The height-wise moment variations in the shear wall are given in Fig. 9(a). The plots show larger moments in the flexible-base model than in the fixed-base model almost throughout the entire height of the wall. Unlike in structural system 2, there is no reversal and reduction in bending moments around the base of the flexible-base system.

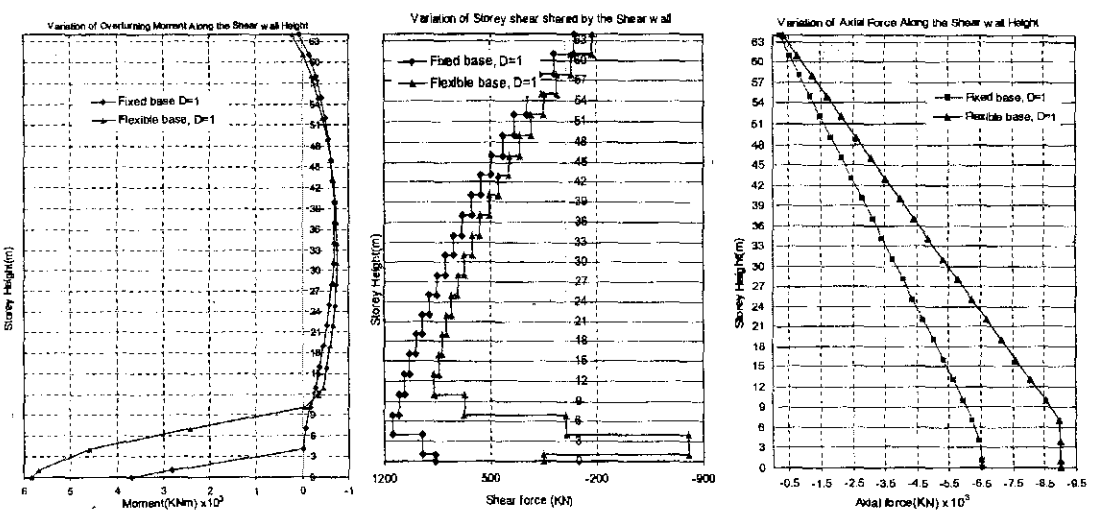
The shear forces in the shear wall are plotted in Fig. 9(b). The shear force differences between the fixed-base and flexible-base models are small for the top 17 stories but become suddenly larger in the lowest three stories. The direction of the shear forces has changed in the flexible-base model at around the base, a situation that was not observed in Structural System 2.

The axial forces in the shear wall are plotted against height in Fig. 9(c). The axial forces in the flexible-base model are consistently larger than those of the fixed-base model, and the difference becomes significant near the base.

ii) Influence of soil type

Keeping a depth of embedment of 3m in all cases constant as in the previous two cases, the soil types were varied and plots of the internal forces in the frame and in the shear wall prepared.

Average differences in beam support moments of 32, 16, and 24 % are observed between Soil Types *A* and *C*, *B* and *C*, and *A* and *B*, respectively. These discrepancies are consistently smaller than those in Structural System 2.



(*a*) (*b*) (c)

Figure 9 Variation of internal forces with height in Shear Wall SW2 for fixed-base and flexible-base models of Structural System 3 for an embedment depth of 1 m in Soil Type *C*: (*a*) bending moment; (*b*) shear; (*c*) axial force

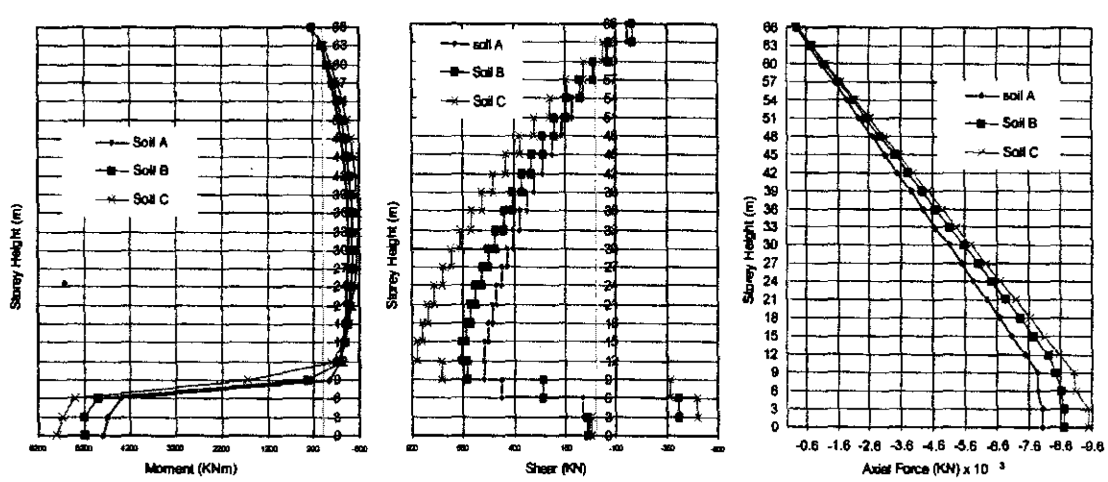
Average differences in beam shear of 32, 14, and 25 % are observed between Soil Types *A* and *C*, *B* and *C*, and *A* and *B*, respectively. Once again, these discrepancies are consistently smaller than those in Structural System 2.

The column axial forces for the three soil types tend to increase with decreasing soil stiffness in the end columns and to decrease in the interior columns. Average differences of 13 and 17% are observed in the exterior and interior columns, respectively, between soil Types *A* and *C*. In this structural system it was seen that larger differences are observed in the internal columns than in the external columns.

The story moments in the shear wall are given in Fig. 10(a) for the three soil classes.

in the axial force with decreasing stiffness of the soil, the difference being largest at the base as in the previous case.

The reaction forces and moments at the base of all the columns in Axis 4 were plotted for the fixed- and flexible-base models with various combinations of foundation embedment depth and soil type. The plots showed excessive differences in bending moments and axial forces in the two models. These variations are larger compared with those in Structural System 2. Such discrepancies can have a big potential to result in a significant change in the foundation and column design.



(*a*) (*b*) (c)

Figure 10 Height-wise variation of internal forces in Shear Wall SW2 for fixed- and flexible-base models of Structural System 3 for an embedment depth of 3 m in the different soil types: (*a*) moment; (*b*) shear; (*c*) axial force

The wall moments increase with decreasing stiffness of the soil for the majority of the height of the wall and the trend reverses around the base of the building. However, the overall difference among the soil types is relatively small.

The shear force variations in the shear wall are presented in Fig. 10(b) for the three types of soils. It can be seen that there is an increase in shear force with decreasing soil stiffness. The relative differences in shear among the different soil types of this structural system are greater than those of Structural System 2.

The axial force variation in the shear wall is given in Fig. 10(c). There is a consistent trend of increase

CONCLUSIONS AND RECOMMENDATIONS

The studies on Structural System 1 representing framed short buildings revealed the following:

- The flexibility of the soil has significantly influenced the internal forces around the supports of beams. Its influence around the spans is negligible. The influence is more significant in the end-bay beams. Extreme differences of up to 110% are observed in bending moments of beams around the end supports between the flexible-base system and the fixed-base system. The average difference in these locations is about 40%.

- Soil flexibility showed relatively smaller influence on shear and axial forces as compared to moments. The influence on the axial forces is the least.

- Notable differences in foundation reaction moments are observed between the fixed-base and flexible-base models.

The studies on Structural System 2 and 3 representing buildings of moderate height supported by dual (frame-wall) structural systems indicate the following.

- The flexibility of the foundation soil influences the internal forces of the frames in a trend similar to that in Structural System 1, and hence most of the above observations are also applicable here. However, the influence tends to increase with increasing height of the building, at least within the range of building height studied.

- In the dual systems, the bending moments in the shear walls of the flexible-base model are larger than those of the fixed-base model in around middle one-third to half of the height of the walls. But the bending moments around the foundation level are less than those of the fixed-base system in Structural system 2. This reversal of trend is not observed in Structural System 3.

- In both Structural Systems 2 and 3, the shear forces in the shear walls of the flexible-base system are less than those of the fixed-base system almost throughout the entire height of the walls except around the base, where the shear forces in Structural System 3 changed direction.

- The axial forces in the shear walls of the flexible-base model are consistently larger than those of the fixed-base model throughout the wall height in both Structural Systems 2 and 3.

- Notable differences in the foundation reaction forces and moments have been observed between the fixed-base and flexible-base models. The differences in vertical reaction forces are modest. In clear contrast to this, significant differences are observed in the bending moments. These differences are highly pronounced in Structural System 3 and are least in Structural system 1. This has a practical significance in that it can significantly influence the design of the columns, the shear walls, and the foundation.

In the study presented above, the most important parameters varied include the type of structural system, the type of foundation soil, and the embedment depth of the foundation. Both framed and dual structural systems are studied with height varying from six to twenty-one stories. The results show that all factors considered have strong influence on the responses. The differences in internal forces of essential lateral-force resisting structural elements like columns and shear walls between the fixed-base and the flexible-base models are found to be significant. The fixed-base model underestimates both axial forces and moments in some columns of the dual system. In the shear walls, whereas the fixed-base model tends to underestimate the bending moments and the axial forces, it consistently overestimates the shear forces. Significant differences are observed in the reaction moments at the foundation level. The practical significance of these observations cannot be overemphasized.

The effects of static SSI can be easily accomplished by introducing simple linear springs at the base of foundation elements. A companion paper provides simple formulas with sufficient theoretical background [2]. Not only can short-term soil deformations be taken into account, but also long-term compressions like consolidation and creep. The additional effort needed in employing such springs is practically insignificant, and current commercial software have features to support the use of such flexible elements.

A more exhaustive study on the influence of SSI on structural response would best be done by considering dynamic loads. Under time-varying forces, the foundation soil plays an additional important role by dissipating energy in form of material and geometric damping. The influence of both soil stiffness and soil damping (dynamic SSI) on the response of structures to dynamic loads is an active field of research currently. A future parametric study on this topic is recommendable.

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