Effects of Sandy Soil-structure Interaction on the Natural Period of RC Building Frames

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Abstract. Building natural period, \( T \), is a key character in building response for wind and seismic induced forces. In design practice, the period, \( T \), is either estimated from empirical relations proposed by the design codes or determined from analytical or numerical models. The effect of the soil-structure interaction is usually neglected in the design practice and analysis models. This paper uses a sophisticated finite element simulation to investigate the effect of soil-structure modeling on the fundamental period of RC buildings subjected to wind and seismic induced forces. A typical interior building frame has been imitated using the frame element for beams and columns with constrains to model the almost-rigid diaphragm nature for floors and roof while a three-dimensional element has been adopted for the raft foundation and the soil mass. Different sandy soils have been considered. Standard Penetration Test, SPT value, has been taken as an identification index for soil nature. All other soil properties have been estimated based on well-accepted correlations. After applying the gravity dead and live loads, an eigenanalysis has been achieved to show how soil flexibility affects the effective stiffness of the structure and the corresponding natural period. Finally, the results are used to introduce a correction factor to modify the natural period estimated from a linear analysis with ideal supports to reflect the aforementioned effects.

Keywords: Soil-structure interaction, Finite Element, Natural Period, RC Buildings, Frames.

1. Introduction

According to Clough and Penzien [1], in earthquake engineering, soil nature has two main effects. Firstly, it can affect the nature of vibratory wave that transfers from rock basement to the natural surface. Secondly, the soil can alter the natural period, \( T \), of the structure and hence changes its dynamic response. In the Uniform Building Code (UBC) [2], the first effect has been simulated by the soil profiles \( S_A \) through \( S_F \) and the corresponding acceleration-based coefficient, \( C_a \), and velocity based coefficient, \( C_v \) [3]. This study deals mainly with the second aspect that has essential aspects not only in seismic loads but also for other dynamic loads, including machine vibration and wind flow.

Physically, the natural period, \( T \), for lateral vibration of building frames represents the time required for the structure to complete one cycle when vibrates freely under initial displacement and/or initial velocity. It is an important factor in building response for wind, seismic, and other lateral forces [3]. In routine design works, the period value, \( T \), is usually estimated from empirical equations like Eq. 1 that has been adopted for decades by American standard [4].

\[
T = C_t (h_t)^{3/2} \tag{1}
\]

where:
\( C_t \), in the metric system, has a value of 0.0853 for steel moment-resisting frames, and value of 0.0731 for reinforced concrete moment-resisting frames and eccentrically braced frames, and a general value of 0.0488 for all other buildings.

\( h_n \) is building height in meters.

With the valuable assistance of digital computers, more elaborate free vibration analyses have been executed by designers to estimate the natural period, \( T \). Unfortunately, most of these computer analyses neglect the soil-structure interaction and adopt ideal supports. Different researchers have considered this effect in an attempt to define a consistent correlation to be considered in the design practice. Anand and Kumar [5] published a review on the academic research related to the seismic soil-structure interaction. The researchers gathered the work of 113 references and summarized the historical development in this area and the different approaches used to solve the problems related to seismic soil-structure interaction. The researchers also presented brief articles about the guidelines included in different regional codes including the United States, Europe, Japan, New Zealand, and India.

Hokabadi and Fatahi [6] conducted a 3D finite element model to study the effect of modeling different foundations on the seismic characteristics of the model including the natural frequency of the frame. The researchers modeled a fifteen-story building and concluded that different foundation models can change the seismic behavior of the model dramatically. Bhojegowda and Subramanya [7] performed finite elements multistory models with different heights; five-levels models, ten-levels models, and fifteen-levels models. These models had various base-fixity types and also different soil types ranging from soft to hard soil to examine the effects of these parameters on the response of the structure including base shear, bending moments, and natural period of the model. The study implied that models with pile foundations can be treated with a fixed base since the difference in response was almost negligible. The natural periods for flexible-footing models were higher than those with fixed ones while the bending moments and displacements were lower.

Guerdouh and Khalfallah [8] carried out a numerical analysis on the effect on soil modeling and interaction on the seismic behavior of a single-story framed structure with a height of 3m and a span of 5m. The concrete frame with a typical cross-section of (0.4m by 0.4m) rested on soil consisting of three layers: top soft soil, middle medium soil, and bottom hard soil, with depths of 10m, 20m, and 50m respectively. The frame was subjected to low, medium, and strong earthquake excitations. The study intended to study multiple response aspects: the effect of soil-structure modeling on both the soil and the frame, the change in the earthquake lateral displacement of the frame, and the earthquake intensity. Different outcomes were drawn from the study emphasizing that the type of soil has a great impact on the seismic response and frames on soft soils showed higher lateral displacement than on harder soils. Some other researchers also introduced valuable work in attempts to cover many parameters relating to the soil-structure interaction with seismic response. These researchers include Belletti et al. [9], Venkatesh & Deshpande [10], Sharma et al. [11], Al Rumaithi [12], Mekki et al. [13], Behnamfar and Alibabaei [14], and Barnaure and Manoli [15]. This study adopts relatively sophisticated finite element models to show how different soil simulations and different soil properties can affect the estimated natural period, \( T \), of building frames.

2. Modeling of Building Frame and Underneath Soil

2.1. Physical Modeling Aspects

To simplify the analysis process, the three-dimensional building frame can be broken down into a series of two-dimensional frames, as indicated in Fig. 1. This approximation is used for decades in analysis and design processes [16]. The superimposed dead and live loads that act in the form of load per unit area can be transformed into line loads that act on the supporting beams, as presented in Fig. 1. For a two-way slab system, triangular and trapezoid loads are a more accurate simulation [17].

2.2. Units

For dynamic and free vibration problems where inertia forces are included, one should be careful regarding the unit system and should be aware that he/she implicitly adopts a specific unit system for
ground acceleration. In this study, a consistent unit system of m, N, kg, second has been respectively adopted for length, force, mass, and time.

2.3. Finite Elements for Frame

For the equivalent frame, the frame finite element indicated in Fig. 2 is adopted in the simulation of beams and columns [18]. ABAQUS Finite element software is utilized to simulate the model and run the analysis and extract the results. The software has a library that contains a variety of elements for the user to choose from based on the required degrees of freedom of the modeled element. In this research, an 8-node linear brick element is employed. The element, recognized as C3D8R, is a reduced integration, hourglass control. As it is based on a kinematic assumption of plane section before loading remains a plane and normal to the member axis after loading, it can generally reduce the three-dimensional behavior of beams and columns into an equivalent one-dimensional simple behavior, [19]. It is adequate for solid sections where there is no possibility of local bending effects [20]. It implicitly neglects shear strain. This approximation is generally accepted for relatively thin members [21]. A cubic Hermite shape function indicated in Eq. 2 is adopted to simulate displacement along element length.

\[ N_i = a_i + b_i \xi + c_i \xi^2 + d_i \xi^3 \]  

(2)

where \( a_i, b_i, c_i, \) and \( d_i \) are coefficients that can be determined in terms of nodal displacement \( q_i \). This formulation is suitable when the element is subjected to distributed forces or inertia forces according to d’Alembert’s principle [22]. The consistent mass matrix has been formulated using Eq. 3 below. Three Gaussian points have been adopted to execute the integration numerically. Finally, rotary inertial components have been neglected to avoid possible computational difficulties [23].

\[ M = \rho A \int_0^{l_e} N_i^T N_i \, dx = \frac{\rho A l_e}{2} \int_{-1}^{1} N_i^T N_i \, d\xi \]  

(3)
2.4. Simulation of Rigid Floors Diaphragm

Even though they are flexible out of their plane, floor systems are almost rigid in their plane [24]. Rigid body constraints are adopted to enhance the proposed model by imposing an infinitely rigid behavior [25]. With this technique, a master node has been selected at mid of each floor; all other nodes within the floor are considered as slave nodes where their horizontal displacements are assumed equal to that of the master node, see Fig. 3. For the computational purpose, this kinematic assumption is rewritten in the form of the transformation matrix, $\mathbf{T}$, that is used in turn to reduce the stiffness matrix of girder as indicated in Eq. 4 below:

$$K_{\text{Reduced}} = \mathbf{T}^T \mathbf{K}_{\text{Original}} \mathbf{T} \quad (4)$$

From Eq. 4 above, one concludes that rigid body constraints not only simulate the rigid diaphragm in a more accurate form but also reduces the corresponding computational efforts.

![Figure 3. Master and slave nodes to simulate the rigid floor diaphragm.](image)

3. Finite Element for Foundation

Foundation support for the typical equivalent frame indicated in Fig. 1 has been assumed to extend from mid-distance between two consecutive frames. Three-dimension elements have been used in the discretization process. According to ACI-318M Code [26], the elastic modulus for concrete can be correlated to its compressive strength, $f'_c$, based on Eq. 5 below. According to Darwin et al. [17], a value of 0.2 is representative of concrete Poisson’s ratio in the elastic range.

$$E_c = 4700\sqrt{f'_c} \quad (5)$$

When shear strain in included in a relatively thin member, as in the case of the foundation, the shear-locking phenomenon may occur due to overemphasis of shear contribution with the full Gaussian integration that is adopted to determine the integration of stiffness matrix [27]. Therefore, a reduced integration with a single Gaussian point located at the center of the element has been adopted in this research [28]. Unfortunately, recently, it has been found that the reduced integration schemes may lead to what is called the spurious zero-energy modes. These modes are deformed into an hourglass shape. In this research, this problem has been overcome through an hourglass control technique where additional stiffness term is adopted to prevent the formulation of the hourglass modes [29]. As indicated in Fig. 1a, two elements have been used along the raft depth to model its possible curvature with the linear brick element [30].
3.1. Finite Element Mesh for Soil
As indicated in Fig. 4b, a linear brick element has been adopted in soil simulation. According to Cook [30], the linear element should be adopted only with low strain gradient and fine mesh. Both conditions are satisfied in the mesh presented in Fig. 4b.

3.2. Final Equations of Motion and Solution Algorithm
After modeling the frame, foundation, and soil mass, they have been assembled to behave as a complete system with the following equation of motion.

\[
\begin{bmatrix} m_{ff} & m_{fs} \\ m_{sf} & m_{ss} \end{bmatrix} \begin{bmatrix} \ddot{v}_f \\ \ddot{v}_s \end{bmatrix} + \begin{bmatrix} c_{ff} & c_{fs} \\ c_{sf} & c_{ss} \end{bmatrix} \begin{bmatrix} \dot{v}_f \\ \dot{v}_s \end{bmatrix} + \begin{bmatrix} k_{ff} & k_{fg} \\ k_{sf} & k_{ss} \end{bmatrix} \begin{bmatrix} v_f \\ v_s \end{bmatrix} = \begin{bmatrix} p_f \\ p_s \end{bmatrix}
\]  

(6)

where the subscript \( f \) and \( s \) refer to the frame and soil respectively. The matrices \( m, c, \) and \( k \) respectively indicate the mass, damping, and stiffness of the system. The stiffness \( k_{fg} \) shows the effect of axial forces on the stiffness and softening of the frame. It can be determined in an exact or approximate scheme. The approximate approach with fine mesh has been adopted here according to the recommendation of Al Zaidee et al. [31]. As the paper concerns with the free vibration, the load vector \( p \) has been dropped from Eq. 6. Damping ratios, \( \xi \), have been used instead of the damping matrix \( c \) to simulate the energy dissipation in the system. This simulation is approximated in nature when applied to a nonproportional system with soil-structure interaction [24]. For the sake of reducing the program run time and avoiding unpreferred numerical computation divergence, tie contact is chosen the simulate the contact between the superstructure frames and foundation.
3.3. Soil Physical Parameters

According to Prakash [32], in a soil dynamic problem, the soil elastic models are applicable for strain range no higher than $10^{-4}$ mm/mm. Although the strain may extend beyond this range in some cases, the elastic model has been adopted to formulate and solve the problem as an Eigenvalue problem [28]. The elastic model is in terms of three basic parameters of elastic modulus, $E$, shear modulus, $G$, and Poisson’s ratio, $\nu$. In the mechanics of material and theory of elasticity, it has been found that only two of these parameters are independent, and the third one can be determined from the following relation [33]:

$$G = \frac{E}{2(1 + \nu)}$$

(7)

Based on regression analyses of extensive test data, dynamic shear modulus, $G$, damping ratio, $\xi$, density, $\rho$, and Poisson’s ratio, $\nu$, have been correlated to standard penetration test, SPT, $N$ value. According to Das and Luo [34], the initial dynamic shear modulus, $G_{\text{max}}$, can be estimated from the following relation for round-grained sand:

$$G_{\text{max}} = 35 \times 161.5 N^{0.34}(\sigma_0)^{0.4}$$

(8)

where $G_{\text{max}}$ and confinement pressure, $\sigma_0$, are in kPa. The initial tangent modulus, $G_{\text{max}}$ can be adopted for shear strain in the range not higher than $10^{-4}$. For larger strain values, the initial shear modulus, $G_{\text{max}}$, can be reduced for a suitable tangent value. For adopted strain range, the dry sandy soil is lightly damped with damping ratio, $\xi$, of 1% [34]. Other soil parameters can be correlated to SPT value based on relations adopted in static analysis. According to Das [35], soil Poisson ratio is related to the internal angle of friction, $\phi$, based on Eq. (9). In turn, the angle, $\phi$, is correlated to the SPT value according to Eq. (10).

$$\nu = 0.1 + 0.3\left(\frac{\phi - 25}{20}\right)$$

(9)

$$\phi = 27.1 + 0.3N - 0.00054N^2$$

(10)

4. Case Studies

A total of six case studies are investigated to evaluate the influence of different soil-foundation modeling on the natural period, $T$, of framed structures. One of the case studies is examined without the modeling the soil mass beneath the foundation. Instead, fixed constraints are assigned to the concrete foundation. The rest of the case studies incorporate the soil-structure interaction through modeling the soil mass as indicated in Figs. 1 and 4. In the five case studies where the soil is modeled, different sandy soils characterized by different standard penetration test values have been studied. SPT values ranging from 10 to 50 are considered and the corresponding soil properties are obtained from the aforementioned relations depending on the SPT value. Table 1 presents the soil properties of the case studies.

| No. | SPT N Value | Angle of Friction, $\phi$ (degree) | Poisson Ratio, $\nu$ | $\sigma_0$ (kPa) | Shear Modulus, $G$ (kPa) | Elastic Modulus, $E$ (kPa) |
|-----|-------------|----------------------------------|---------------------|-----------------|------------------------|--------------------------|
| 1   | 10          | 30.1                             | 0.176               | 100             | 78026                  | 183479                   |
| 2   | 20          | 32.9                             | 0.219               | 100             | 98762                  | 240683                   |
| 3   | 30          | 35.7                             | 0.260               | 100             | 113361                 | 285612                   |
| 4   | 40          | 38.3                             | 0.300               | 100             | 125009                 | 324898                   |
| 5   | 50          | 40.9                             | 0.338               | 100             | 134862                 | 360824                   |
Typical concrete raft foundation for all cases is defined in the finite element model with the geometric and material properties indicated in Table 2.

Table 2. Foundation properties.

| Compressive strength, f_c' (MPa) | Width, B, (m) | Thickness, h, (m) | Moment of inertia, I (m^4) | Elastic Modulus, E (kPa) |
|---------------------------------|--------------|-------------------|---------------------------|-------------------------|
| 28                              | 3            | 0.60              | 0.0540                    | 24870062                |

Table 3. Elements properties.

| Frame     | Compressive strength, f_c' (MPa) | Dimensions (m x m) |
|-----------|----------------------------------|---------------------|
| Beam      | 28                               | 0.30x0.60           |
| Column    | 28                               | 0.30x0.60           |

To simulate the actual loads that act on each floor of the framed structure, a combination of both superimposed dead load and live load is applied on the beams of each floor as line loads. The values presented in Fig. 1 are applied in each of the cases studied. To better interpret the effect of different soil properties on the natural period of the system, the stiffness parameter, \( \beta \), is introduced [35]:

\[
\beta = \sqrt{\frac{B_k}{4E_f I_f}}
\]  

(11)

where:

- \( k \) is the soil subgrade modulus, in kN/m^3, and \( E_f \) and \( I_f \), are the elastic modulus and moment of inertia of the footing, in kPa and m^4 respectively.

5. Results and Discussion
The results of the above case studies are presented in this section. The results of the natural vibration properties from the finite element model for the fixed-base model are presented in Table 4.

Table 4. Natural vibration properties of the case studies.

| No. | SPT N Value | Natural Frequency, \( f_n \) (1/sec) | Natural Period, \( T_n \) (sec) | \( T_n / T_{n \text{Fixed-base model}} \) |
|-----|-------------|--------------------------------------|---------------------------------|----------------------------------|
| 1   | Fixed base  | 0.664                                | 1.506                           | ----                             |
| 2   | 10          | 0.812                                | 1.232                           | 0.818                            |
| 3   | 20          | 0.814                                | 1.229                           | 0.816                            |
| 4   | 30          | 0.816                                | 1.225                           | 0.814                            |
| 5   | 40          | 0.816                                | 1.225                           | 0.814                            |
| 6   | 50          | 0.817                                | 1.224                           | 0.813                            |

The effect of different soil properties on the natural period of the framed structure is shown in Fig. 5. It can be seen, within the case studies where the soil mass is modeled, from Table 4 and Fig. 5 that the higher the SPT value of the soil, the higher the natural frequency of the building frame. Even though the influence is low, the results seem intuitive considering that higher SPT values imply stiffer soils that contribute to higher building frequencies. Although the comparison between the effect of soil types is reasonable, the effect of soil-foundation interaction and foundation constraint on the natural properties of the framed structure seems more interesting. While intuitive judgment may predict higher natural frequencies, and lower periods, for building frames with fixed-base models over models where soil mass is simulated, the results show the opposite. The natural periods of the structure in the five case studies where soil-structure interaction is considered represents about 81% of the model where fixed constraints are assigned to the foundation base. The reason behind this behavior is due to the effect of soil mass in
the model. Despite that the fixity increases the stiffness of the system, the contribution of adding the soil mass to the system has a higher impact on the system resulting in a higher natural period and lower frequency.

Figure 5. Relative natural period vs soil-foundation stiffness coefficient.

6. Conclusion

The effect of soil-structure interaction on the natural period of building frames is examined in this study utilizing sophisticated finite element models. A total of six case studies are investigated; one with a fixed-base foundation and the rest are modeled by simulating the soil mass beneath the foundation. A typical interior building frame has been imitated using the frame element while different sandy soils have been considered where soil-structure is modeled. Standard Penetration Test, SPT value, has been taken as an identification index for soil nature. All other soil properties have been estimated based on well-accepted correlations. Results show that the building frames modeled with a fixed-base foundation has approximately 22% higher natural period than where the soil mass is modeled. Variations of case studies that may include different span lengths, different column layout for floors, different floor levels, and a wider range of soil properties could be examined in future studies to investigate this ratio.

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