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AN INVESTIGATION ON EFFECT OF SUBGRADE REACTION MODULUS OF SOIL ON NATURAL PERIOD OF LOW RISE BUILDINGS

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Abstract. *Soil structure interaction (SSI) is an important topic when seismic performance of structures is investigated but rarely taken into account in seismic performance evaluation of low rise buildings. Seismic performance of structures is generally evaluated with three different approaches as equivalent linear earthquake method, modal superposition method and time history analysis method. Equivalent linear earthquake method is the most widespread analysis method for seismic performance evaluation of low rise buildings. Seismic codes in the world generally propose approximate natural period formulas to be used in equivalent linear earthquake analysis procedure. Despite that soil properties have a considerable effect on natural period of buildings; there is no soil related term in approximate natural period relations proposed in the seismic codes. This study aims to introduce the importance of subgrade reaction modulus of soil on natural period of buildings and produce a relation between these two phenomena. In accordance with this purpose, a number of relations being used over the world are examined. Consequently a number of novel approximations are introduced for use of design engineers.*

1 INTRODUCTION

During earthquakes buildings are exposed to base excitations and gives different responses to those excitations. Buildings responds to those excitations with three components: structure, foundation and soil underlying the foundation. As these components are combined with each other, structure, foundation and soil interacts with each other, this phenomenon is known as Soil Foundation Structure Interaction (SFSI) or simply Soil Structure Interaction (SSI) [1].

Soil Structure Interaction is rarely taken into account during dynamical analysis of low rise buildings. The simplifications and approximations made during dynamical analysis of low rise buildings, such as natural period approximations, neglects effect of SSI. ASCE 7 [2] and Eurocode 8 [3] are some of the important seismic codes in the world. The natural period approximations recommended in these seismic codes do not take SSI into account for low rise buildings.

There is not an exact definition for the terms high rise or low rise buildings, but it may be defined as buildings that have few number of storeys or height of the building is under a certain value. In ASCE 7 [2] the approximate natural period formula is recommended for buildings that have 12 or less number of storeys. In some seismically risky zones in Turkey, buildings are not allowed to have more than 3 or 4 storeys. Accordingly, in this study we examined a building with 3 storeys.

The examined building in this study is a typical low rise building with 3 storeys and is symmetric in both lateral directions. Also typical cross sections are defined for all beams, all columns and all slabs. Since we consider low rise buildings, building is modeled as a reinforced concrete structure. Floor plan of the examined generic building is shown in Figure 1.

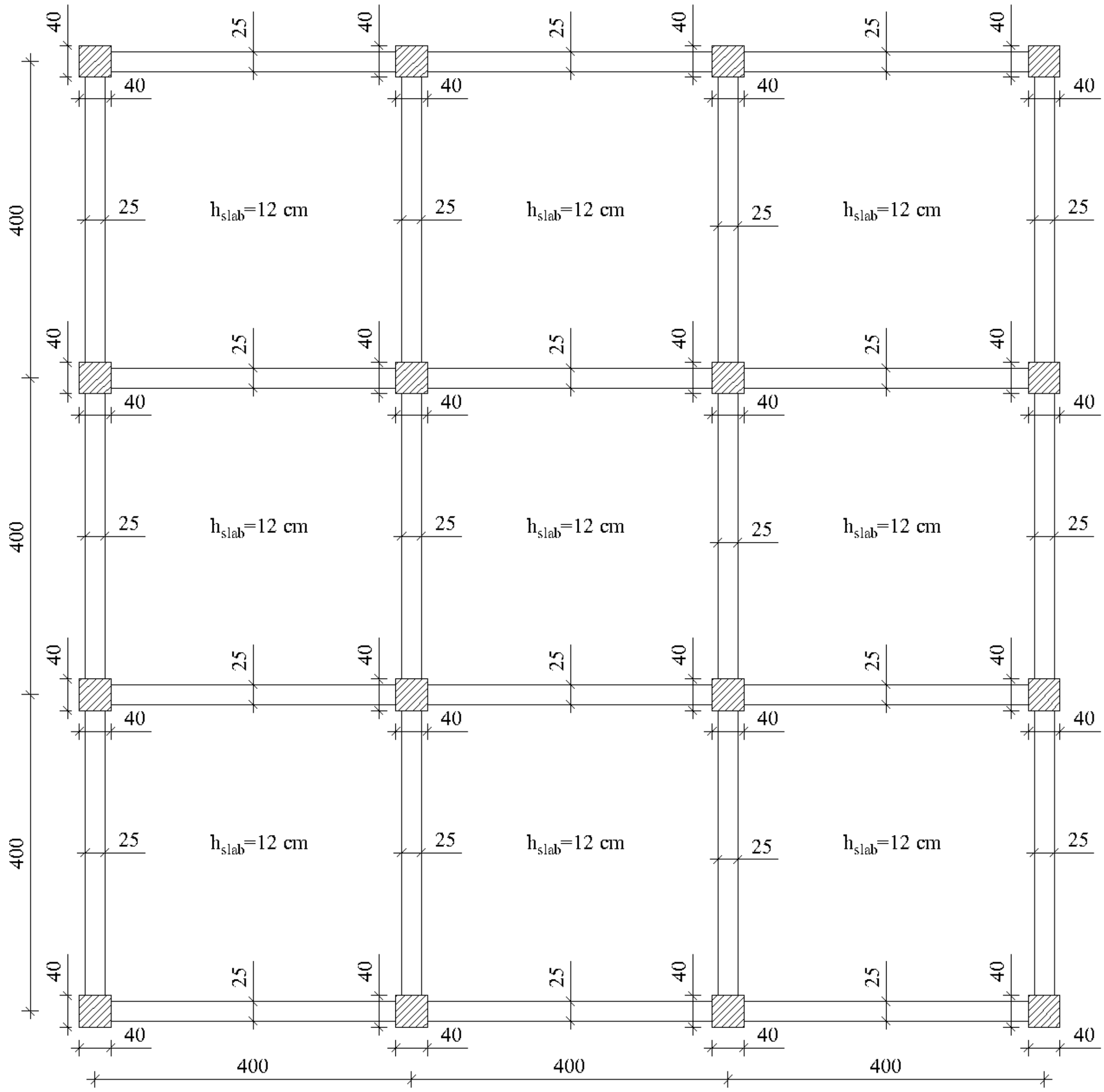

Figure 1 – Floor plan of the investigated building

The most widespread approach to consider SSI is the well-known Winkler Springs Method. In this approach, underlying soil layer is modeled as linear elastic springs in both lateral and vertical directions. Stiffness of those springs represents the subgrade reaction modulus of underlying soil layer.

In this study we aim to introduce novel approximations for natural period of low rise buildings which takes SSI into account. Accordingly a number of modal analysis are performed for a generic low rise building and we introduced a number of new approximations for first natural period of low rise buildings.

2 INVESTIGATION OF SUBGRADE MODULUS EFFECT

2.1 Properties of Investigated Building

As stated before, all columns and all beams are modeled with the same cross section. All beams are modeled as rectangular frame elements with dimensions of 50 cm depth and 25 cm width. All column elements are modeled as rectangular frame elements with $40\ \text{cm} \times 40\ \text{cm}$

dimensions. All slab elements are modelled as shell elements having a bending thickness of 12 cm. Also the foundation of the building is modeled as a shell element with a thickness of 100 cm.

All structural members are modelled with the same linear elastic material which represents reinforced concrete material. Young's modulus for this material is defined as $E = 3\times10^7$ kN/m^2 and Poisson's ratio is defined as $\upsilon = 0.2$. For this material mass per unit volume is defined as $\rho = 2.5$ kNs^2/m/m^3.

As shown in floor plan given in Figure 1, the investigated structure has 3 bays in X direction and Y direction. In both directions bay widths are equal to each other and 4 meters. This symmetric floor plan is adopted to simplify the problem and focus only on first natural period of the building which is equal to second natural period. As stated before the investigated building has 3 storeys and each storeys has the same height as 3 meters.

With those properties mentioned above, the investigated typical low rise building is defined and some modal analysis are performed.

2.2 SSI Procedure and Analysis

In this study Winkler springs method is employed to take SSI into account. In Winkler springs method, the underlying soil layer modeled as linear elastic springs and stiffness of these springs-spring constants- represents the subgrade reaction modulus of the soil layer. Lateral and vertical springs are modeled at column ends. Since the soil layer is continuous along the foundation or floor area, each spring set at each column end represents an area. Columns at inner points represents the area of a bay which can be calculated as $Area = 4\times4 = 16$ m^2 while columns at internal points on edges represents half of that area as $Area = 8$ m^2 and columns at corners represents quarter of that area as $Area = 4$ m^2. Spring constants calculated by using those areas and soil subgrade modulus.

$$K_s = k_s \times Area \tag{1}$$

To perform modal analysis OpenSees [4] software is utilized. Firstly, the investigated structure is modeled with a fixed base which means neglecting the SSI. Then, the modal analysis are performed considering SSI by using Winkler springs. At this step, subgrade reaction modulus of the soil layer is increased gradually and modal analysis performed repeatedly. To represent the subgrade reaction modulus values encountered generally, subgrade modulus values are increased gradually from 500 kN/m^3 to 10000 kN/m^3.

The calculated first natural periods are divided by the period value that neglects SSI to determine a simple ratio. As subgrade reaction modulus values increases, that ratio decreases exponentially. By using this relation two nonlinear regression coefficients are determined which relates period of SSI model to period of non-SSI model as a function of subgrade reaction modulus.

First natural period of the building with fixed base is determined as $T_{fix} = 0.2544$ sec. For subgrade reaction modulus values from 500 kN/m^3 to 10000 kN/m^3, first natural period of the building is determined as given in Table 1.

k_s (kN/m^3)	T (sec)	k_s (kN/m^3)	T (sec)
500	0,9751	5500	0,3535
1000	0,7014	6000	0,3447
1500	0,5829	6500	0,3372
2000	0,5140	7000	0,3308
2500	0,4683	7500	0,3253
3000	0,4356	8000	0,3204
3500	0,4110	8500	0,3161
4000	0,3918	9000	0,3123
4500	0,3764	9500	0,3089
5000	0,3639	10000	0,3059

Table 1 – First natural period and subgrade reaction modulus

Beside the first natural period values the ratio determined by dividing first natural period values of SSI models by first natural period of non-SSI model, can be plotted as shown in Figure 4.

$$\Gamma\left(k_s\right) = \frac{T_{SSI}}{T_{FIX}} \tag{2}$$

$$T_{SSI} = \Gamma\left(k_s\right).T_{FIX} \tag{3}$$

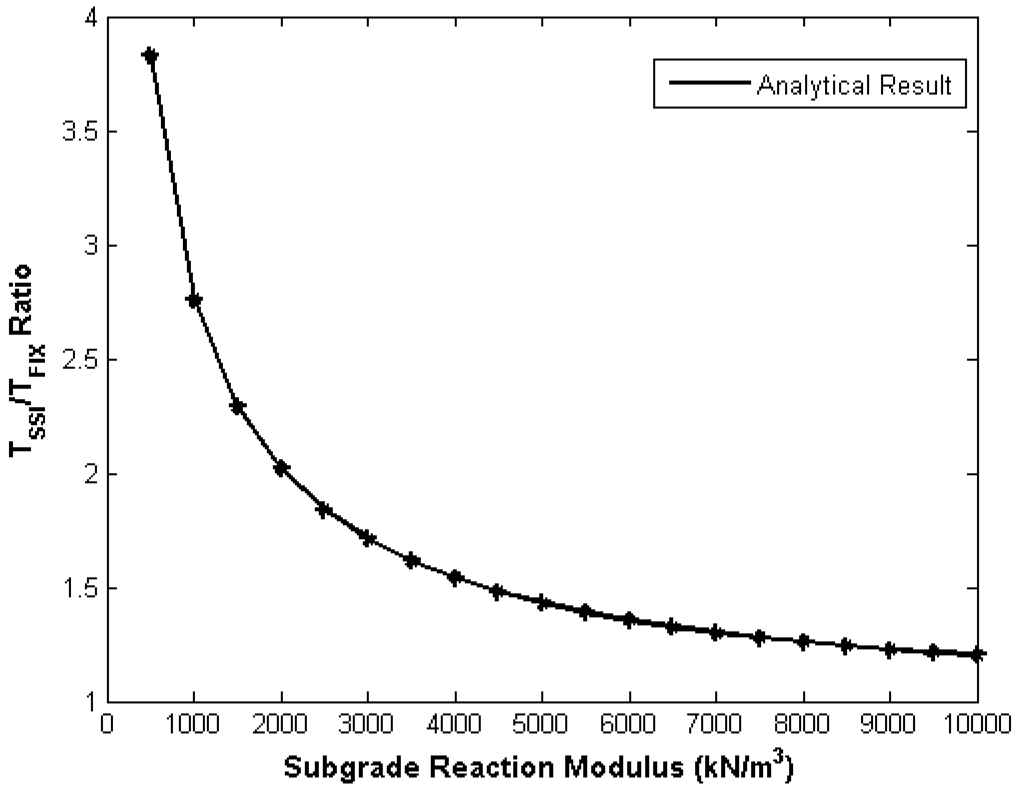

Figure 4 – First natural period ratio with respect to subgrade reaction modulus

In Figure 4 the graph shows the first natural period ratio determined by dividing period of SSI model by period of non-SSI model. As this plot is obtained by using analytical results, this curve is not an approximation. This curve represents the real relation between subgrade reaction modulus and $\Gamma\left(k_s\right)$.

The curve shown in Figure 4 can be represented by an inverse exponential function or inverse parabolic function. While using non-linear regression to determine an appropriate function to that curve, an inverse parabolic expression is recommended, regarding physical meaning of the problem.

The recommended relation is in the form shown below;

$$\Gamma(k_s) = 1 + \frac{\beta_1}{k_s} + \frac{\beta_2}{k_s^2} \tag{4}$$

Suitability of the recommended relation can be evaluated by considering that infinite subgrade reaction modulus yields 1, which corresponds to the fixed base condition. At the recommended expression, the third term is added to smoothen the expression.

The determined regression coefficients are as given below;

$$\begin{aligned} \beta_1 &= 2{,}2.10^3 \\ \beta_2 &= -4.10^5 \end{aligned} \tag{5}$$

Thus the recommended relation between the periods of SSI model and non-SSI model is determined as;

$$\Gamma(k_s) = 1 + \frac{2200}{k_s} - \frac{400000}{k_s^2} \tag{6}$$

In Figure 5 the graph shows the first natural period ratio determined by the recommended mathematical expression.

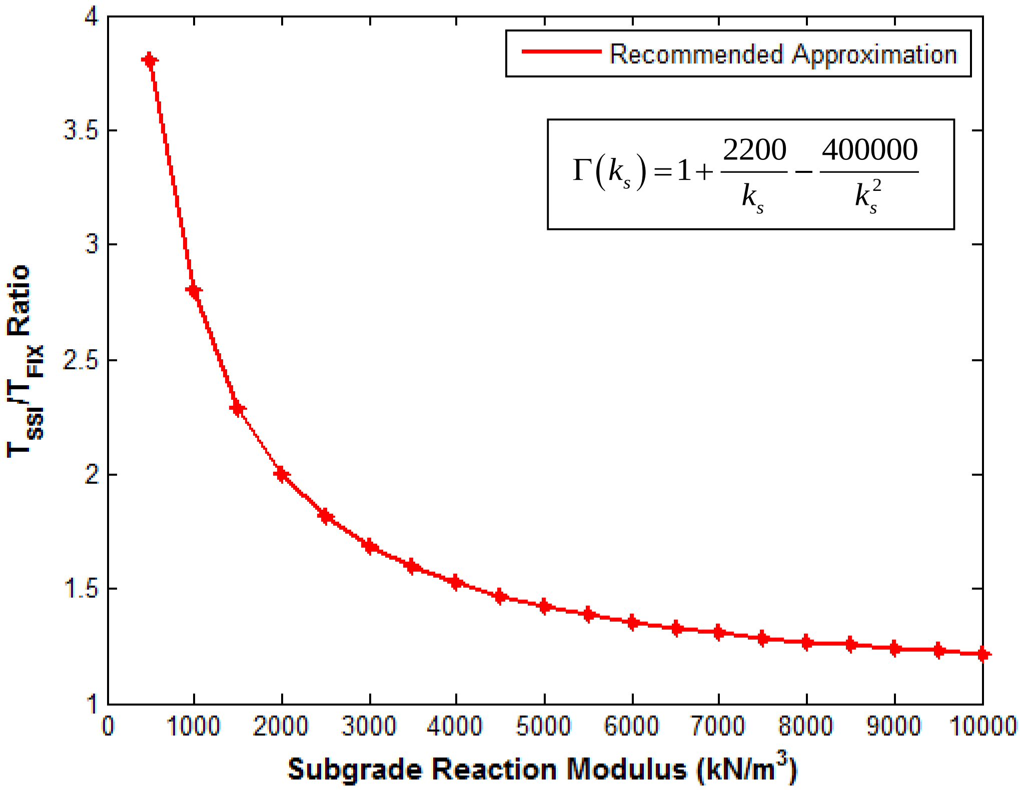

Figure 5 – Approximation for first natural period ratio with respect to subgrade reaction modulus

Thus the first natural period of structure while considering SSI, can be approximated by the relation given below.

$$T_{SSI} = \left(1 + \frac{2200}{k_s} - \frac{400000}{k_s^2}\right).T_{FIX} \tag{7}$$

3 CONCLUSION

In this study effect of subgrade reaction modulus on first natural period of low rise buildings is investigated. By utilizing nonlinear regression a novel approximation is introduced which relates first natural period of buildings determined by neglecting SSI to first natural period determined by not neglecting SSI. Then it can be said that the approximations recommended in prominent seismic codes to determine first natural period of low rise buildings can be modified. The introduced expression may be seen inconsistent since all analysis procedure considers a typical building with typical dimensions. However, the expression can give satisfactory results for low rise buildings, since aim of this study refers to low rise buildings. Nevertheless, further study is going on to introduce novel approximations for buildings with varying dimensions.

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