©2018 Published in 2ND International Symposium on
Natural Hazards and Disaster Management 04-06 MAY 2018 (ISHAD2018 Sakarya Turkey)

Static Foundation Stiffnesses by Considering Reduced Soil Shear Modulus for Soil-Structure Interaction Analysis

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Abstract

The goal of this study is to discuss in detail how to evaluate the effect of the strain-dependent shear modulus under seismic loads on the impedance functions used in the sub-structure method for idealizing the soil-foundation interaction problem. It has been written a MATLAB code for addressing these purposes. The case-study example is considered as a 4-story reinforced concrete building located in Istanbul. The load bearing system consists of shear walls and moment resisting frames with a total height of 12m from the basement level. The foundation system are composed of two different sized rectangular footings placed on clayey soil. In the numerical analyzes, two different plasticity states of the clayey soil were discussed (Herein, PI=13 and 16). In the first phase of this work, the shear modulus reduction factor was not considered in the analysis algorithm. Static stiffness values depending on the embedment depth of two rigid rectangular foundations were numerically calculated for translation and rocking vibrational modes. Afterwards, the translational and rotational static foundation stiffnesses by considering the effect of the reduced shear soil modulus have been obtained through the developed MATLAB code. It can see obviously from the analysis results that the strain induced in soil will depend on the extent of the earthquake demand. It is clearly observed that when the strain range increases, the static stiffness of the foundation medium decreases dramatically. The overall response of the structure can be affected considerably because of the degradation in soil stiffness even for a moderate earthquake. Therefore, it is very important to employ the corrected dynamic shear modulus for earthquake analysis including soil-structure interaction effects.

Key words: Soil-foundation interaction, sub-structure approach, impedance functions, reduced shear modulus, clay soil.

1. Introduction

The seismic performance of the geometrically large-scale rigid structural systems especially founded on soft soil is influenced by interaction between the superstructure, stiff foundation slab, and the geologic medium surrounding the foundation [1, 2]. Both the deformability of the supporting soil of the structure and geometrical parameters of the foundation basemat as well as the frequency content of the considered input motions modify overall dynamic response of the soil-structure coupled system. Numerical methods that can be employed to evaluate the dynamic soil structure interaction SSI effects on structural response can be classified as direct [3-5] and substructures approaches [6-8]. The most important parameter that will affect the numerical results of the soil-structure interaction problem is the value of the soil shear modulus that will be considered in the calculation of impedance functions [9, 10]. This geotechnical parameter plays an essential role on the dynamic behavior of the site and the structural vibrations under earthquake ground motion. Variation in soil shear strength with shear deformation under cycling loads makes difficult to select an appropriate shear modulus in the computation of the static

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stiffnesses of the rigid footing for achievement a more realistic dynamic soil-foundation interaction model. This paper deals with the effects of strain-dependent stiffnesses of the underlying soil on the impedance functions used in the sub-structure method for idealizing the soil-foundation interaction for various footing dimensions, embedment depths and clay plasticity.

2. Soil-Foundation Model and Solution Algorithm

In this study, the effect of local soil conditions on the dynamic behavior of the superstructure was investigated by the impedance functions defined in the foundation-soil interface and used in the substructure method of the soil-structure interaction problem. In this method, the deformation stiffness of the foundation medium corresponding to the rotational and lateral vibrations was evaluated according to the spring stiffness parameters concentrated at a single point on the foundation-soil interaction surface, which are expressed depending on the dimensions of the foundation plate and the mechanical properties of the soil medium including the material and radiation damping. A solution algorithm based on impedance functions for soil-structure interaction (SSI) analysis was developed in the MATLAB programming language in order to indicate the effect of the soil characteristics on foundation motion as well as the structural behavior. Furthermore, the stiffness loss of the foundation medium due to effect of the shear modulus in function of shear strain under dynamic loads was included in these numerical analyses. In general, the impedance functions k_j for translational and rotational vibrations of a rigid rectangular foundation can be written in the form of static foundation stiffness (K_j), dynamic stiffness modifiers (α_j) depending on excitation frequency of the dynamic load, and embedment correction factor (η_j):

$$k_j = K_j \; x \; \alpha_j \; x \; \eta_j \tag{1}$$

$$K_j = GB^m f\,(B/L,\ \nu),\ \alpha_j = f\,(B/L,\ a_o\,),\ \eta_j = f(B/L,\ D/B) \tag{2}$$

where K_j is a function of shear modulus (G), foundation dimensions (B, L) and Poisson ratio (ν) of the soil. Detailed information about the parameters mentioned in the equation (*2*) and commonly used values are given in [11]. Herein, only static stiffness parameters (K_j), which are named as simplified impedance functions (α_j=1), were computed within the frame of the developed analysis method. That means the response of the rigid rectangular footings was obtained by taking impedance values that are independent of the excitation frequency. In this study, the effect of degradation of soil stiffness on the static parameters under cyclic loads is reflected by the reduced shear modulus depending shear strain level.

3. Illustrative Numerical Example

The case-study for the soil-structure interaction problem is addressed as a 4-story reinforced concrete building structure with a total weight of 9633.6 KN located in Istanbul. The structural system consists of shear walls and moment resisting frames having a total height of 12m from the basement level. The dimensions of the footings are considered as 2m wide by 17m long below the moment frames and 7m wide by 17m long below the shear walls. Natural circular frequency of the superstructure is 41.9 Hz, which was obtained from the numerical analysis. The considered soil- foundation-structure system and the flexible base model to be utilized in impedance analyses is depicted in Figure 1.

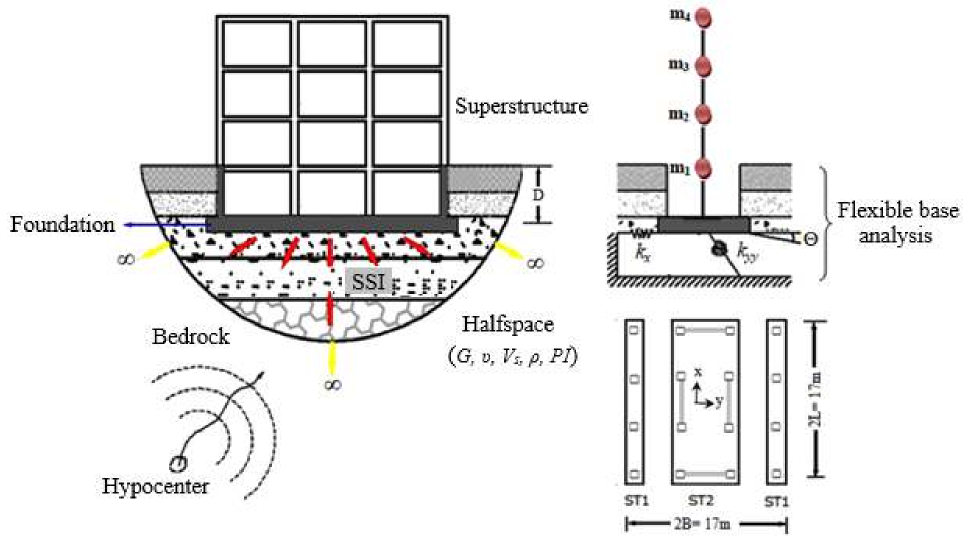

Figure 1. Schematic illustration of soil-foundation-structure system considered in the impedance analysis

The vibration response of the rigid foundations founded on clayey soil are investigated for two different plasticity (Herein, PI=13 and 16). Geotechnical parameters of the underlying soil are summarized in Table 1.

Table 1. Clayey soil characteristics of Istanbul/Kadiköy considered in SSI analysis

Soil group	Soil type	Local soil class	ρ [kN/m³]	G [kN/m²]	V_s [m/s]	ν	PI [%]	h_1 [m]
C	Stiff clay	Z2	13.95	83000	244	0.226	16	3.5
D	Soft clay	Z3	14.27	52600	192	0.388	13	2.5

The strain dependent shear modulus curves for stiff and soft clay are given in Figure 2.

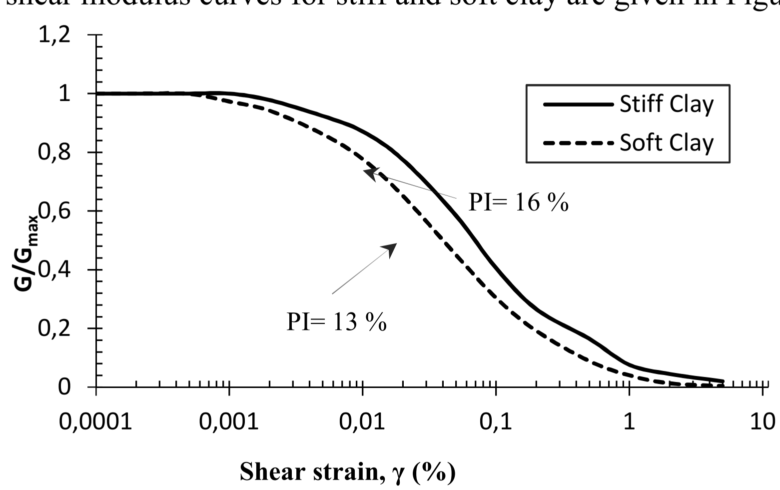

Figure 2. Variation of dynamic shear modulus with strain amplitude for two different clayey soil conditions

4. Results of the Analyses

Parametric analyzes were performed by taking into account both size and embedment depth of the footings. Three different embedment ratio (D/B=0, 0.25 and 0.5) are defined in the impedance analysis. The rectangular foundations, which have a size of 2m x 17m below the moment frames, are named as ST1 while the other 7m wide by 17m long below the shear wall is called as ST2. In the first phase of this work, the shear modulus reduction factor was not considered in the analysis algorithm. The static stiffness values of two rigid rectangular foundations resting on clayey soil with different plasticity were obtained for translation and rocking vibrational modes. The numerical predictions of the rigid foundation response for horizontal and rocking components are presented and compared in Table 2 and 3, respectively.

Table 2. Static stiffness depending on foundation embedment ratio for translation vibration mode

Rectangular foundation	Local soil class	Horizontal static stiffness [kN/m]		
		Foundation embedment ratio		
		D/B=0	D/B=0.25	D/B=0.5
ST1	Stiff clay (Z2)	1.3910×10^{6}	1.6071×10^{6}	1.7673×10^{6}
	Soft clay (Z3)	9.7008×10^{5}	11.2080×10^{5}	12.3250×10^{5}
ST2	Stiff clay (Z2)	2.3754×10^{6}	2.9402×10^{6}	3.3588×10^{6}
	Soft clay (Z3)	1.6566×10^{6}	2.0506×10^{6}	2.3425×10^{6}

Table 3. Static stiffness depending on foundation embedment ratio for rocking vibration mode

Rectangular foundation	Local soil class	Rocking static stiffness [kNm]		
		Foundation embedment ratio		
		D/B=0	D/B=0.25	D/B=0.5
ST1	Stiff clay (Z2)	6.8051×10^{7}	8.5065×10^{7}	10.2080×10^{7}
	Soft clay (Z3)	5.4542×10^{7}	6.8179×10^{7}	8.1818×10^{7}
ST2	Stiff clay (Z2)	1.4548×10^{8}	1.8227×10^{8}	2.1988×10^{8}
	Soft clay (Z3)	1.1660×10^{8}	1.4609×10^{8}	1.7623×10^{8}

Reviewing the reported values in Table 1 and Table 2, it is clearly observed that the increase of the ground contact surface and the embedment depth of the foundation basemats lead to an increase of the static stiffness parameters in all considered modes of vibration for the case of stiff and soft clayey soils. When the plasticity of the clayey soil decreases, the soil stiffness to which the surface foundations are supported decreases by more than 40% and 25% for lateral and rotational vibration modes, respectively. It is also noted that the effect of foundation embedment (D/B=0.5) on rotational stiffness (more than 50% for ST1) is more effective than the lateral stiffness (more than %25 for ST1) for two considered soil conditions. Based on numerically calculation, the lateral and rotational foundation stiffness by considering the variation of the reduced shear soil modulus with strain level in the case of stiff and soft clayey soil conditions were reported in Figure 3 and 4, respectively.

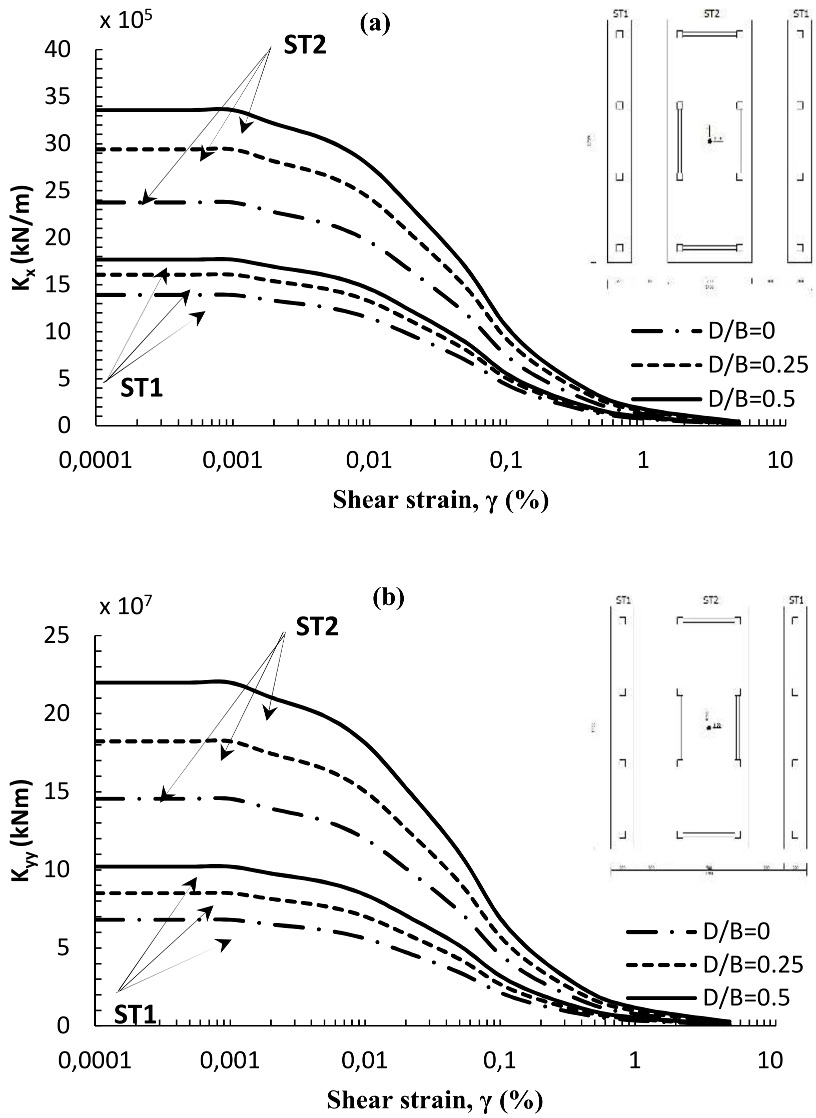

Figure 3. Variation of static stiffness with strain amplitude for horizontal and rocking vibration modes in the case of stiff clayey soil

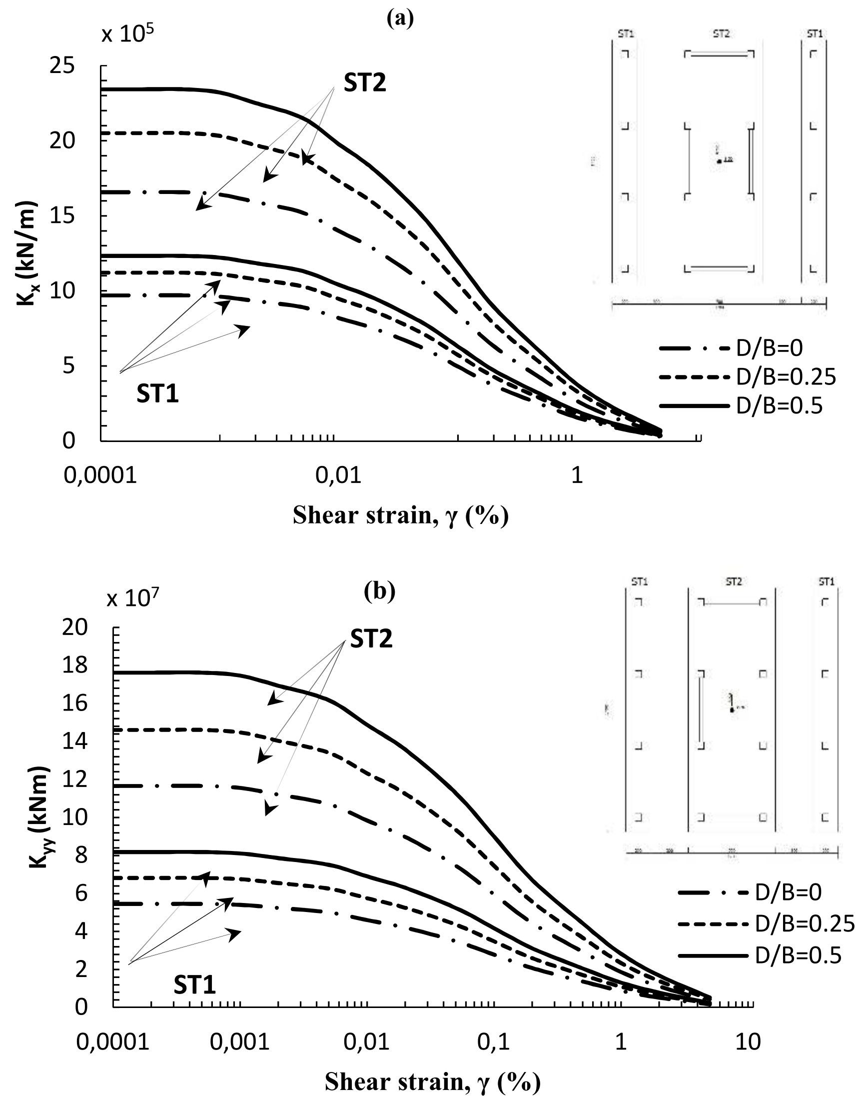

Figure 4. Variation of static stiffness with strain amplitude for horizontal and rocking vibration modes in the case of soft clayey soil

In this particular case, it can be deduced from these curves that the shear strain level significantly modifies the foundation stiffness even at hard clayey soil. The predicted static stiffness parameters due to the maximum shear modulus obtained from the site investigations correspond to very small shear deformations. However, it can be obviously seen that the static stiffness to be used in impedance functions when considering the reduced shear modulus is reduced by almost 20% in moderate shear deformations and by more than 90% in very large deformations for all considered vibrational modes. Considering the obtained values, it becomes apparent that the static stiffness is dependent on shear strain level. In addition, it is clearly to observe that as the width and embedment depth of the rigid foundation increases (Area of ST1<ST2), the static stiffness increases and this increase is around 70% for both cases of the soil.

5. Conclusions

This study deals with the effects of strain-dependent spring parameters for all considered vibration modes used in the substructure method. A solution algorithm in the MATLAB code was developed by using simplified impedance functions for modeling the soil-foundation interaction problem to ensure the seismic safety of major engineering structures to be built on low-bearing ground conditions in the active earthquake region. It is concluded that the size of the contact surface, the embedment depth of the building footings and the strain dependent shear modulus as well as the plasticity of the supporting clayey soil alter overall dynamic response of the structures. Based on the analysis results, it should be noted in realistic solutions that the shear modulus related to the shear strain level will depend on the extent of the earthquake demand. It is clearly observed that when the shear strain range increases under seismic loads, the static stiffness of the foundation medium decreases dramatically. The overall response of the structure can be affected considerably because of the degradation in soil stiffness even for a moderate earthquake. Therefore, it is very important to employ the corrected dynamic shear modulus for earthquake analysis including soil-structure interaction effects.

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