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(RESEARCH ARTICLE)

Effect of raft thickness and soil modulus on frequency and amplitude of building frame

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Abstract

The paper presents the limited study on the evaluation of the response of the dynamic soil structure interaction analysis of a two storeyed building frame resting on raft foundation using finite element method. The components of the building frame such as beams, columns and slabs along with the raft are modeled using 20 noded isoparametric continuum elements. The soil surrounding the foundation is modeled in the simplified manner using discrete independent springs. The interface of soil and raft has been accounted for by incorporating 16 node interface elements in the modeling. Further, the components of the superstructure and substructure are treated to behave in the linear elastic manner whereas the soil media is idealized to behave in the non-linear manner. The effect of raft thickness and soil modulus is evaluated on the dynamic response of the frame. The response is considered in terms of the frequency and amplitude. The result indicates that the dynamic loading and SSI has a considerable effect on the response of the structure.

Keywords: Building frame; Raft foundation; Non-linear springs; Dynamic response; Amplitude; Frequency

1. Introduction

An analyst or a designer is mainly concerned with the analysis and design of a variety of structures. All these structures are exclusively supported by soil and hence, the subject of soil-structure interaction has come into existence and has attracted the attention of the analysts for last four-decades. In current design practice, structural engineers usually disregard any influence that the settlement of the supporting ground may have on the response of framed structures. Likewise, in foundation design, analyses of actual settlements are based upon a flexible loading pattern with no assessment of the effect of the stiffness of the structure on the patterns and magnitudes of foundation settlements. Although this procedure of neglecting the coupling or interaction between soil and structure tends to simplify the mathematical analysis of the problem, it is, however, an oversimplification of reality.

Two important characteristics that distinguish the dynamic soil- structure interaction system from other general dynamic structural systems are the unbounded nature and the non-linearity of the soil media. Another effect which is also taken into account concerns the interaction of the structure with the foundation, which provides both a more realistic boundary condition as well as damping model due to radiation effect. Of the three widely used methods of SSI analysis, viz. (i) Elimination Method, (ii) Sub-structure Method and (iii) Direct Method, the direct method has become more attractive to researchers and engineers because it can consider the non-linearity of the unbounded soil as long as sufficiently accurate transmitting boundaries can be developed.

The way the soil medium is modelled during SSI analysis is integral in accurately representing the inelastic structural response and nonlinear behaviour of the underneath supporting soil due to seismic excitation. At present, there are

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three general methods available to represent the soil medium for soil-structure interaction analysis of structures, namely, Winkler Model (spring model), Lumped Parameter on Elastic Half Space and Numerical Methods.

2. Literature review

Many interactive analyses in the context of static loading as well as dynamic loading have been reported in the literature. Jennings and Bielek [1] studied the dynamics of building-soil interaction wherein soil was modeled by a linear elastic half space and building structure by n- degree of freedom oscillator. Vaish and Chopra [2] proposed sub-structure approach for analyzing the complex structure-foundation systems. Luco and Hadjian [3] studied the feasibility of representing a 3-D SSI problem by plain strain model and errors involved in such representation. Novak [4] evaluated effect of piles on dynamic response of footings and Structures and underscored the importance of damping in the dynamic analysis aimed at quantifying the effect of SSI.

Chandrasekaran and Pankaj [5] studied the dynamic SSI behaviour of the framed buildings considering 2-D structural system by considering the system as plain strain FE problem and treating the soil as linearly elastic. Gupta *et al.* [6] proposed a three dimensional hybrid model incorporating good features of the various approaches and eliminating undesirable approaches. Novak and Hifnawy [7] tried to consider the aspect of soil damping in a rational manner and evaluated effects of SSI on damping of structures using simple but approximate energy consideration and complex eigen value analysis. Pais *et al.* [8] suggested two types of effects namely, kinematic interaction and inertial interaction while accounting for SSI. Markis *et al*. [9] emphasized the non-linear analysis while examining the problem of dynamic soil-pile foundation- structure interaction of a bridge structure supported on pile group.

Curras *et al.* [10] reported experimental and analytical study for pile group supported structure in the context of dynamic beam on a non-linear Winkler model foundation analysis. Roy and Dutta [11] investigated the effect of SSI on dynamic behaviour of building frames on grid foundation by incorporating the aspect of infill brick wall. Bhattacharya *et al.* [12] studied the effect of soil- flexibility on dynamic behaviour of building frames on raft foundation Sushma and Pradeep Kumar [13] reported dynamic soil- structure interaction analysis of a high rise structure in a visco-elastic half space. Sawant and Chore [14] presented dynamic analysis of single storeyed building frame supported on pile foundation using time history analysis.

Deepa and Nandakumar [15] reported seismic soil-structure interaction studies on multi-storey frames. Choudhari and Kadam [16] studied the effects of piled raft on design of high rise building considering soil- structure interaction. Chougule and Dyavanal [17] reported seismic soil structure interaction on G +6 storied building frame (bare and thick infill frame) resting on different founding strata. Halkude *et al.* [18] reported seismic response of R.C. frames with raft footing considering soil-structure interaction. Roopa *et al* [19] reported soil- structure interaction analysis of G+12 storied R.C. building with raft foundation embedded in clayey soil located at Chennai. Raghuveeran and Hashifa [20] presented the effect of seismic soil- structure interaction on eight storeyed R.C. bare frame resting on pile grid foundation. Suresh and Jagdeesh [21] reported dynamic soil-structure interaction analysis of a G+10 storied R.C. building frame supported on footing.

Based on the above literature survey, an analysis of a two storeyed building frame supported on raft embedded in soft marine clay has been presented to evaluate the effect of the raft thickness and soil modulus on the dynamic response of the building frame considered in this investigation. The dynamic response is considered in terms of the frequency and amplitude. The effect of raft thickness and soil modulus is evaluated for maximum frequencies and amplitudes. The response is obtained for the frequency range of 1 to 20 rad/sec; the total time is divided in to 400 steps of 0.05 sec.

3. Particulars of the problem

A 3-D two storeyed building frame resting on raft foundation with different thicknesses is considered for the study. The frame, 3 m high is 10 m × 10 m in plan with each bay being, 5m ×5m. The slab, 200 mm thick, is provided at top and at first storey level. The slab at the top of the first and second storey is supported over 300 mm wide and 400 mm deep beams. The beams are resting on columns of size 300 mm × 300 mm. The raft embedded in soft marine clay, a cohesive type of soil mass, is considered for the present study. While the dead load is considered according to the unit weight of the materials of which the structural components of frame are made up of, for the purpose of the parametric study presented here. The soil properties, interface element and properties of raft are given in Table 1. Figure 3shows the half geometrical model of building frame with fixed column base and group of four piles. The interface shear stiffness (k_s) is taken as G/10 and the interface normal stiffness is taken as 100G, in which G is the shear modulus of soil. The octahedral (τ_{oct}) shear stress is limited to undrained cohesion of clay soil (using half unconfined compressive strength of soil).

Table 1 Raft and soil properties for parametric study

Soil properties	
Modulus of Elasticity, Es	10000, 20000, 30000 and 40000 kPa
Poisson's ratio, μs	0.4
Density, γs	18 kN/m3
Yield stress, σy	100 kPa
Interface element	
Normal stiffness, Kn	1.0 × 106kN/m3
Tangential stiffness, Ks	1000 kN/m3
Raft properties	
Modulus of Elasticity, Ep	25 GPa
Poisson's ratio, μp	0.2
Density, γp	25 kN/m3
Thickness	0.5, 0.75, 1.0, 1.25 and 1.5 m

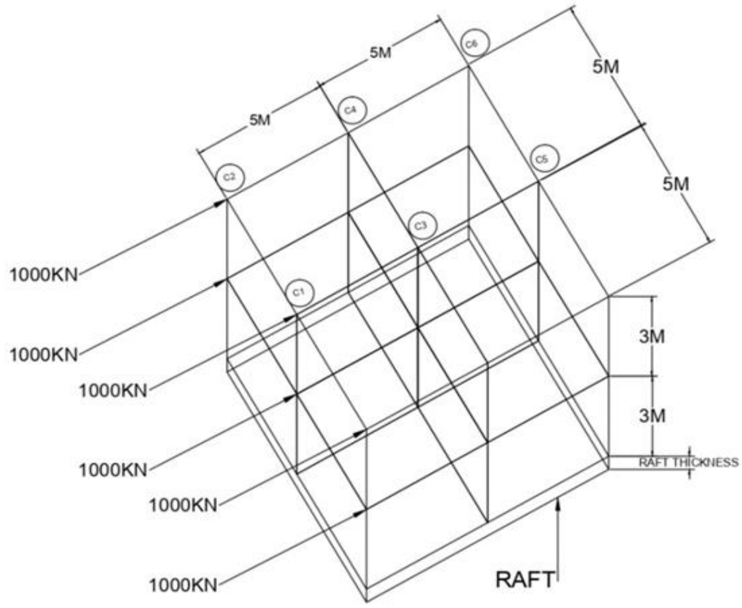


Figure 1 Typical building frame with raft considered in the present study

4. Methodology

Various components of building frame along with the raft (slab, beam and column) are discretized using 20 node continuum element. Soil supporting raft is modeled considering non-linear Winkler springs. The soil behaviour is considered non-linear. In case if linear analysis, the relation between soil reaction (*p)* and transverse displacement (*w)* through modulus of subgrade reaction $k_s$as:

$p = k_s w$.

$$[K]_{soil} = \int_V [N]^T k_s \, [N] \, dv$$

In the second approach, the relation between soil reaction (*p)* and transverse displacement (*w)* is expressed through an hyperbolic relationship.

$$p = k_{\max} w / (1 + k_{\max} w / p_u)$$

In which, k_{max} is initial tangent modulus and p_u is the ultimate soil resistance. In the incremental analysis, tangent modulus is used to compute stiffness of soil over the element.

$$k_s = \frac{d\,p}{d\,w} = \frac{k_{\max}}{\left(1 + \dfrac{k_{\max} w}{p_u}\right)^2}$$

To evaluate displacements at each time step by solving the incremental dynamic force equilibrium equation, the implicit time stepping method is used. The Newmark-beta method is a method of numerical integration used to solve differential equations. It is widely used in numerical evaluation of the dynamic response as in finite element analysis to model dynamic systems. Dynamic force equilibrium equation in incremental form is expressed as:

$$[K]_{dy} \{\Delta q_i\} = \Delta F_i + \left(\frac{1}{\beta \Delta t}[M] + \frac{\alpha}{\beta}[C]\right)\{\dot{q}_{i-1}\} + \left(\frac{1}{2\beta}[M] + \left(\frac{\alpha}{2\beta} - 1\right)\Delta t [C]\right)\{\ddot{q}_{i-1}\}$$

$$\text{where} \quad [K]_{dy} = \left(\frac{1}{\beta \Delta t^2}[M] + \frac{\alpha}{\beta \Delta t}[C] + [K]\right) \quad (3)$$

The equivalent stiffness matrix, $[K]_{dy}$ in the dynamic analysis is assembled in global stiffness vector {*A*} using skyline storage scheme. Global force vector {*B*} on right hand side is updated at every time step and system is solved for unknown incremental displacements. Then total displacement, velocity and acceleration vectors are updated which are used to calculate force vector for next time step.

For the interaction analysis, a numerical procedure is developed using Fortran-90 and pursuant to this, a software program Non-Linear Build-Frame (NLBF) is developed.

5. Results and discussion

After assessing the accuracy of the program in the context of simple problems of structural engineering and soil-structure interaction; and further, implementing it on the published work, the said program is used in the present study. In the parametric study conducted for the specific frame presented here, the response of the superstructure considered for the purpose of comparison includes maximum frequencies and amplitudes.

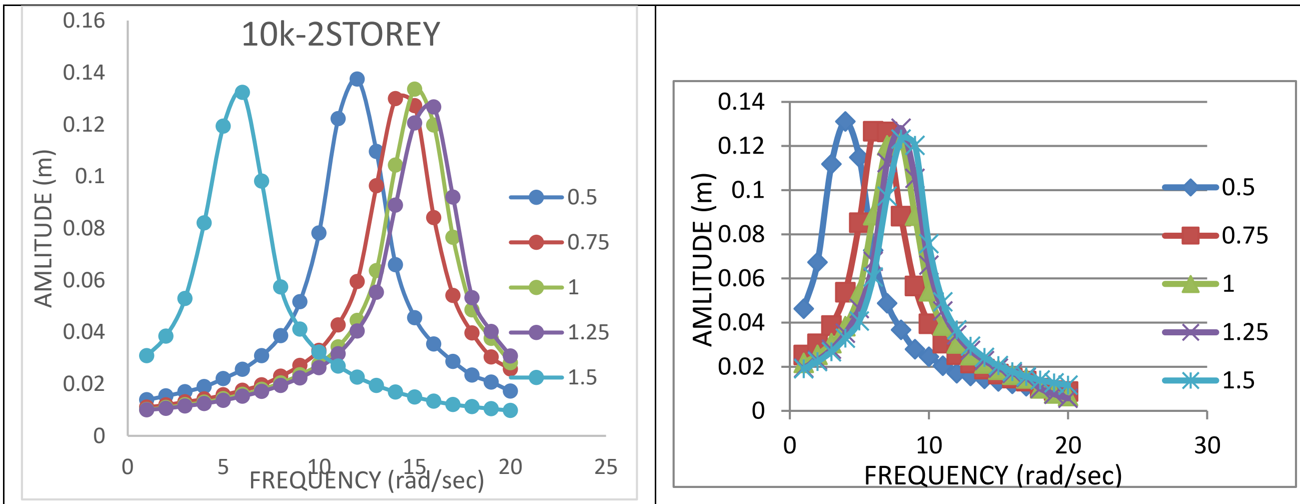
The values of the maximum frequencies and amplitudes in respect of interactive analysis for each the raft thickness with different soil modulus is given in Table 2. The corresponding percentage increase or decrease in amplitude and fundamental frequencies due to consideration of different raft thicknesses and soil modulus in the context of interactive analysis is also indicated in the afore-mentioned table in brackets. Similarly, the variation in the frequencies and amplitudes considered in the present investigations is shown in Fig. 3 (a-d).

Table 2 The frequency and corresponding amplitudes for different raft and soil modulus

	E_s = 10000kPa	E_s = 20000 kPa	E_s = 30000 kPa	E_s = 40000 kPa

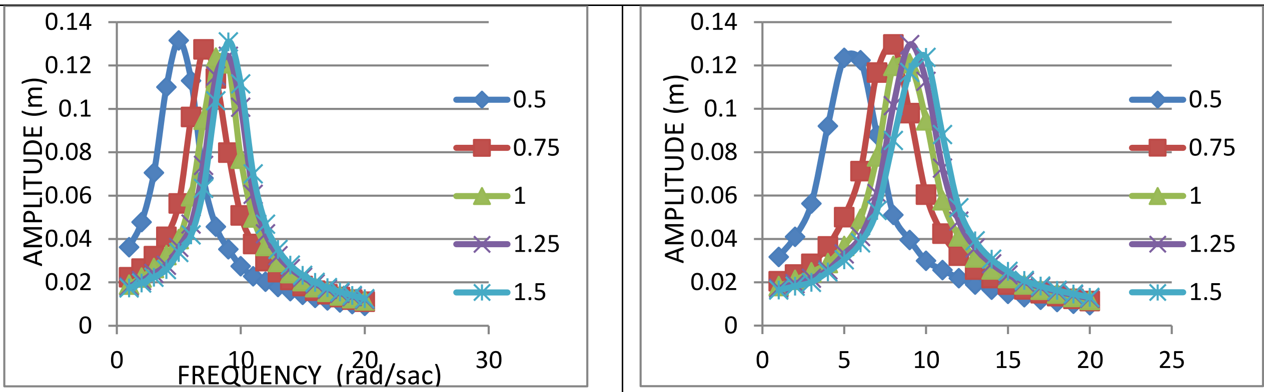
Raft thickness (m)	ω	A_m	ω	A_m	ω	A_m	ω	A_m
0.5	15.2	0.13892	15.4	0.13432	15.5	0.1316	15.5	0.12591
0.75	15.4 (0.64%)	0.13005 (-6.82%)	15.6 (1.29%)	0.12673 (-5.99%)	15.7 (1.27%)	0.12855 (-2.37%)	15.8 (1.93%)	0.13083 (3.76%)
1	15.5 (1.97%)	0.13484 (-3.03%)	15.8 (2.60%)	0.12421 (-8.14%)	15.8 (1.93%)	0.12549 (-4.87%)	15.9 (2.58%)	0.12106 (-4.01%)
1.25	15.6 (2.63%)	0.12672 (-9.63%)	15.8 (2.60%)	0.12877 (-4.31%)	15.9 (2.58%)	0.12426 (-5.91%)	15.9 (2.58%)	0.12963 (2.87%)
1.5	15.6 (2.63%)	0.13229 (-5.01%)	15.8 (2.60%)	0.12509 (-7.38%)	15.9 (2.58%)	0.13091 (-5.3%)	16 (3.22%)	0.12375 (-1.75%)

From Table 2, it is observed that the fundamental frequencies corresponding to the prominent peaks when compared with that obtained in the context of 0.5 m thick raft, increases with the increase in the raft thickness. Also, it is observed that, with increase in the soil modulus fundamental frequencies increases by and large. For the lowest soil modulus (E_s = 10000 kPa) considered in this investigation, the percentage variation in the fundamental frequency is in the range of 0.64- 2.63%. The frequency increases by 0.94% and 1.97% for two higher raft thicknesses, i.e. 0.75 m and 1 m. However, the increase in frequency for next higher raft thicknesses (1.25 m and 1.5 m) remains same, i.e., 2.63%. The amplitude, however, is found to decrease, the decrease being in the range of 3- 9.6%. The amplitude decreases by 6.8% for 0.75 m thick raft, then again decreases by 3% for 1 m thick raft followed by 9.6 % and 5 % decrease for next two raft thicknesses considered in the study.



(a) Soil modulus *Es*=10000kPa

(b) Soil modulus *Es* = 20000 kPa



(c) Soil modulus *Es* = 30000 kPa

(d) Soil modulus *Es* = 40000 kPa

Figure 3 Frequency-Amplitude response for different soil modulus

For next higher value of soil modulus, i.e., Es = 20000 kPa, the fundamental frequency is found to increase in the range of 1.3 to 2.6%. The frequency is found to increase by 1.3 % for 0.75 m thick raft and the increase in frequency for further raft thickness remains same, i.e., 2.6%. The amplitude is found to decrease with raft thickness, the decrease being 6%, 8%, 4.3% and 7.4%, respectively. For the soil modulus of 30000 kPa, the percentage increase in frequency is found to be 1.3% and 1.9 in respect of the raft thickness of 0.75 m and 1 m. For next two raft thicknesses, i.e., 1.25 m and 1.5 m, the increase in the frequency is found to be 2.6%. Correspondingly, the percentage decrease in amplitude is found to be 2.4, 4.9, 5.9 and 5.3, respectively. For the highest soil modulus considered in the present investigation, i.e., 40000 kPa, the amplitude is found to increase by 1.9% for 0.75 m thick raft and for subsequent thicknesses of the raft considered in the study, the increase is found to remain same, i.e., 2.6%. However, the amplitude is found to increase by 3.75% for 0.75 m hick raft, decrease by 4% 1 m thick raft, again increase by 2.87% for 1m thick raft and thereafter, decrease by 1.75% for 1.5 m thick raft.

When the response, i.e., frequency and amplitude, is considered with respect to the raft thickness and in the context of the increasing soil modulus, generally, it is observed that the frequency increases with soil modulus. It is also observed that the frequency remains same for any two higher values of the soil modulus, especially in case of the raft thickness of 0.5 m, 1 m and 1.5 m. As regards the amplitude, it is found to decrease with increase in soil modulus for 0.5 m thick raft. For 0.75 m thick raft, the amplitude decreases for Es =20000 kPa and thereafter, again increases. For 1 m thick raft, the amplitude is found to decrease for Es= 20000 kPa, increase for Es= 30000 kPa and again decrease for the highest value of soil modulus. For 1.25 m thick raft, the variations in amplitude follows the trend of increase, decrease and again increase whereas in respect of 1.5 m, thick raft, the trend observed follows decrease, increase and again decrease. However, it may be noted that although the amplitude vary with respect to the soil modulus, the variation is too marginal to be neglected.

For higher soil modulus, magnitude of amplitude is lesser as compared to the lower soil modulus in respect of every raft thicknesses except the raft thickness 0.75 and 1.25m. No definite trend is observed in the magnitude of maximum amplitude. Maximum amplitude is a complex phenomenon. It is not only a function of stiffness of raft soil system, but it is also dependent on the mass involved in the vibration and external frequency of excitation.

6. Conclusion

The fundamental frequencies corresponding to the prominent peaks decreases with the increase in the raft thickness for respective peak. Though with increase in raft thickness, the stiffness of raft-soil system increases, natural frequencies decrease due to increase in the mass involved in vibration. Similar trend is observed in the frequency corresponding to maximum amplitudes.

The maximum amplitude decreases with the increase in the raft thickness. Further, with increase in the soil modulus fundamental frequencies increases. For higher soil modulus, magnitude of amplitude is lesser as compared to lower soil modulus in respect of every raft thicknesses. As expected with the increase in soil modulus, soil stiffness increases and fundamental frequencies corresponding to peaks also increase while peak amplitudes, decrease.

Compliance with ethical standards

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Disclosure of conflict of interest

All the authors would like to declare that there is no conflict of interest relevant to this article.

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