Effect of Static Stiffness of Soil on Internal Force Distribution of Building Structures Subjected to Earthquake Loads

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Research Article

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Abstract

The soil structure interaction model is developed by substructure modeling method. For the purpose of comparative study, the SSI depth is varied by 0m, 1m, 3m, and 5m. To consider this case the foundation soil of firm soil, soil class-A and the soft soil, soil class-C is used to comparative study. By considering rigid foundation, the soil can be replaced by a set of equivalent springs and dashpots in the inertial interaction analysis. The soil structure interaction can be modeled by using equivalent static spring modeling method and static stiffness of spring can be calculated by using the supporting soil properties. To calculate elastic static stiffness of soil the most well-known G. Gazetas equation is used. The static stiffness calculated shows that for the increased depth of soil structure interaction there is increased static stiffness. So, the calculated static stiffness is used as elastic spring constant and it is assigned on the footing column base of building structure which modeled by SAP200 software. Time history analysis is conducted by applying earthquake load on the structure by using SAP200 V 14.

I. Introduction

The response of a structure during an earthquake depends on the characteristics of the ground motion, the surrounding soil, and the structure itself. The SSI depth of the structure is a depth or height of the footing column in which the superstructure is contacted with the sub-structural foundation part and which shares the behaviour of the structural and supporting soil [6]. Implementing Soil-Structure Interaction effects enables the designer to assess the inertial forces and real displacements of the soil-foundation structure system precisely under the influence of free field motion. The influence of the SSI in the dynamic behaviour of the structure is reflected in an increase in the vibration period as well as increase in the system damping in comparison with the fixed-base model, which does not consider the supporting soil. The inclusion of the soil in the structural analysis provides results, stress and displacement values, which are closer to the actual behaviour of the structure than those provided by the analysis of a fixed-base structure [4].

When compared to the fixed base scenario, Soil Foundation Structure Interaction significantly reduces the peak acceleration of the structure in all cases. Soil Structure Interaction generally reduces the peak acceleration compared to the fixed base but to a lesser degree than Soil Foundation Structure Interaction and less consistently across the structures and earthquake records records [3]. The estimation of earthquake motions at the site of a structure is the most important phase of seismic design as well as retrofit of a structure. In classical methods used in structural analysis, it is assumed that, the motion in the foundation level of structure is equal to ground free field motion. This assumption is correct only for the structures resting on rock or very stiff soils. Traditionally, in analysis of the rigid base structures, input motion at the base of the structure is taken as equal to the free field ground motion. In the case of a flexible -base structure, in addition to the added rocking component to the horizontal motion of the structure, a part of the structure’s vibrating energy will transmit to the soil layer and can be dissipated due to radiation damping results from the wave propagation and hysteresis damping of the soil materials [7].

According to [8] Structures are expected to deform in-elastically when subjected to severe earthquakes, so seismic performance evaluation of structures should be conducted considering post-elastic behaviour. Therefore, a nonlinear analysis procedure must be used for evaluation purpose as post-elastic behaviour cannot be determined directly by an elastic analysis. The more effective way of nonlinear analysis tool to determine post elastic behaviour or inelastic deformation behaviour of structure is Time History Analysis [5]. SAP2000, a state of the art, general- purpose, three - dimensional structural analysis software program, is used as a tool for performing the Time History Analysis. The SAP2000, which are fully integrated into the program, allow quick and easy implementation of to model the soil-foundation interface by using equivalent static spring constant.

Ii. Method And Material

Methodology of the study starts with modelling of soil structure interaction of the building structure with frame sections. Modelling rules of ATC-40 is used as a guideline for modelling the structure considered for this study. Dimensions of beams and columns are selected, by considering minimum section provision for structural members and the section are analysed and checked for the linear elastic analysis in SAP2000. So, the proved sufficient frame sections are going to be used in nonlinear analysis for the comparative study parameters. All the joints are detailed by automatic meshing and the diaphragmatic action are defined in horizontal direction to give the attention for the stiffness of the building model [4].

Soil structure interaction can be modelled by substructure modelling that is by determining elastic spring stiffness constant and then assigning the value at the base of modelled SSI on SAP2000. Substructure modelling approach, designated the Baseline Model (or MB) except that kinematic base rocking was applied to the base of vertical foundation springs along with depth-variable ground motions by using SAP2000. Springs were elastic, with no compression capacity limit, and zero tension capacity. However, the limitations good matches developed between computed and observed responses were reported using the baseline modelling (MB) approach [7].

The foundation itself is rigid, the soil can be replaced by a set of equivalent springs and dashpots in the inertial interaction analysis. The inertial interaction analysis can be performed by applying inertial forces to the masses of the structure. The Figure 1 below shows that how the structure can be modelled by using elastic spring at the base of the structural system.

Springs was used to capture interaction between the foundation and the underlying soil during earthquake loading. In order to determine the appropriate parameters of the springs the overall vertical foundation static elastic stiffness was first calculated. This was done using procedures set out by [2], which use the small strain shear modulus of the foundation soil by considering the shear wave velocity for the given soil class can be defined as ([4].

$$Gs = \rho s^2 * Vs^2 \quad (1)$$

Since the response behavior of the soil- structure system for the given loading depends on its soil class, due to the different density of the soil and its shear wave velocity. The shear modulus of the foundation can be directly determined by using density and shear wave velocity of the given soil class as shown in equation above. The following soil foundation parameters are used for the calculation of shear modulus.

Table 1 Soil-Foundation Parameters for shear modulus of the foundation

Soil type	Soil class	Shear velocity	Density (kg/m^3)	Shear Modulus(N/m)	Poison's ratio
Hard soil	A	600m/s	1800	$6.48*10^8$	0.3
Medium soil	B	350m/s	1600	$1.96*10^8$	0.4
Soft soil	C	200m/s	1600	$6.4*10^7$	0.4

According to [2] the static stiffness of the spring for the modeled soil-structure interaction for the foundation of any shape and by considering soil class-A and soil class-C by varying depth of SSI of, 0m (fixed base), 1m, 3m and 5m is summarized below. In this table Kx is the lateral static spring constant along the x-axis in units of KN/m, Ky is the lateral static spring constant along the y-axis in KN/m, Kv is the vertical static spring constant in KN/m, Krx is the rocking static spring constant about x-axis in KNm, Kry is the rocking static spring constant about y-axis in KNm and Kt is the torsional static spring constant in KNm. The left-right direction on the plane of the paper is considered as the x-direction. The elastic static springs shown below are then assigned at the base of the building structures with the respective degrees of freedom in the analysis of the building to obtain the study parameters that are Bending Moments, Story Shear and Floor Displacement for Time History Analysis.

Table 2 spring static stiffness calculated according to [2]

	Spring static stiffness (x10^7)					
	Soil class-A			Soil class-C		
	1m	3m	5m	1m	3m	5m
K_x	2.30	2.96	3.52	2.31	2.73	3.12
K_y	2.30	2.96	3.52	2.31	2.73	3.12
K_z	2.33	2.78	3.16	2.56	3.31	3.26
K_{rx}	4.25	4.86	5.27	4.53	4.79	5.31
K_{ry}	6.17	6.91	7.30	4.35	4.88	5.45
K_t	11.20	11.20	11.20	6.23	6.23	6.23

The vertical static stiffness is more influenced by increase in SSI depth than the other static stiffness's and the soil static stiffness has practically no influence on torsional static stiffness. Except in the torsional mode, the static stiffness's of elastic spring increase with the increased SSI. Moreover, the soil type has an effect on stiffness values in such a way that static stiffness's generally decrease from Soil Type-A to Soil Type-C.

Iii. Results And Discussion

A. Comparative study of building on soil class-A

a) Comparison of Story bending Moment

The static stiffness of soil has influenced the bending moments, which for the fixed-base and the Flexible-base cases are given below for column and for beam respectively. when comparing the average Story Bending Moment of structural system in both beam and column there is a significant increase for the fixed base with SSI depth of 1.0m for the value of 22.64% less than in column and 9.97% in beam.

This is because of soil flexibility influences internal stress distribution on the frames. But for the increased SSI depth, there is increased static stiffness, there is a decrease in bending moment, when comparing 1.0m embedment with 3.0m embedment 11.01% decrease of moment in column and 8.31% decreased moment in beam, again comparing 3.0m embedment with 5.0m 15.53% decrease of moment in column and 10.57% increase in beam.

b) Comparison of Story shear force

To study the effect of SSI depth variation, the column shear force comparison only is considered. The shear force diagram of the column shows that there is a significant increment of about 3.53% from fixed base to 1.0m SSI depth. For further increment of SSI depth as compared with 1.0m depth there is about averagely 9.97% reduced in 3.0m and 7.05% reduction in 5.0m depth of SSI. Graphically those cases of average shear in both structural systems for different SSI depths.

c) Comparison of Floor Displacement

The floor displacement obtained from the fixed base structural system differs significantly from the flexible one. For the structural system the variation of 1.05% increment is observed from fixed to 1.0m and 5.47% decreased when 3.0m embedded, 3.78% increased again in 5.0m embedded.

B. Comparative study of Building on soil class-C

a) Comparison of Story bending Moment

For the purpose of comparative study to know the influence of embedment depth on the two extreme soil case soil classes, soil class-C is again taken in to study. The bending moment is influenced by varying the SSI depth of structures. When taking in to consideration flexibility of 1.0m SSI depth with fixed base there is increment of averagely about 14.53% in column and 5.65% in beam, then increasing the SSI depth to 3.0m and comparing with 1.0m SSI depth there is reduction of 4.07% in column and 4.65% in beam is observed and this number is again reduced to 3.11% in column and 0.94% in beam, when increasing the SSI depth to 5.0m. the chart below describes graphically the influence of SSI depth on soil class-C.

b) Comparison of Story Shear Force

the shear force difference is observed from the analysis output in column. The flexible base Story shear force is increased averagely to about 3.54% than 1.0m SSI depth and again the variation is changed when comparing 1.0m of SSI depth of 3.0m and it is reduced to the 5.04%, it becomes to 3.13% decreased.

c) Comparison of Floor Displacement

When comparing the floor displacement observed in analysis output, there is about averagely 4.61% of increment from fixed base than for flexible one, and when comparing 1.0m SSI depth with 3.0m it shows that 4.80% averagely reduced floor displacement and when considering the 5.0m embedment depth the floor displacement is reduced insignificantly to 0.60%.

Iv. Conclusions

- Fixed base structural system bending moment is influenced by changing the fixed base to the flexible base of structural system and it increased moment to the average of not less than about 15.04% in column, 9.75% in beam for soil-A and 10.66% in column, 3.84% in beam for soil-C, but this increment of the bending moment in between fixed and flexible base system changes its behavior to the average decreasing of not less than about 10.28% in column, 8.8% in beam for soil-A and 3.43% in column, 7.87% in soil class-C for each increment of the SSI depth.
- For the two soil classes considered due to the small static stiffness of soil class-C the effect of fixed base and flexible base systems the bending moment distribution variation is less than soil class-A.
- For the increased SSI depth, the bending moment is decreased to 3.0m depth and it starts to increase when changing SSI depth to 5.0m.
- Floor shear force distribution of the structural column influenced by the static stiffness of the supporting soil. There is about 8.13% in soil-A and 5.12% in soil-C increment is observed for 0m SSI depth and 7.9% in soil-A and 5.09% in soil-C decreasing is observed for each increment of SSI depth.
- For 0m SSI depth floor displacement is averagely increased about 2.2% for soil-A and 6.83% for soil-C and if SSI depth increased there is averagely reduction of about 4.01% for soil-A and 3.79% for soil-C occurs. This is due to the increased base static stiffness increases the load absorption and the load transferred to the frame system is decreased.

Declarations

- **Ethical Approval: there is no attachment with ethical consideration and ethically approved.**
- **There is no funding source adopted**

- **there is no interest of conflict and competing regarding this research article**
- **this paper is our original article work and the analysis and the data adopted is our intensive effort.**
- **all authors are contributed to this article starting from data collection to data analysis and interpretation**

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Figures

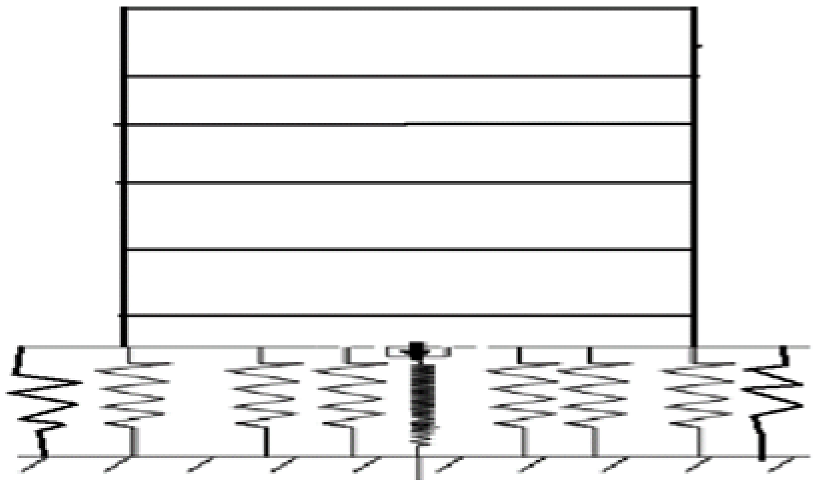

Figure 1

Spring modeling of the Structural Model for the selected structural system

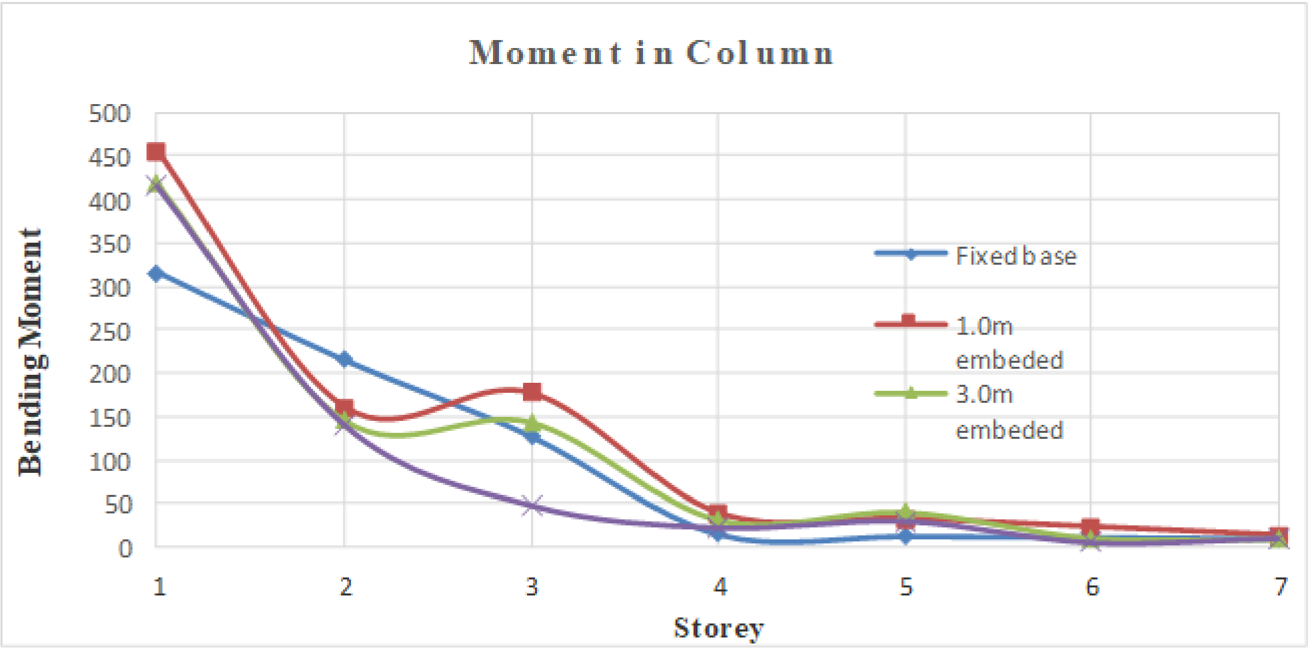

Figure 2

Moment in Column for Fixed and Flexible Base Structure of building in soil-A

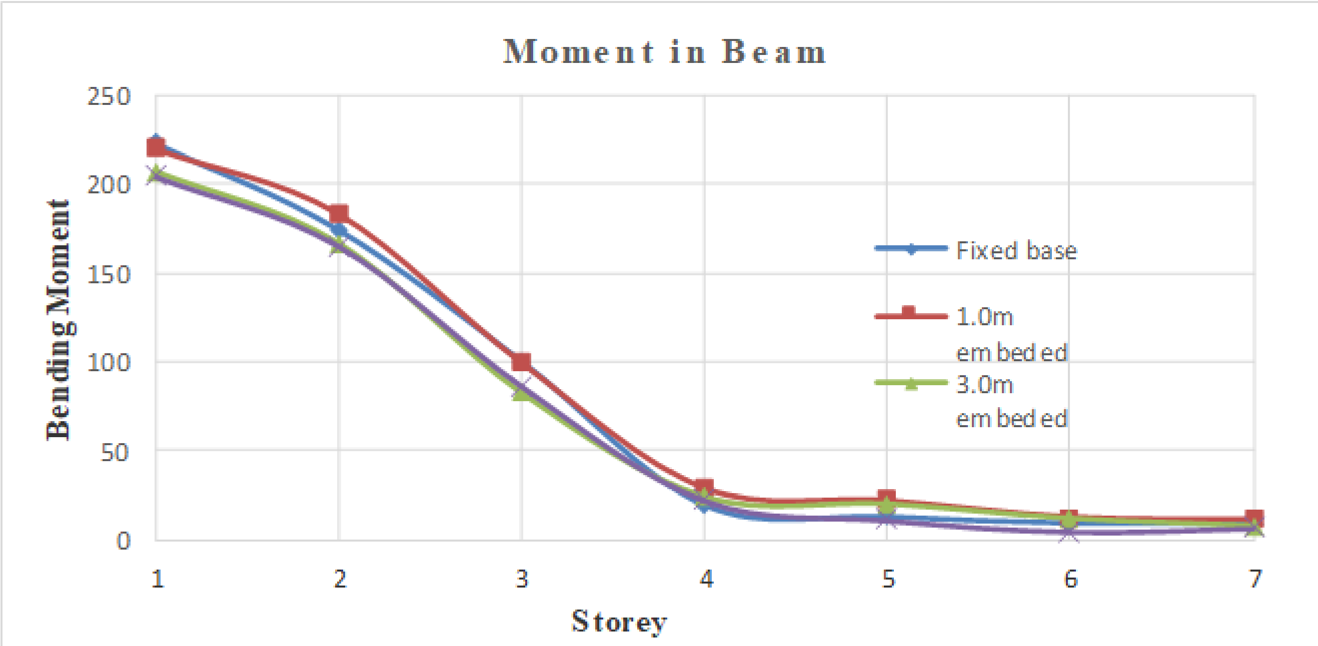

Figure 3

Moment in Beam for Fixed and Flexible Base Structure of building in soil- A

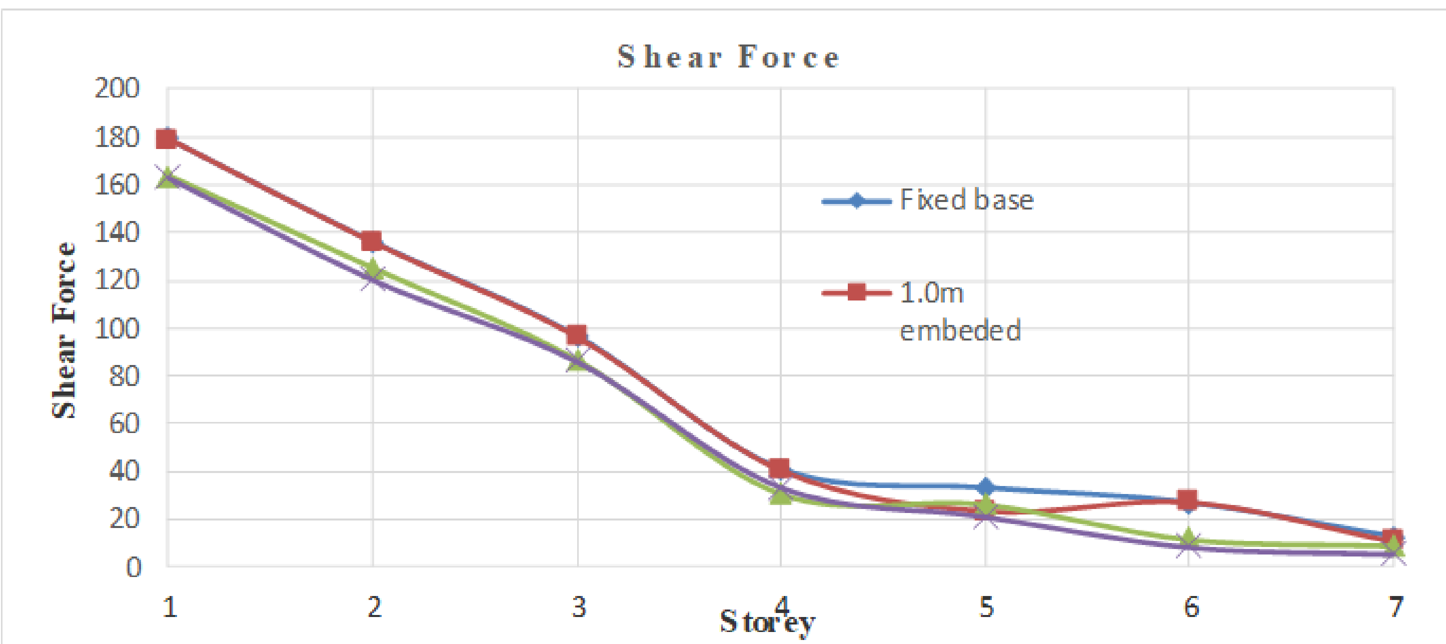

Figure 4

Shear in column for Fixed and Flexible Base Structure of building in soil-A

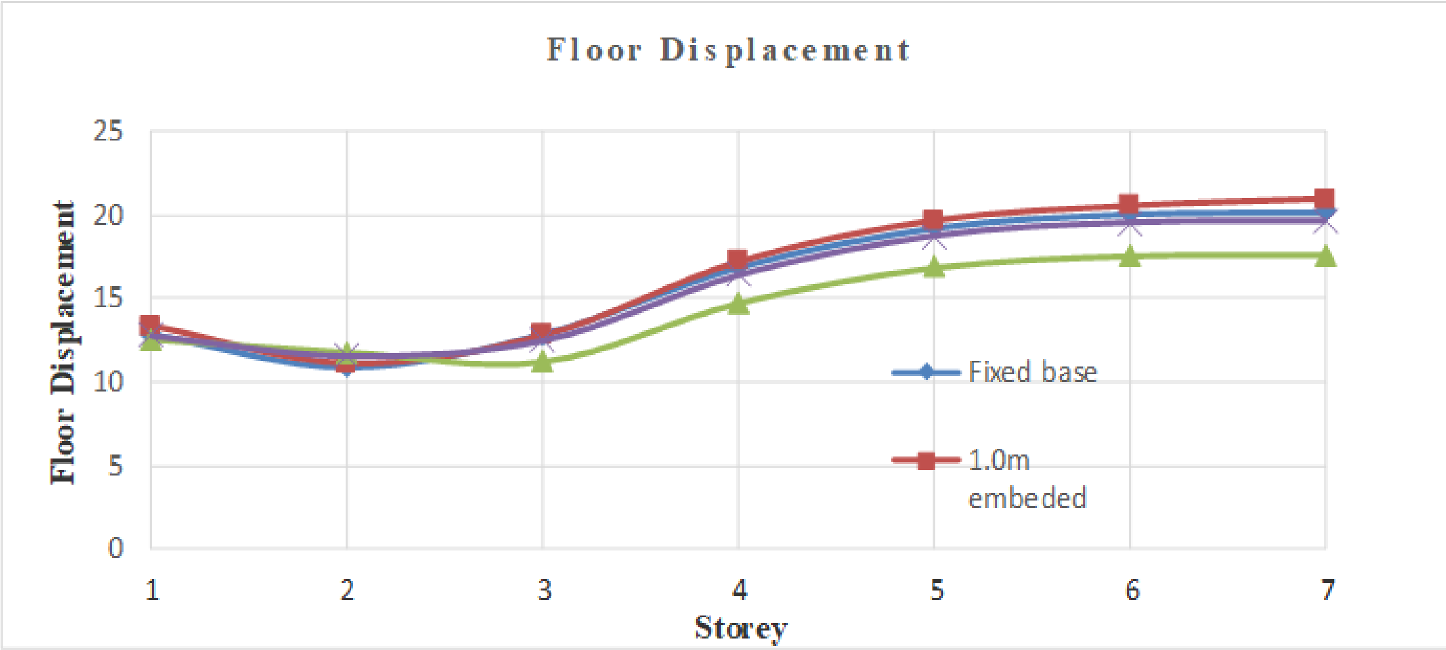

Figure 5

Floor Displacement for Fixed and Flexible Base Structure in soil-A.

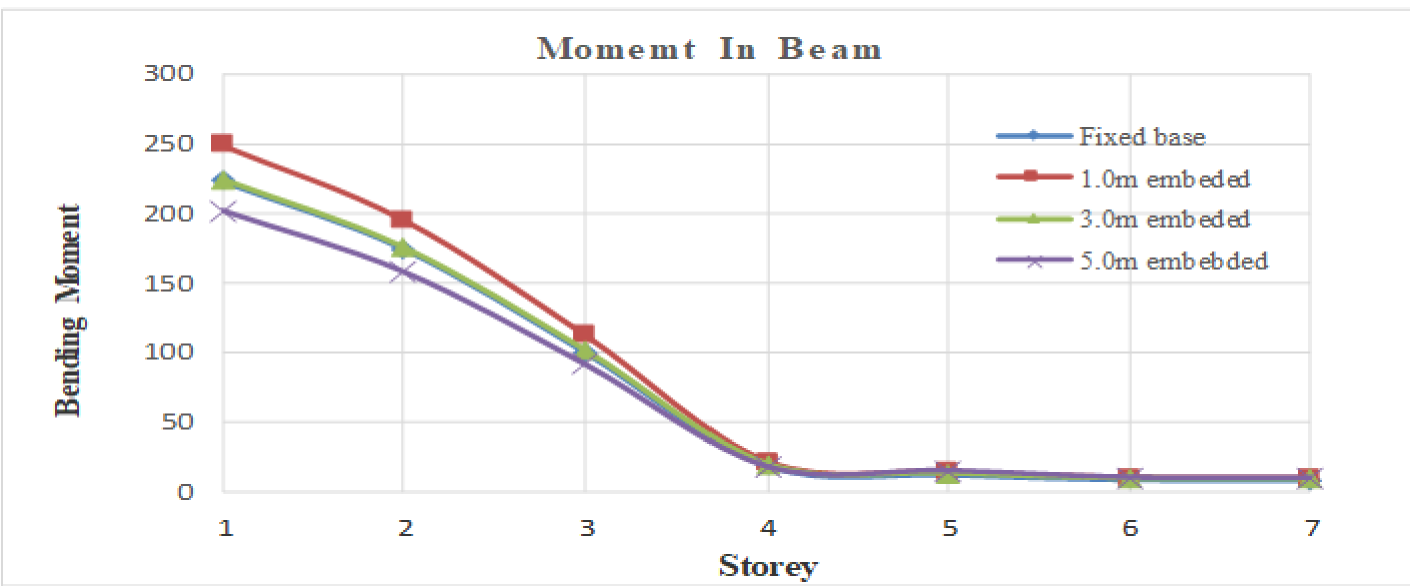

Figure 6

Moment in Column for Fixed and Flexible Base Structure of building in soil –C

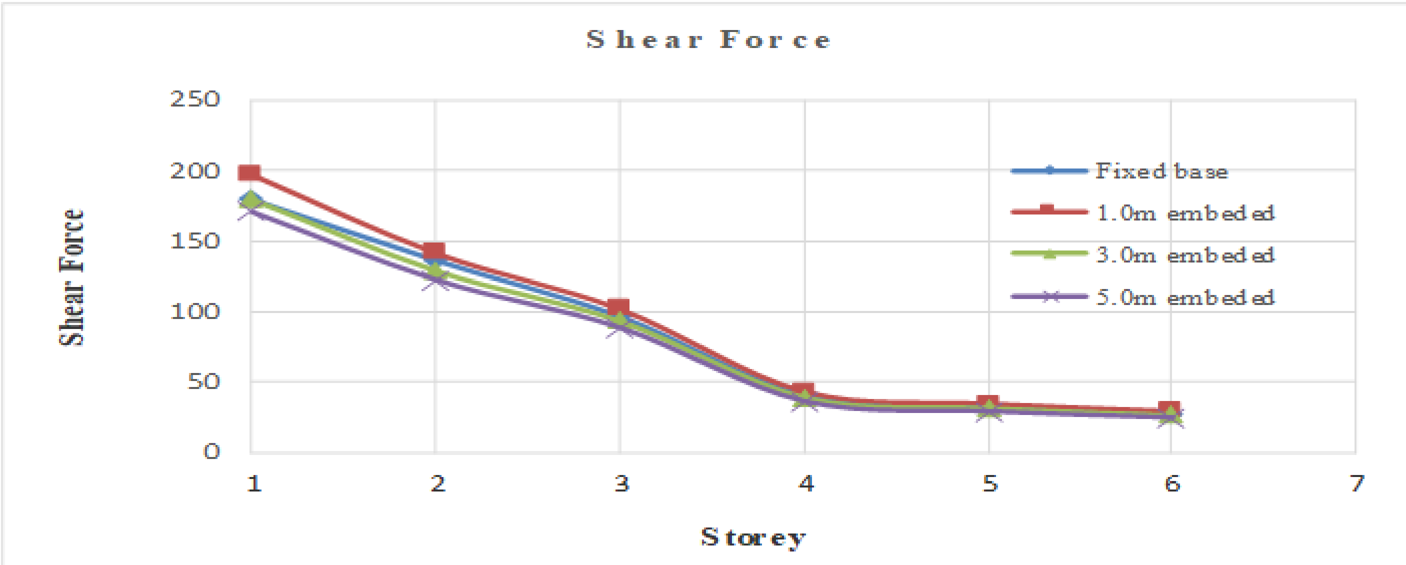

Figure 7

Moment in Beam for Fixed and Flexible Base Structure of building in soil-C

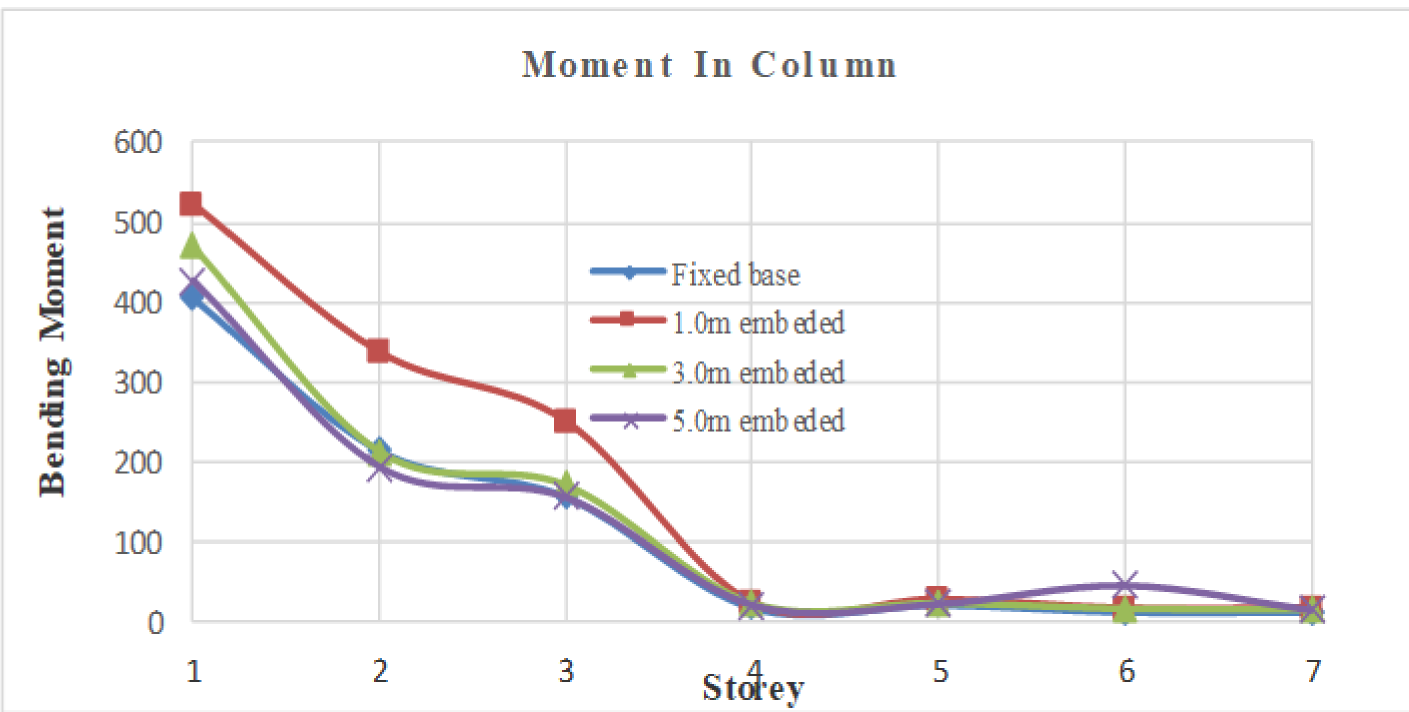

Figure 8

Shear in column for Fixed and Flexible Base Structure of building in soil-C.

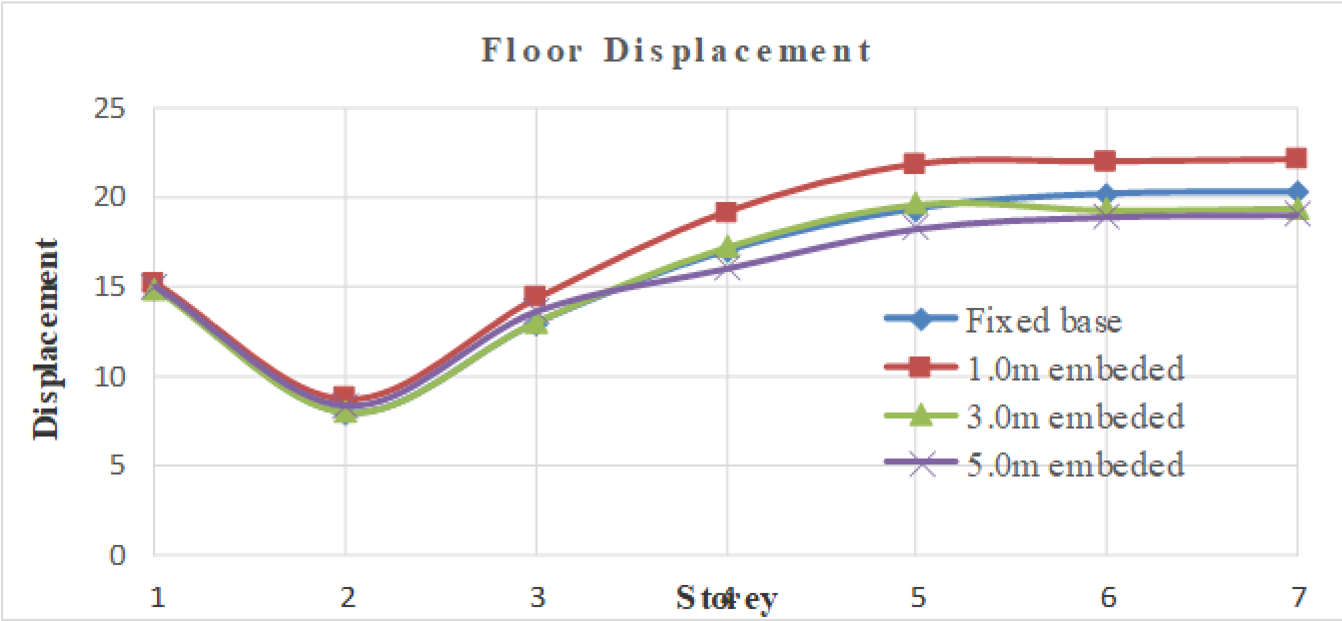

Figure 9

Floor Displacement for Fixed and Flexible Base Structure in soil-C.