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Seismic Response of RC Frame Buildings: Theoretical Formulation and Modeling with Soil-Structure Interaction Analysis

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Abstract:

"Seismic Response of RC Frame Buildings: Theoretical Formulation and Modeling with Soil-Structure Interaction Analysis," offers a comprehensive exploration of the seismic response of reinforced concrete (RC) framed structures, with particular emphasis on soil flexibility. Through a meticulous response spectrum analysis, the study delves into the influence of soil flexibility on buildings of varying heights, ranging from five to nine storeys, considering both fixed and flexible support conditions across diverse soil types.

The research draws the following significant conclusions:

Significance of Soil-Structure Interaction (SSI): Incorporating soil-structure interaction (SSI) into the analysis leads to a noteworthy extension of the natural time period of the structure. This parameter stands as a linchpin in grasping the lateral response of framed structures, underlining its pivotal role in the precision of seismic design calculations.

Soil Flexibility and Amplified Base Shear: Enhanced soil flexibility is found to correlate with a proportional increase in base shear. This phenomenon is most pronounced in soft soil conditions, where base shear experiences substantial escalation, particularly in taller buildings.

Roof Displacement as a Performance Indicator: Roof displacement, a crucial indicator of structural performance, exhibits an upward trajectory owing to the cumulative effects of SSI. Notably, soft soils manifest higher roof displacements, with these variations becoming more pronounced as the building's height increases.

The insights garnered from this analysis underscore the profound influence of SSI on a building's seismic response. Furthermore, the study highlights that advancements in finite element methods (FEM) and computer technology have significantly facilitated the integration of SSI into structural analysis. Therefore, it is imperative to harness these advancements fully to enhance our comprehension of structural behavior and to promote the adoption of secure construction practices in seismic-prone regions.

1. INTRODUCTION:

The Flexibility of soil reduces the overall stiffness of the structure and increased the natural period of the system. Considerable change in spectral acceleration with natural period is observed from the shape of the response spectrum curve. Thus, the change in the natural period may alter the seismic response of any structure considerably. In addition to this, soil medium imparts damping due to its inherent characteristics. Moreover, the relationship between the periods of vibration of structure and that of supporting soil is important regarding the Seismic response of the structure. The soil interaction should be accounted for the analysis of dynamic behavior of structure and to predict the overall structural response.

When a structure is subjected to an earthquake excitation, it interacts with the foundation and the soil, and thus change the motion of the ground. Soil-Structure interaction broadly can be divided into two phenomena: a) Kinematic interaction and b) inertial interaction. Earthquake ground motion causes soil displacement known as free-field motion. However, the foundation embedded into the soil will not follow the free field motion. This inability of the foundation to match the free field motion causes the kinematics interaction. On the other hand, the mass of the superstructure transmits the inertial force to the soil, causing further deformation in the soil, which is termed as inertial interaction.

Due to rapid urbanization and scarcity of the land one is Compelled to construct the structure on available land areas. Property line Construction is inevitable in urban areas such as Kathmandu Valley. Due to this reason condition of eccentric footing arises. The remedy for such condition is use of combines footing, strap footing or Trapezoidal footing. Although mandatory rules are there for requirement of these types of foundation, there is still presence of false practice of using eccentric condition of foundation. This condition may cause change in performance of the superstructure. Past earthquake has shown poor performance of buildings under the circumstances of improper foundation design. Therefore, to account the effect of foundation condition in seismic performance of building dynamic characteristics of structure should be analyzed considering the interaction between soil, foundation and soil.

2. LITERATURE REVIEW

Sachindra Prasad Rijal (2017) has conducted thesis work titled" Performance of Reinforced Concrete Building Considering Infill Walls and Soil structure interaction Effects". His work confirmed that the variation of the fundamental time period of structure under the consideration of SSI. He also added into conclusion that the lateral storey displacement and the story drift underestimates the values in the case of consideration of SSI effect.

Sujal Maharjan (2016) has conducted thesis work titled" Impact of Soil Structure Interaction on the response of structures with underground stories". This work concluded that consideration of all the basement is more conservative approach than clipped base method and SSI gives much closer result to actual demand.

Singh and Mala (2016) used soil model with continuum approach. Story shear was observed to decrease at the upper and middle floors and increase in bottom stories when soil structure interaction was considered.

Roopa et al. (M. Roopa, H.G. Naikar, D.S. Prakash, 2015) conducted research on "Soil Structure Interaction Analysis on a RC Building with Raft foundation under Clayey Soil". Their research work concluded that response of the tall building founded on clayey soil has significant increase compared to conventional approach of assuming fixed base.

Thusoo, Modi, Kumar, & Madahar, 2015) concluded that the deflection in cases, where the soil is hard or medium, is significantly less as compared to the buildings on soft soils. Along with this, for moderately stiff soil, as the size of the building increases, deflection response also increases significant. The spectral acceleration response pattern changes drastically as stiffness of base soil decreases. And confirms that time period of all the response increases while considering Soil-Structure Interaction effects.

(M.G. Kalyasnshetti, S.A. Halkude, Y.C. Mhamane, 2015) conducted research on "Seismic Response of RC Building Frames with Strap Foooting Considering Soil Structure Interaction" and drew a conclusion that SSI effects can be controlled by providing strap beams so that base stiffness increases which ensures the stability and performance of structure

Shrabony Adhikary et al. (Adhikary, paul, & singh, 2014) has done research on "Modelling of Soil-Foundation-Structure System" and they concluded that the flexibility of soil reduces the overall stiffness of the structure and increases the natural period of the system. They used shape of the response spectrum curve where considerable change in spectral acceleration with natural period is observed.

3. THEORETICAL FORMULATION AND MODELING

3.1 Approaches to model the soil

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

3.1.1 Structure on rigid supports

In general, the earthquake response analysis of structures, soil structure interaction is ignored and the supports of the structure are assumed to move directly in accordance with the prescribed earthquake motion. At first, all supports are assumed to be act as a single rigid block and only one directional movement of structure is considered. In this case, the column bases are restrained against all degree of freedom below ground level as shown in figure-2. The superstructure is analyzed without considering the foundation and supporting soil medium and that the motion applied to the building's base is a previously recorded earthquake acceleration history. The response of an N-story building with plan symmetric about two orthogonal axes to earthquake ground motion along an axis of symmetry can be computed as a function of time, which is summarized step by step form.

l. Define the ground acceleration $\ddot{U}g(t)$ numerically at every time step Δt.

2. Define the structural properties.

a. Determine the mass matrix m and lateral stiffness k.

b. Estimate the modal damping ratio ζ_n.

3.Determine the natural frequencies ω_n and natural modes ϕ_n of vibration.

4.Determine the modal components S_n of the effective earthquake force distribution.

5.Compute the response contribution of the n^{th} mode by the following steps, which are repeated for all modes, n = l, 2,.., N:

a. Perform static analysis of the building subjected to lateral forces Sn to determine the modal static response.

b. Determine the deformation response $D_n(t)$ and pseudo acceleration response $A_n(t)$ of the nth mode SDF system to $\ddot{U}_g(t)$, using numerical methods (Duhamel Integral).

6. Combine the modal contribution to determine the total response.

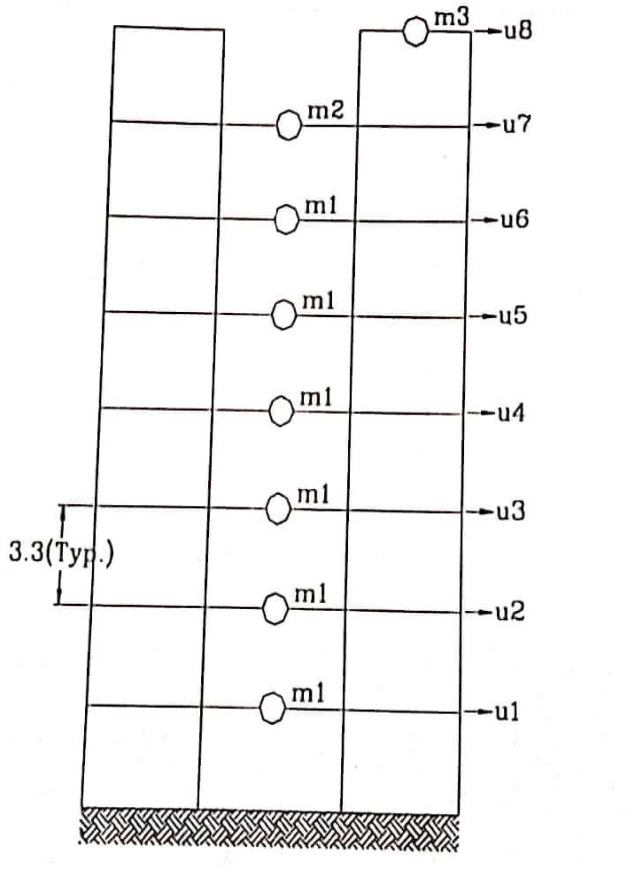

Figure 3-1:Fixed Based Support

3.1.2 STRUCTURE ON SPRING MODEL

In this case the foundation material is far from rigid and that its deformations may contribute appreciably to the earthquake response, especially if the structure are very stiff. Thus, in formulating this analysis, this foundation flexibility is modeled by interposing a body of soil between the structures and rigid soil. In the analysis of building of the type shown in figure - 3, the flexible soil layer is modeled by a linear elastic spring and dashpot added at the base of the structure for vibration control. The rigid base supports this spring and dashpot. Through which previously recorded earthquake acceleration history is applied to the spring base.

3.2 Idealization by Discrete Springs

Effect of SSI is considered by equivalent springs with six degrees of freedom (DOF) as shown in fig.2. The stiffness along these six DOF is determined as per George Gazetas and is shown in Table 1.

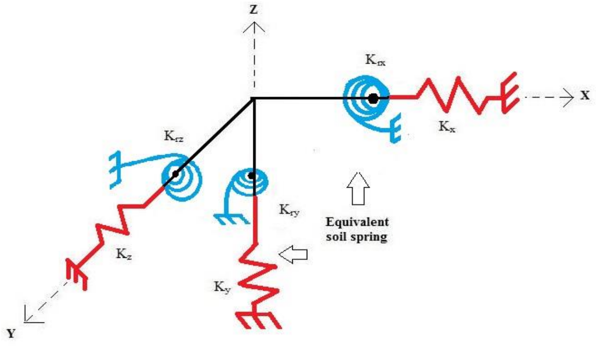

Figure **Error! No text of specified style in document.**-2:Equivalent Spring Stiffness Along six DOF (Gazetas 1991)

K_y, K_z =Stiffness of equivalent soil springs along the translation degree of freedom along X, Y and Z-axes. K_{rx}, K_{ry}, K_{rz} = Stiffness of equivalent rotational soil springs along the rotational degree of freedom along X, Y and Z-axes.

4. ANALYSIS AND DISCUSSION

The RC framed buildings are analyzed for three different soil conditions, soft, medium and hard. For each soil type, three different structures modeling; with fixed support, spring support are done. There are all together twenty-seven structural model with different support condition and different soil condition which are analyzed by linear static analysis and Response Spectrum Analysis based on IS response Spectra. For the comparison of the performances, the outcome obtained from Response Spectrum Analysis has been adopted.

4.1 Analysis of Building on Soft, Medium and Hard Soil

4.1.1 Comparison of Fundamental Period of Buildings

The time period of Vibration in first mode is known as fundamental time period of the structure. The variation in the fundamental periods of five storey, seven storey and Nine storey building for Fixed base and Flexible base and combined representation for all support condition for soft, medium and hard soil are shown in figure below. The building with flexible support condition has higher time period than that of building with fixed support.

Table 4-1: Fundamental Time period of Buildings

Support Condition	Fundamental Time Period (sec)								
	Five Storey			Seven Storey			Nine Storey		
	Soft	Medium	Hard	Soft	Medium	Hard	Soft	Medium	Hard
Fixed Base	0.91	0.91	0.91	0.89	0.89	0.89	1.07	1.07	1.07
Spring Model	1.59	1.51	1.32	1.95	1.52	1.35	2.68	2.00	1.70

5 RESULT VALIDATION

For Validation of the result firstly a sample work was carried out according to research paper presented by Halkunde et.al.(2014). A five storey building was modelled as per the properties provided by the author in the research paper. Calculation and analysis procedures were carried out as explained in the research paper. the calculation of soil springs for the five storey building is tabulated in table 5-4 and 5-5. Response spectrum analysis was carried out to access the performance of the building and hence the results obtained were compared with the results in research paper.

Following table shows the calculation of soil springs for mat foundation for five storey structure. the values of the spring obtained were equal to the values provided in research.

Table 5-1 Soil properties Calculation for Mat foundation

Required Parameter	Soil Parameter	Footing Type
		Mat Foundation
E	Modulus of Elasticity (E) (KN/m^2)	15000
v	Poisson's Ratio (v)	0.4
G	E/2(1+v) (KN/m2)	5357.1429
γ	Unit weight (KN/m^3)	16
B	Half width of rectangular foundation (m)	7
L	Half length of rectangular foundation (m)	7
A_b	Area of foundation=L* x B* (m^2)	196
χ	$A_b/4L^2$	1
I_{bx}	MOI	3201.3333
I_{by}	MOI	3201.3333
I_{bz}	MOI	228.6667

Table 5-2 Soil Spring Calculation for Mat Foundation

Degree of Freedom	Soil Spring Stiffnes s (KN/m)
Vertical (K_z)	283750
Horizontal (Lateral Direction) (K_y)	210938
Horizontal (Longitudinal Direction) (K_x)	210938
Rocking (About Longitudinal) (K_{rx})	110199 13
Rocking (About Lateral) (K_{ry})	113999 10
Torsion (τ)	688915

The FEM Model for Five Storey Building With Mat Foundation is shown below.

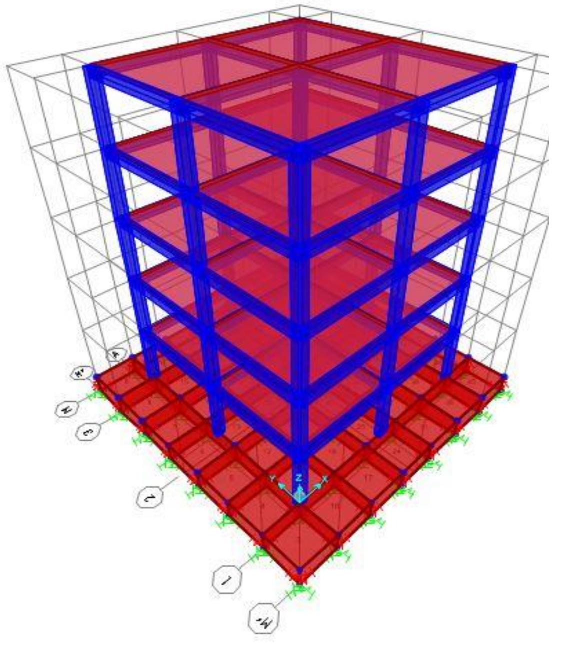

Figure 5-1 FEM model for Five storey building with mat foundation

The results obtained after modal analysis and response spectrum analysis and comparison with results from research paper is shown in table below.

Table 5-3 Comparison Table Five Storey Building for Mat Foundation

	Time Period (sec)	Roof Displacement(mm)
From Research Paper	1.36	20
From Modelling	1.34	24.5

Here a small difference in result is obtained in case of time period as well as roof displacement. The difference may be due to the difference in the loads applied in the structure between the research paper and model. Since a small difference in result is obtained, therefore the procedure has been applied in my research work for analyzing the performance of the various building considering SSI.

Halkunde et. al . also has done study considering a two storey building with different soil condition. the variation of roof displacement for 2 bay two storey building is shown in following table along with comparison with two storey and its corresponding roof displacement for mat foundation form my research work. Hence roof displacement increases as the flexibility in the soil increases.

Table 5-4: Comparison of Roof Displacement of 5 storey Building with Halkude et.al

Soil Type	Soft	Medium	Hard
Haklkude et al. (2014)	7	5.5	4.9
From My Research (Mat Foundation)	84.49	71.11	20.32

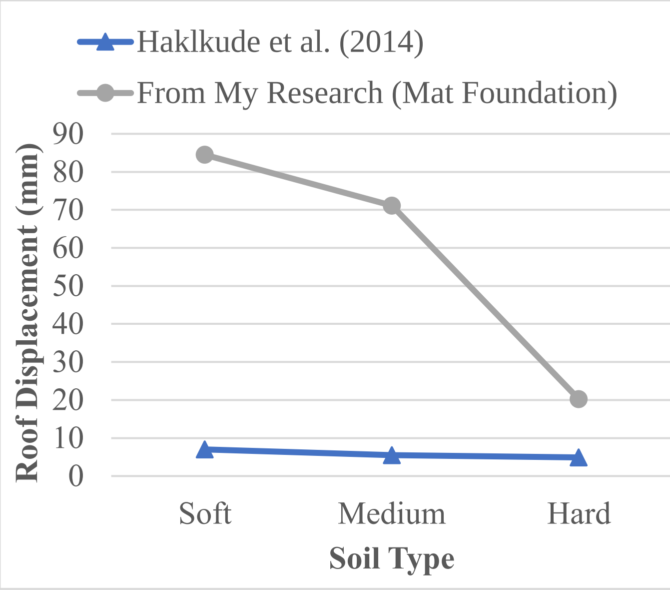

Fig Comparison of Roof Displacement of Two Storey Building with Halkude et. al

From above figure we can see similar decrement pattern in roof displacement as flexibility of soil increases from soft soil to hard soil. The values of roof displacement are different building configuration. Response spectrum analysis is carried out in my research as well as by Halkunde et. al.

6. CONCLUSION:

The seismic response of RC framed structures with consideration for soil flexibility was thoroughly investigated through response spectrum analysis in this study. The analysis focused on assessing the influence of soil flexibility on five, seven, and nine-storey buildings with both fixed and flexible support conditions in various soil types. The following conclusions were drawn from this study:

Incorporating soil-structure interaction (SSI) into the analysis leads to an increase in the natural time period of the structure. This parameter is essential for understanding the lateral response of framed structures, and its accurate assessment is crucial for seismic design calculations.

Increased soil flexibility results in a corresponding increase in base shear. This effect is most pronounced in soft soils, where base shear increases significantly, especially with taller buildings.

Roof displacement, considered a primary indicator of structural performance, also increases due to the combination of SSI. Soft soils exhibit higher roof displacements, with variations becoming more prominent as the building's height increases.

The findings from this analysis underscore the significant impact of SSI on a building's seismic response. Incorporating SSI into structural analysis has been made more accessible through advancements in finite element methods (FEM) and computer technology. It is essential to fully utilize these advancements to enhance our understanding of structural behavior and ensure the adoption of safe construction practices.

7. RECOMMENDATIONS: Based on the study's findings and the complexities of soil-structure interaction, the following recommendations are made for further research and development in this area:

While this study employed a simplified spring support model for soil-structure interaction, future studies should consider using a more realistic approach, such as the elastic continuum method, to provide more precise outcomes.

Expanded studies should explore quantitative comparisons of various foundation types and their impact on structural members, sizes, construction costs, and overall project economy.

Future research should delve into the incorporation of nonlinear soil properties and kinematic interaction in soil-structure interaction studies to provide a more comprehensive understanding of real-world conditions.

The scope of research can be extended to include other types of structures, such as steel and masonry buildings, incorporating soil-structure interaction in their design and analysis.

These recommendations aim to advance the knowledge and practice of soil-structure interaction analysis, ensuring safer and more resilient structural designs in seismic-prone regions.

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