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Seismic Response of RC Frame Building Considering Soil Structure Interaction

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Abstract

Foundation is a load transferring part of structure to soil. Recent trends have made replacement of conventional practice of isolated and eccentric footing with Mat foundation. Necessity to choose Mat foundation over conventional isolated footing is when the bearing capacity of soil is considerably low.However,consideration of properties of soil in contact with the foundation has not been applied in detail practice,which is also called Soil structure interaction (SSI).Literatures have revelaed that incorporating soil structure interaction (SSI) will significantly affects the performance of structures.Our study have used Winkler's method to model the foundation soil as spring.Moreover,three different buildings of five, seven and nine storeys were modeled using finite element method to incorporate the soil structure interaction effects.Performance parameter to measure the performance of the structures was done using Roof displacement.This paper reports the change in natural time period, roof displacement and base shear due to consideration of SSI and concludes with the urge of consideration of SSI in structurla analysis and design.

Keywords

Soil Structure Interaction (SSI), Mat foundation, Winkler's method, Spring Method, Roof Displacement, Natural time period, Base shear

1. Introduction

Urbanization in rapid pace and deficiency of land have encountered the construction of multistory buildings.In these buildings, the superstructure consists of moment resisting frame,shear walls,core walls and combination of these elements.Dominant footings in these buildings are Isolated and Eccentric footing where property line construction is unavoidable.These imperfect design practice has been exposed by recent Gorkha Earthquake in which valley suffered massive structural destruction.The probable solution for such condition can be use of combines footing, strap footing or Trapezoidal footing, however there is no any strict follow of suggested pattern.Our study focuses on soil of low bearing capacity where structural engineers have recommended mat foundation as a best solution.Along that condition,mat foundation can be used when there is a need of increasing the ultimate bearing capacity which can be obtained by increasing in width of the foundation,bringing deeper soil layers in effective zone, equalizes the differential settlement and bridges between the cavities.In addition ,mat foundation can be used when heavy loads coming from superstructure and individual footing covers more than 50% of floor area due to small allowable pressure of soil and buildings where basement is to be provided below ground water table.Mat foundation has ensured the quality of structures in stability and functionality compared to isolated and eccentric footing. However,there is a gap to effectiveness of Mat foundation unless we considered the behavior of soil and structure in response to each other which is termed as soil structure interaction (SSI). Moreover, it can be defined as a collection of phenomena in the response of structures caused by the flexibility of the foundation soils, as well as in the response of soils caused by the presence of structure, the foundation, and the geologic media underlying and surrounding the foundation, to a specified free-field ground motion. The term free-field refers to motions that are not affected by structural Vibrations or the Scattering of waves at, and around, the foundation.

Soil structure interaction questioned the traditional method which is basically a design focused on superstructure strength and underestimate the importance of sub-structure and soil properties.Moreover, importance of SSI is reflected due to two major reasons,since flexibility of soil reduces the overall stiffness of the structure and increased the natural period of the system which alters the seismic response of any structure considerably and soil medium imparts damping due to its inherent characteristics.

Various researches are found interested in this research,[1] has made study of soil spring and damping constant which were used to represent soil structure interaction and determine the width of the linear soil finite element model,[2] has conducted thesis work titled"Analytical modeling for soil-structure interaction based on the direct method" incorporating SSI in the dynamic time history analysis and came with result that value of base shear is affected,[3]had added concluded that the design forces in a structure can only be accurately estimated after considering the influence of static as well as dynamic soil-structure interaction,[4] conducted research on "Soil Structure Interaction Analysis on a RC Building with Raft foundation under Clayey Soil" and summarized that the response of the tall building founded on clayey soil has significant increase compared to conventional approach of assuming fixed base. Similarly, [5] has conducted thesis work titled "Soil-pile-structure interaction effects on High-rise Building under Seismic Shaking" and came with conclusion that soil structure consideration increases the time period of the structure whereas displacement, overturning moment and base shear decreases which are based on Winkler approach.Recently [6] has conducted thesis work titled "Comparison Between Dynamic Response of RC Building with Various Foundation Types" considering SSI for different condition of soil for Combined Footing, Strap Footing & Eccentric Isolated Footing in which eccentric isolated foundation shows poor performance with high roof Displacement than other foundation types and gets more critical with increase in soil flexibility. Our study tries to findout the deficiency of SSI effects under the usage of mat foundation which has been neglected.Study incorporates three different soil type namely Hard, Medium and Soft soil.Winkler Model has been used to study the properties of soils.The idea of the Winkler foundation model is to idealize the soil as a series of springs which displaces due to the load acting upon it. In another hand, structural modeling has been done with Finite element approach. Primary indicator for evaluating the performance of the structure is Roof displacement.

Our study finds out that natural time period of structure increases due to consideration of SSI effect where Natural time period is primary parameter that relates to lateral response of framed structures. Moreover,increment in base shear has been found out which is due to increase in soil flexibility. Roof displacement is also observed to be increasing due to incorporation of SSI. Significance of our study is to implementation of these findings during design of structure.

2. Methodology

A conceptual framework for the detailed analysis of this study is shown in Figure 1as below:

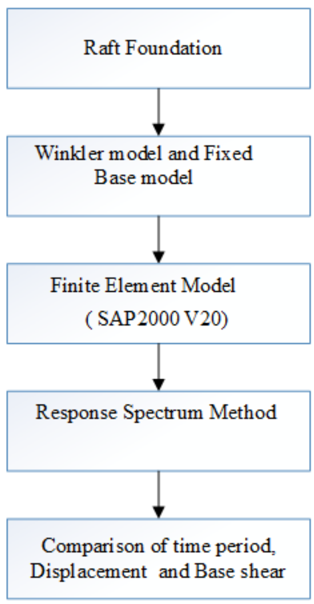

Figure 1: Flowchart for Methodology

2.1 Approaches to model the soil

In a number of consulted literature about soil models, there are two main approaches to model the soil beneath a foundation, these models are known as the Winkler and the Continuum model.

2.1.1 Winkler Model

The idea of the Winkler foundation model is to idealize the soil as a series of springs which displace due to the load acting upon it. Method describes soil according to the linear stress-strain behavior and uses only one parameter (the modulus of sub-grade reaction, better known as the "K" parameter) to represent the soil.Soil medium is represented by a number of identical but mutually independent, closely spaced, discrete, linearly elastic springs. According to the idealization, deformation of foundation is due to confined loaded region only.
Idealization of Winkler model is shown in Figure 2 below:

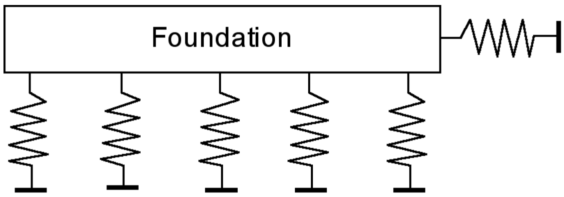

Figure 2: Winkler Model

2.1.2 Idealization by Discrete Springs

Effect of SSI is considered by equivalent springs with six degrees of freedom (DOF) as shown in Figure 2. The stiffness along these six Degree of Freedom(DOF) is determined as per Gazetas 1991 which is shown in Figure3 and formula for these stiffness calculate as shown in Table1

Table 1: Spring Stiffness Formulae (Gazetas 1991)

Degrees of freedom	Stiffness of equivalent soil spring
Vertical	[2GL/(1-ν)](0.73+1.54χ0.75) with χ = Ab/4L2
Horizontal (lateral direction)	[2GL/(2-ν)](2+2.50χ0.85) with χ = Ab/4L2
Horizontal (longitudinal direction)	[2GL/(2-ν)](2+2.50χ0.85)-[0.2/(0.75-ν)] GL[1-(B/L)] with χ = Ab/4L2
Rocking (about longitudinal)	[G/(1-ν)]Ibx0.75(L/B)0.25[2.4+0.5(B/L)]
Rocking (about lateral)	[G/(1-ν)]Iby0.75(L/B)0.15
Torsion	3.5G Ibz0.75(B/L)0.4(Ibz/B4)0.2

Where, Ab=Area of foundation considered, B and L =Half-width and Half-Length of rectangular foundation, Ibx, Iby, Ibz = Moment of Inertia of foundation area with respect to longitudinal, lateral and vertical axes respectively.

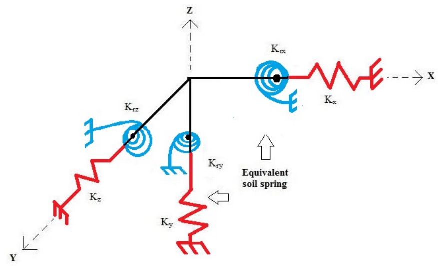

Figure 3: Equivalent Spring Stiffness Along six DOF(Gazetas 1991)

where,Ky, Kz =Stiffness of equivalent soil springs along the translation degree of freedom along X, Y and Z-axes. Krx, Kry, Krz = Stiffness of equivalent rotational soil springs along the rotational degree of freedom along X, Y and Z-axes.

2.2 Finite Element Model

The Finite Element Model (FEM) of Building with different support condition is shown in figure below. The modeling is made in SAP2000 V20 software. The beam and column are modeled as line elements, slabs as thin shells and foundation is modeled as a solid elements with soil idealized as springs at bottom of the foundation. Three different buildings were considered in analysis namely five storey ,seven storey and nine storey .Their properties are shown in Table2,Table3 Table4,Table5.

Table 2: Description of 5 storey Building

Comp.	Description	Data (m)
Frame	Number of storey	5
	Number of bays in X direction	3
	Number of bays in Y direction	3
	Storey height (m)	3
	Bay width in X direction (m)	4
	Bay width in Y direction (m)	4
	Size of beam (m)	0.35x0.23
	Size of column (m)	0.35x0.35
	Thickness of slab (m)	0.125
Foundation	length of mat footing(m)	14
	width of mat footing (m)	14
	Thickness of mat (m)	0.5

Table 3: Description of Seven Storey Building

Component	Description	Data (m)
Frame	Number of storey	7
	Number of bays in X direction	3
	Number of bays in Y direction	3
	Storey height (m)	3
	Bay width in X direction (m)	4
	Bay width in Y direction (m)	4
	Size of beam (m)	0.45x0.3
	Size of column (m)	0.45x0.45
	Thickness of slab (m)	0.125
Foundation	length of mat footing(m)	18
	width of mat footing (m)	18
	Thickness of mat (m)	0.6

Table 4: Description of Nine Storey Building

Comp.	Description	Data (m)
Frame	Number of storey	9
	Number of bays in X direction	3
	Number of bays in Y direction	3
	Storey height (m)	3
	Bay width in X direction (m)	4
	Bay width in Y direction (m)	4
	Size of beam (m)	0.45x0.3
	Size of column (m)	0.5x0.5
	Thickness of slab (m)	0.125
Foundation	length of mat footing(m)	19
	width of mat footing (m)	19
	Thickness of mat (m)	0.75

Table 5: Material Properties of the Building

SN	Material Properties	Value
1	Grade of concrete for all sturctural elements	M20
2	Modulus of elasticity of concrete of concrete	2230 (N/mm^2)
4	Unit Weight of concrete	25KN/m^3
5	Grade of steel for all structural elements	500N/mm^2
7	Modulus of elasticity of Steel	2x10^5 N/mm^2
8	Unit Weight of Steel	78.5 KN/m^3

Table 6: Material Properties of Footing and Soil Mass as per Bowels (Bowels,1998)

Soil Type	Modulus of Elasticity (KN/m^2)	Poisson's Ratio(μ)	Units Weight (γ) (KN/m^3)
Hard Soil	65000	0.3	18
Medium Soil	35000	0.4	16
Soft Soil	15000	0.4	16

2.3 Dynamic Analysis Using Response Spectrum Method

Response Spectrum method was used to analyze the structure for the dynamic properties of RC frame such as fundamental Time Period of Building, Base Shear and Roof Displacement.

2.4 Parametric Study

For the parametric study ,three different types of soil condition are taken. The calculation of soil springs for respective foundation and soil conditions namely soft soil, medium soil and hard soil were considered and properties for soil are tabulated in Table6.

3. Result and Discussion

Response spectrum was conducted for various models then ,roof displacement and base shear response of the structures are plotted. The following section shows the response of structures for soft soil condition.

3.1 Mat Foundation on Soft Soil of Five storey building

Finite element model of the structure with Mat foundation with five storey is shown in Figure 4 Natural time period of the model was obtained as 1.59 seconds from modal analysis. Roof displacement and base shear response is represented in Figure 11 and Figure 14 respectively. Maximum roof displacement was 84.49 mm. Likewise maximum Base shear was found to be 530.46 KN.

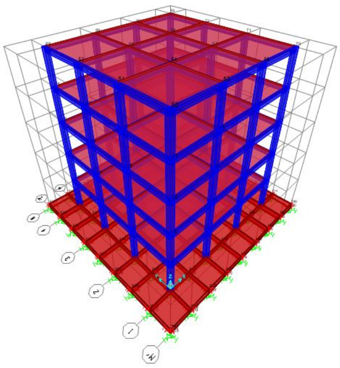

Figure 4: FEM model of Five Storey Building with Spring Support Condition

3.1.1 Mat Foundation on Soft Soil of Seven storey building

Finite element model of the structure with Mat foundation with five storey is shown in Figure5. Natural time period of the model was obtained as 1.94 seconds from modal analysis. Roof displacement and base shear response is represented in Figure11 and Figure14respectively. Maximum roof displacement was 37.35 mm. Likewise maximum Base shear was found to be 566.76 KN.

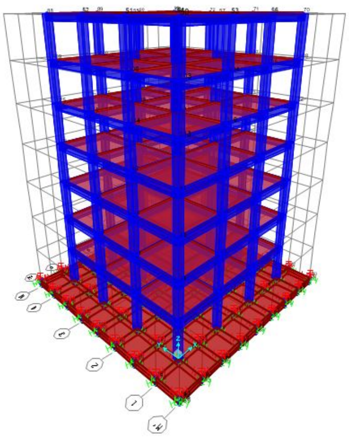

Figure 5: FEM model of Seven Storey Building with Spring Support Condition

3.1.2 Mat Foundation on Soft Soil of Nine storey building

Finite element model of the structure with Mat foundation with five storey is shown in Figure6 Natural time period of the model was obtained as 2.67 seconds from modal analysis. Roof displacement and base shear response is represented in Figure11 and Figure 14 respectively. Maximum roof displacement was 38.72 mm. Likewise maximum Base shear was found to be 561.09 KN

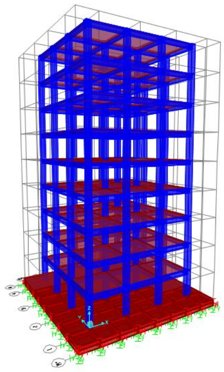

Figure 6: FEM model of Nine Story Building With Spring Based Condition

3.2 Fixed Base Condition

Finite element model of the structure with fixed base condition is shown in Figure7 . Natural time period of the model was obtained as 0.91 sec,0.89 sec ,1.07 sec from modal analysis for five,seven and Nine storey respectively..Maximum roof displacement were 20.15 mm ,20.47 and 25.13 r for five,seven and Nine storey respectively. Likewise maximum of base shear was found to be 594.59 KN,978.35 KN and 1079.60 KN for five, Seven and Nine story respectively.

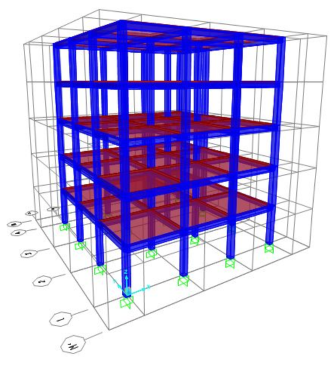

Figure 7: FEM model of Five Storey Building With Fixed Based Condition

3.3 Natural Time Period

The variation of natural time period for various types of support as well as soil condition is shown in Figure8,Figure9 and Figure 10.observation shows, with the consideration of SSI natural time period of the structure increases and more significant in soft soil.

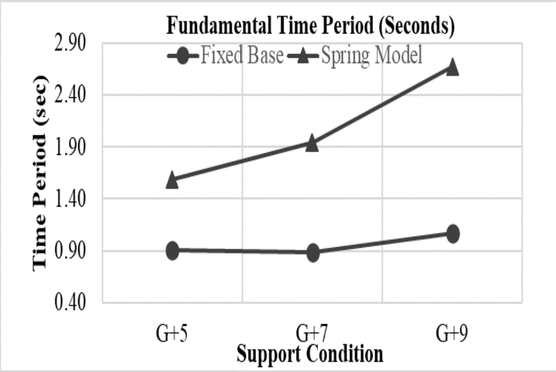

Figure 8: Variation of Fundamental Time Period For soft soil For Different storey building

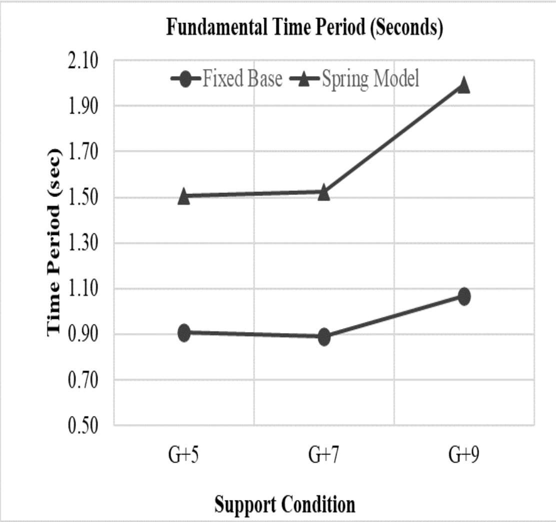

Figure 9: Variation of Fundamental Time Period For Medium soil For Different storey building

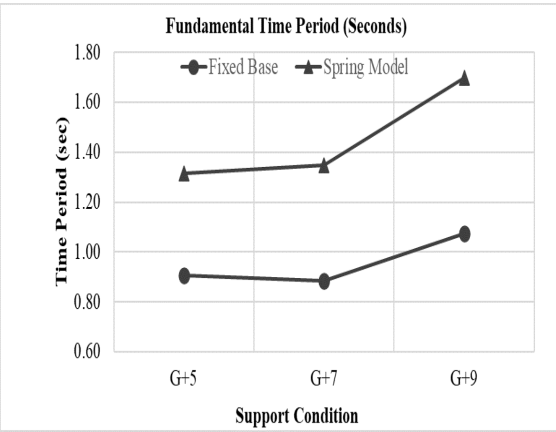

Figure 10: Variation of Fundamental Time Period For Hard soil For Different storey building

3.4 Roof Displacement

The variation of Roof Displacement for various types of support as well as soil condition is shown in Figure 11 and Figure12 and Figure13.Consideration of SSI effects has made roof displacement of the structure increased and showed positive relationship with in soil flexibility.

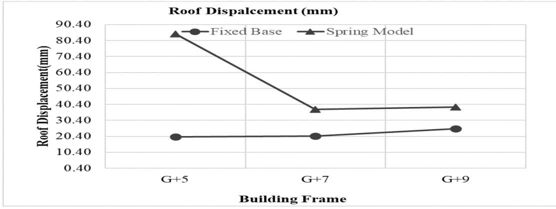

Figure 11: Variation of Roof Displacement For soft soil conditions For storey variation

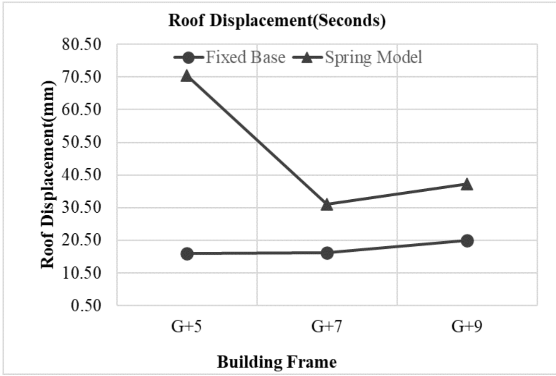

Figure 12: Variation of Roof Displacement For medium soil conditions For storey variation

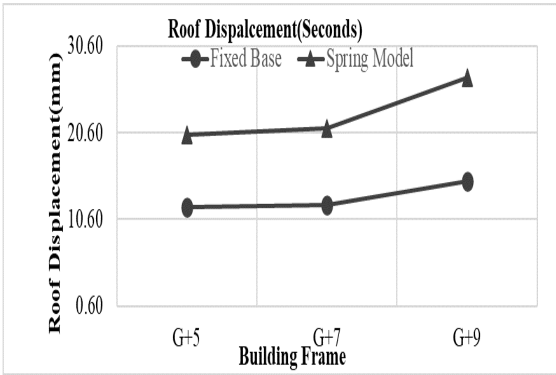

Figure 13: Variation of Roof Displacement For hard soil conditions For storey variation

3.5 Base Shear

The variation of base shear for various types of support as well as soil condition is shown in Figure14,Figure15 and Figure 16.It is observed that base shear increases in base flexibility.

4. Conclusion

In order to understand the behavior of the RC framed structure incorporating the soil flexibility, a response

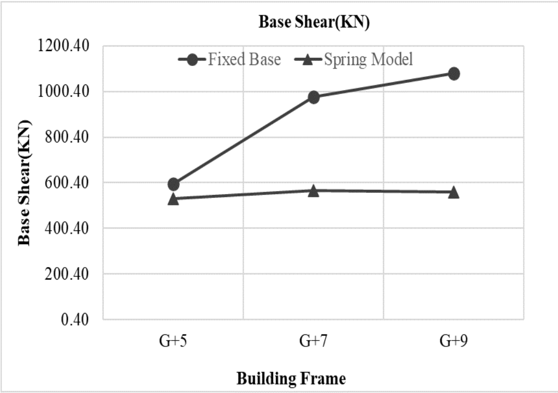

Figure 14: Variation of Base shear for soft soil conditions for storey variation

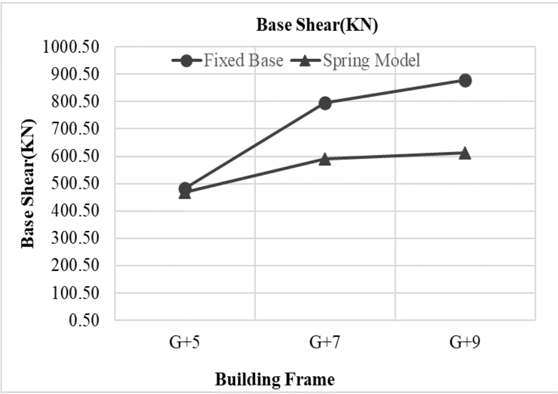

Figure 15: Variation of Base shear for medium soil conditions for storey variation

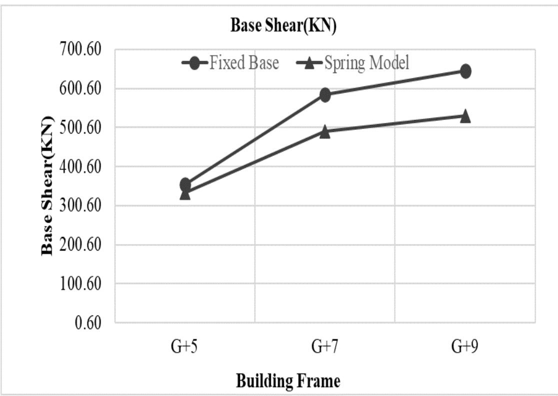

Figure 16: Variation of Base shear for Hard soil conditions for storey variation

spectrum analysis is performed. Five storey ,Seven storey and Nine storey buildings were analyzed for fixed and flexible supports in different soil conditions with evaluating parameters such as roof displacement,base shear and fundamental time period.Furthermore,during earthquake SSI effect shows significant changes in response of building. To incorporate SSI in structural analysis it has been easier with development in FEM and computer technology. This evolution in field of engineering should be exploited in fullest to better our knowledge about structural behavior so that safe construction practices are adopted.

5. Recommendation

- Our study is based upon on spring support which idealizes soil as springs however, elastic continuum method could be adopted in further study .
- Study of Nonlinear properties of soil can be carried to more in-depth view of soil properties.

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