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The Behaviour of Building Frames on Raft Foundation using Dynamic Analysis

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Abstract:

When designing building frames for seismic reasons, the effect of soil flexibility is typically disregarded, and the design is executed using the outcomes of dynamic analysis with a fixed base condition. Because the overall lateral stiffness of the structure decreases as a result of soil flexibility, the lateral natural period lengthens. The building frames situated on the Raft foundation may experience a significant change in seismic response due to this extension of the lateral natural period (T). Therefore, it is imperative to consider the soil's flexibility, also known as soil structure interaction, when doing analysis on the foundation's supporting layer.

This paper examines how asymmetric building frames with raft footings behave dynamically when subjected to seismic forces that involve soil-structure interaction. The analysis is performed with SAP 2000*V21 FEM software. The structure is idealized as a three-dimensional space frame, with slabs modeled as a thin shell with four noded plate elements and six degrees of freedom at each node, and beams and columns modeled as two noded line elements. The soil is represented as equivalent springs with one (Winkler) and six (Modified Winkler) degrees of freedom; the stiffness of these springs varies depending on the type of soil and is determined by its dynamic shear modulus and poissons ratio. The Modified Winkler and Winkler raft foundations are modeled as thin shells with four noded plate elements, each with six degrees of freedom, and are criticized so that the element aspect ratios are equal to one.

To assess the impact of soil structure interaction on building frames, the response is compared for a range of building frames with and without consideration of soil flexibility in terms of fundamental Natural Period, Seismic Base Shear, and Max. Lateral Displacement. The parametric study for Zone V takes into account the influence of various parameters, including the number of bays, stories, span lengths, and soil types (i.e., soft, medium, and stiff).

It is discovered that the fundamental lateral natural period and seismic base shear of the system are significantly altered by the influence of soil flexibility on building frames. As soil stiffness decreases, the lateral natural period and seismic base shear increase as a result of soil flexibility. Additionally, it has been noted that as the number of bays increases, so do the building's base shear and lateral period. As the number of bays and stories increases, so does the maximum lateral displacement.

Key words: Soil structure interaction, Natural period, Base shear, Max. Lateral displacement, Raft footing.

1 Introduction

Any structure that is subjected to seismic force during an earthquake experiences motions within it due to the waves that reach it. The building's or structure's layout, as well as the vibrational properties of the structure, determine these motions. The structure must overcome its own inertia in order to respond to the motion, which causes an interaction between the structure and the soil. In this context, the interdependent behavior between soil and structure that controls the overall response is called interaction behaviour. Analyzing foundation and structure independently has long been standard procedure. The calculation of typical load distributions within building frames is predicated on the notion that the base of the structure is fixed and that the load is transferred by direct bearing on solid rocky strata at the base of the foundations. Without a doubt, this presumption is true in general if the superstructure is significantly more compliant or flexible than the soil layer that the foundations are built upon. On the other hand, if the opposite is true that is, if the structure is substantially stiffer than the soil medium the soil's flexibility may have a major impact on the structure's response.

A few previous studies have shown that analyzing the structure with a fixed base condition results in a lower estimation of some response quantities. The natural period of a system may increase as a result of soil flexibility, which may reduce the overall stiffness of the structural systems. Therefore, a significant change in the way building frames respond to seismic forces may result from such an increase in the lateral natural period. Therefore, the current study has been conducted to determine how different parameters affect the dynamic response of building frames resting over raft foundations and incorporating soil flexibility with that of a fixed base.2.MODELING AND ANALYSIS METHOD.

For the interaction analysis, the superstructure (3D frame), Raft foundation and soil are considered as single interactive unit and is modeled using SAP2000 V21 FEM structural analysis software package.

Superstructure of building frame is idealized as 3 dimensional space frame consisting of columns in each storey and beams and slabs at each floor level(fig. 1). Two noded line elements with six degrees of freedom at each node represent beams and columns in each storey. Flexible floor diaphragm for slab at each floor level is discretized and is modeled as thin shells with four noded plate elements having six degrees-of-freedom at each node(three translations and three rotations in their respective coordinate directions).

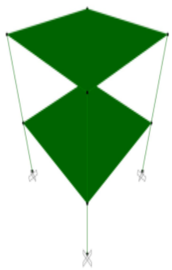

Figure 1

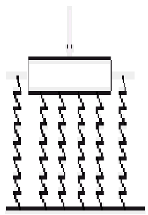

Figure 2

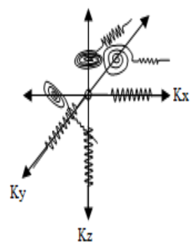

Figure 3

Raft foundation is discretized and modeled as thin shells with four noded plate elements having six degrees-of-freedom at each node.
The soil considered is sandy clay and is idealized using two types of soil models, namely, Winkler Model(WM) as per which one translational spring at each node of foundation along vertical(Z) direction is considered to simulate the effect of soil flexibility(fig.2) and Modified Winkler Model(MWM) as per which three translational and three rotational springs about three mutually perpendicular directions are considered to simulate the effect of soil flexibility (fig.3).
Any torsional effects are automatically considered in the model. The ground motions can be applied in 1, 2 or 3 directions individually or simultaneously. In the present study earthquake load is applied individually along horizontal X and Y directions.

Dynamic analyses (Response Spectrum Method) is carried out as per IS 1893-2002 (part 1) for structure modeled with fixed base(Non Interaction Analysis) and flexible base (Interaction Analysis)using SAP2000 V21.

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2 SCOPE OF THE PRESENT STUDY

2.1 *Description of Building Model with Raft Foundation*

For the present study, Two bay Two bay – one, two and four storied reinforced concrete moment resisting frame buildings are chosen (without considering stiffness of infill). The storey height of base story is 4.5m (termed Ratio of Base storey to higher stories Hr=1.5 henceforth) and is kept at 3m for all the other stories in the model. In order to introduce certain amount of unsymmetry in the structures considered, the independent spans of the 2bay 2 bay structure is taken as 6m and 3m (henceforth referred as Ratio of higher to lower span Sr=2). No parapets on the roof storey but all-round brick infill masonry wall (230 mm thick) in the intermediate stories, is considered in the structure. The building is modeled as bare frame; however masses of the walls are included. To study the effect of soil flexibility, lumped mass spring model is used. The stiffness of the springs is used to represent soil flexibility.

2.2 *Input design data for building models with raft foundations*

The material properties considered are: Young's modulus of M25 concrete, E= 25$\times$ 10^6 kN/m2,Density of Reinforced Concrete= 25 kN/m^3,Density of brick masonry= 20 kN/m^3, Dead load intensities like Floor finishes = 1.0 kN/m^2,Roof finishes= 2.0 kN/m^2,Live load intensities on Roof = 1.5 kN/m^2 and on Floor = 3.0 kN/m^2,Member properties taken are: Thickness of Slab=150mm,Column size =350 mm $\times$ 500 mm, Beam size=250 mm $\times$ 600 mm, Thickness of wall=230 mm, Earthquake live load on slab as per clause 7.3.1 and 7.3.2 of IS: 1893-2002 (Part 1) is calculated as: Roof= 0.25x1.5=0.375 KN/m^2,Floor =0.25 $\times$ 3.0 = 0.75 KN/m^2. Seismic data: Seismic Zone V, Response spectra = As per 1893(part 1)2002, Importance factor =1, ,Response reduction factor = 5.

The foundation dimensions were designed for gravity load and all its load combinations, using STAAD ETC software package, The raft with plan dimensions 11mx11m is adopted for all building models with the thickness of raft being 300mm,400mm and 500mm for Single storey,two storey and four storey building frames respectively.

2.3 *Soil Parameters Considered*

The type of soil considered is sandy clay **(Bowles, 1996)** classified as soft, medium and stiff soil based on Dynamic shear modulus(G). Properties of soil types considered in this study are Stiff(Type-I with μ=0.2 and G=30000 KN/m^2); Medium(Type-II with μ=0.25 and G=20000 KN/m^2)and Soft (Type-IIIwith - μ=0.3 and G=10000 KN/m^2).

4. CALCULATION OF STIFFNESS OF ELASTIC SPRINGS FOR RAFT FOUNDATION-SOIL MODELS.

The Raft foundation is discretized such that the aspect ratio of each element is equal to 1.0 and the soil system is idealized by one translational spring at each node for Winkler Model and six springs at each node(three translations and three rotations)for Modified Winkler Model. The area of element of footing influencing each node is considered for calculating stiffness of the spring at that node.

4.1 *Winkler Model*

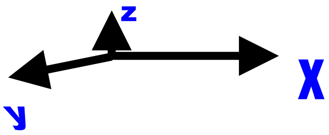
The stiffness of the spring represented by subgrade modulus of soil(ks^1) is calculated using Vesic's equation (1961a, 1961b), adopted from Bowles (1996).

$$ks^1 = 0.65 * \sqrt[12]{\frac{E_s B^4}{E_f I_f}} * \frac{E_s}{1-\mu^2} \; , \qquad kN/m^2$$

$$ks = \frac{ks^1}{B} \; , \qquad kN/m^3$$

Where, ks = modulus of Unit subgrade modulus reaction, kN/m^3;E_s,E_f =Elastic Modulus of soil and footing, respect tively, kN/m^2;B=Width of each dicretized element of the Footing, (m); I_f =moment of inertia (m^4) based on cross section (not in Plan); μ = Poisson's ratio and

$$E_s = \frac{2G}{(1+\mu)}$$



Degrees of freedom	Stiffness of equivalent soil springs
Vertical (Kz) in kN/m	$\frac{GL}{1-\mu}\left[0.73 + 1.54\left(\frac{B}{L}\right)^{0.75}\right]$
Horizontal (Ky) (Lateral direction) in kN/m	$\frac{GL}{2-\mu}\left[2 + 2.5\left({}^{B}/_{L}\right)^{0.85}\right]$
Horizontal (Kx) (Longitudinal direction) in kN/m	$\frac{GL}{2-\mu}\left[2 + 2.5\left({}^{B}/_{L}\right)^{0.85}\right] - \frac{GL}{0.75-\mu}\left[0.1\left(1-\frac{B}{L}\right)\right]$
Rocking(Krx) (About the longitudinal,x-axis) in kN-m	$\frac{G}{1-\mu} I_x^{0.75}\left({}^{L}/_{B}\right)^{0.25}\left[2.4 + 0.5\left({}^{B}/_{L}\right)\right]$
Rocking(Kry) (About the lateral,y-axis) in kN-m	$\frac{G}{1-\mu} I_y^{0.75}\left[3\left({}^{L}/_{B}\right)^{0.15}\right]$
Torsion (Krz) in kN-m	$3.5GI_{bz}^{0.75}\left({}^{B}/_{L}\right)^{0.4}\left({}^{I_{bz}}/_{B^4}\right)^{0.2}$

Figure 4. Global axes direction considered in SAP

Fig.4 shows the global axes direction considered in SAP2000V14.

4.2 ***Modified Winkler Model***.

The stiffness of springs in each translational and rotational directions are calculated as suggested by Gazetas(1991) and recommended by ATC-40 and tabulated in Table 1.Table 1. Stiffness of equivalent soil springs along various degrees of freedom (ATC40, adopted from George Gazetas, 1991)

μ - Poisson's ratio

B, L –width and length of a rectangular foundation respectively, in m.

I_x, I_y, and I_{bz}, - Moment of inertia, in m^4 of the foundation area with respect to longitudinal, lateral and vertical axes respectively.

G = Dynamic shear modulus in kN/m^2 , which depends on type of soil.

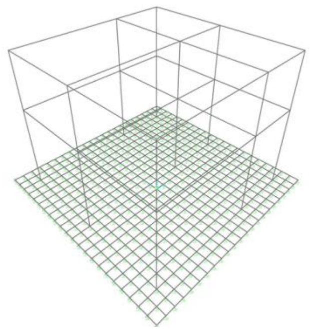


Figure 5. Finite Element idealizations of the building foundation soil interactive system for Winkler model.

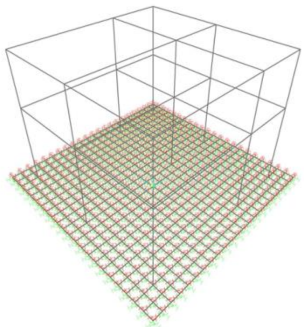


Figure 6. Finite Element idealizations of the building foundation soil interactive system for Modified Winkler Model.

Fig. 5 and Fig. 6 show the finite element idealization of the building frame - raft foundation -soil interactive system for WM and MWM respectively.

5. RESULTS AND DISCUSSION

Here, only Fundamental natural period , Base shear and Maximum lateral displacements obtained from Interaction Analysis(IA) are compared with Non Interaction Analysis (NIA)

5.1 *Lateral Natural Period*

Variation of Fundamental natural period, Tn with shear modulus of three types of soil for Zone V are plotted for the two types of soil models and frame type of 2bay 2bay 1storey,2 storey and 4 storeies with Sr=2 and Hr=1.5 in Figure 7 and shown in Table 1. For any frame type and soil model considered, there is similar variation in Tn with shear modulus of soil, i.e. it slightly decreases with increase in shear modulus.In comparison to NIA, Tn substantially increases in the interaction analysis as the structure foundation soil system is rendered flexible.

The degree of variation depends on type of soil model and soil type. Story- wise variation of natural period is as shown in Table 1, and Fig. 10. It is evident that the natural period is relatively higher as number of stories is increased. Tn of all the models are greater than the values of NIA in all types of soils. Between the soil models, WM is observed to predict maximum variation with respect to NIA.

Table 1. Fundamental Natural Period, Sec

Type of Frame	Model Type	Fixed	Spring		
			Stiff	Medium	Soft
2bayx2bay-1Storey: Sr=2	MWM	0.14	0.16	0.16	0.16
	WM		0.17	0.17	0.17

2bayx2bay-2Storey: Sr=2,Hr=1.5	MWM	0.481	0.50	0.50	0.51
	WM		0.50	0.51	0.51
2bayx2bay-4Storey: Sr=2,Hr=1.5	MWM	0.85	0.88	0.8	0.89
	WM		0.89	0.89	0.91

Table 2. Base Shear ,kN

Type of Frame	Model Type	Fixed	Spring		
			Stiff	Medium	Soft
2bayx2bay-1Storey: Sr=2	MWM	100.99	103.94	104.8	107.45
	WM		100.99	103.64	103.4
2bayx2bay-2Sroey: Sr=2,Hr=1.5	MWM	315.2	316.86	317.15	317.9
	WM		315.41	315.8	314.66
2bayx2bay-4Storey: Sr=2,Hr=1.5	MWM	702.09	409.23	559.1	654.21
	WM		400.96	543.2	627.95

Table 3. Maximum Lateral Displacement, mm

Type of Frame	Model Type	Fixed	Spring		
			Stiff	Medium	Soft
2bayx2bay-1Storey: Sr=2	MWM	0.7956	1.0188	1.033	1.0692
	WM		1.0692	1.087	1.1232
2bayx2bay-2Storey: Sr=2,Hr=1.5	MWM	9.4536	8.5104	10.38	10.588
	WM		8.5932	10.63	10.966
2bayx2bay-4Storey: Sr=2,Hr=1.5	MWM	24.962	15.415	21.08	26.302
	WM		15.592	21.39	26.932

5.2 *Change in Base Shear*

Table 2, Fig.8 and Fig.11 show the resulting base shear(V_B) for different number of stories of the frame and types of soil. It is seen that increase in number of stories increases the base shear. Also observed is the decrease in base shear values from soil type soft to stiff which is more effective for 4 storey than one and two storied structures.

Comparing V_B values of both soil models and also NIA, MWM shows higher values of V_B followed by WM upto 2 storey, where as for 4 storey frame NIA shows higher values of V_B followed by MWM and WM.

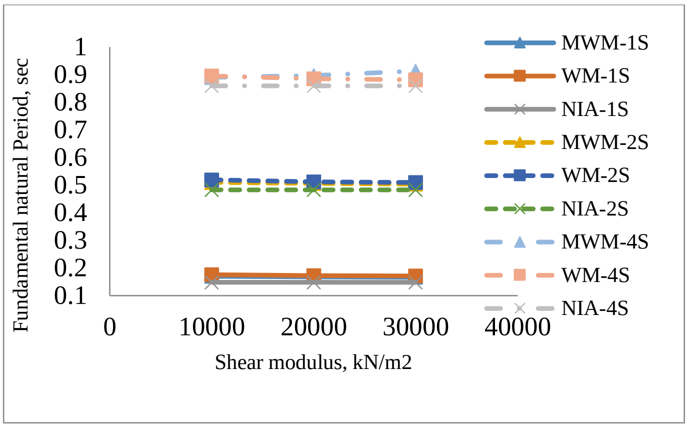


Figure 7. Variation of Fundamental Natural Period with Shear Modulus of Soil

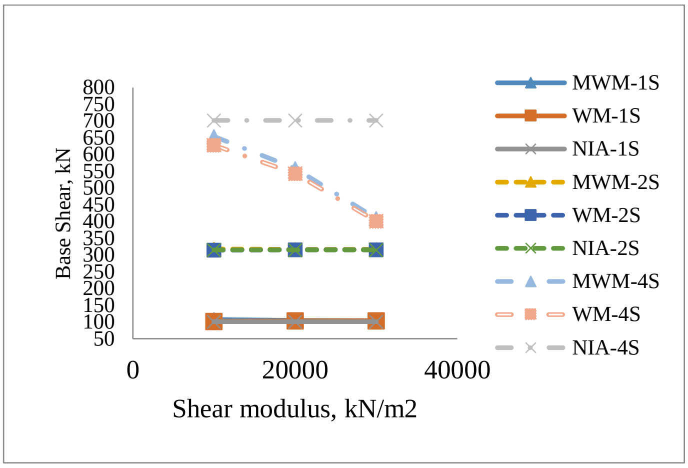


Figure 8. Variation of Base shear with Shear Modulus of Soil

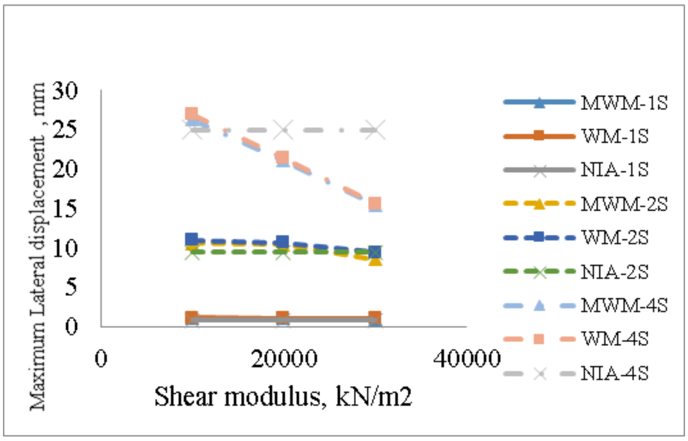


Figure 9. Variation of Max.Lateral Displacement with

Shear Modulus of Soil

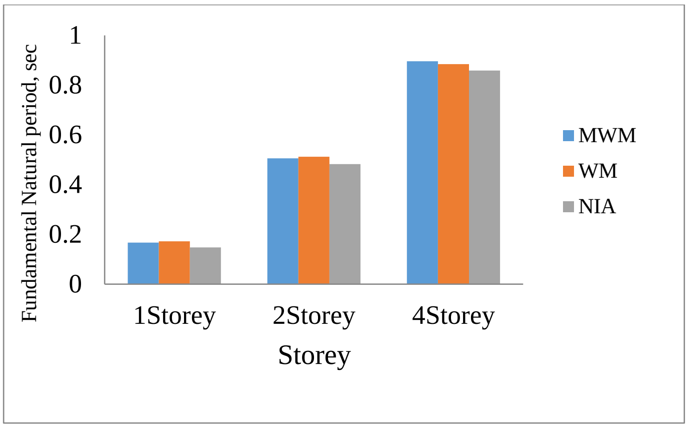


Figure 10. Variation of Fundamental Natural Period with Storey variation for Medium soil(Type II Soil)

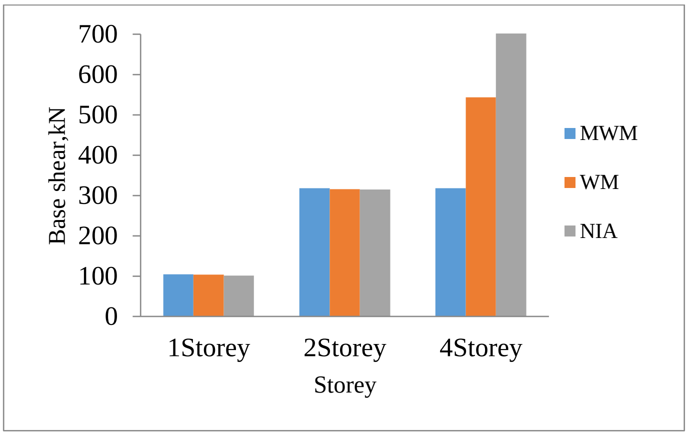


Figure 11. Variation of Base Shear with Storey variation for Medium soil(Type II Soil)

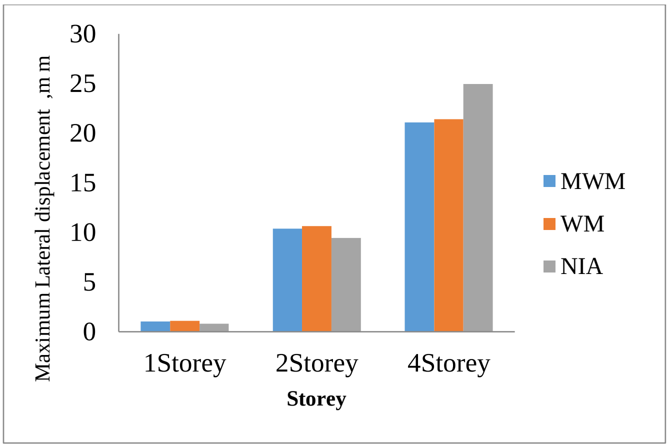


Figure 12. Variation of Max.Lateral Displacement with Storey variation for Medium soil(Type II Soil)

5.3 *Maximum Lateral Displacement*

The lateral displacement(Δ**)** values in the table 3 are those which are obtained as maximum values out of different modes of deformation. As Moment of Inertia along X-direction is high, displacements along Y-direction are relatively higher.

In comparison to Non interaction analysis Fig.9 and Fig.12 , Δ substantially increases in the interaction analysis as the structure foundation-soil-system is more flexible than that with fixed ends.

Trend of variation of Maximum lateral displacement with type of soil is almost same for all soil models i.e. it decreases with increase in stiffness of soil. Δ values for NIA are relatively higher than other two models followed by WM and MWM for 2 and 4storey frames where as WM shows higher values in 1 storey frames followed by WM and MWM.

6. CONCLUSIONS

The present study makes an effort to evaluate the effect of soil flexibility on dynamic characteristics of building frames resting on Raft foundation, namely the Lateral natural period , Seismic base shear and Maximum lateral displacement. The study leads to the following conclusions.

1.The behavior of the structure is rendered flexible due to IA , as a result of which substantial increase in Tn and Δ and moderate increase in $V_{B,}$ occur. For the sandy clay soil considered, the fundamental natural period of 3D-frames is maximum for type III(soft soil) and decreases as the shear modulus of soil increases.
2 .Effect of increase in number of storeys from 1 to 2 and 2 to 4 results in substantial increase in Tn in both IA and NIA.
3.Base shear values due to Interaction analysis are found to be higher than that of Non-Interaction analysis which is more predominant in longitudinal direction of the 3D frame. As number of storeys increases from 1 to 2 and 2 to 4 base shear increases
4.The top storey sway(Δ) values along any of the horizontal directions decreases as the shear modulus of soil increases. For the frame 2bayx2bay-4 storey, as soil changes from soft to hard Δ reduces by 70.62%(MWM) and 72.73%(WM). As number of storeys increases from 1 to 2 and 2 to 4, Δ increases by about 10 & 2.03 times in MWM, 9.78&2.012 times in WM and 11.88 & 2.64 times in NIA.

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