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QUALITATIVE INVESTIGATION OF THE EFFECT OF SOIL MODELING APPROACH ON DYNAMIC BEHAVIOR OF A SMALL-SCALE 2-DOF STRUCTURE WITH PILE FOUNDATION

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Abstract. *Known as a sophisticated phenomenon in civil engineering problems, soil structure interaction has been under deep investigations in the field of Geotechnics. On the other hand, advent of powerful computers has led to development of numerous numerical methods to deal with this phenomenon, resulting in a wide variety of methods trying to simulate the behavior of the soil stratum. This survey studies two common approaches to model the soil's behavior in a system consisting of a structure with two degrees of freedom, representing a two-storey frame structure made of steel, with the column resting on a pile embedded into sand in laboratory scale. The effect of soil simulation technique on the dynamic behavior of the structure is of major interest in the study. Utilized modeling approaches are the so-called Holistic method, and substitution of soil with respective impedance functions.*

1 INTRODUCTION

Among various methods used to simulate the effect of soil-structure interaction (henceforth referred to as SSI), substitution of the substructure with appropriate springs and dashpots has attracted considerable attention. Relative ease of modeling and compared to many common methods, less computational power demand are mentioned among the major reasons of popularity of this approach [1, 2, 3]; however, simulating the problem with a full three dimensional finite elements (FE) model is another common approach in practice. This approach, also called Holistic method, has been developed since the promotion of computing power, as long as the usually high number of degrees of freedom (DOF) requires fairly high computational demand. Impedance functions, which in fact represent the springs and dashpots modeling the substructure, have been extensively investigated in literature; however, the work presented by Novak et al. [4] is one of the pioneers in the field. Hence, the methodology proposed there is adopted here, shortly explained and tested on a case study. Finally, judgment is made on the prediction capability of the model when compared to the Holistic method.

2 IMPEDANCE FUNCTIONS OF SINGLE PILES

Presented in [4], Novak proposes stiffness constants and constants of equivalent viscous damping for single vertical piles. The soil's shear modulus is considered to be either constant or varying with depth according to a quadratic parabola, the tip of the pile could be either fixed or pinned and the constants are given for both end-bearing and floating piles. Figure 1 provides an illustration of global directions and naming conventions used in this work.

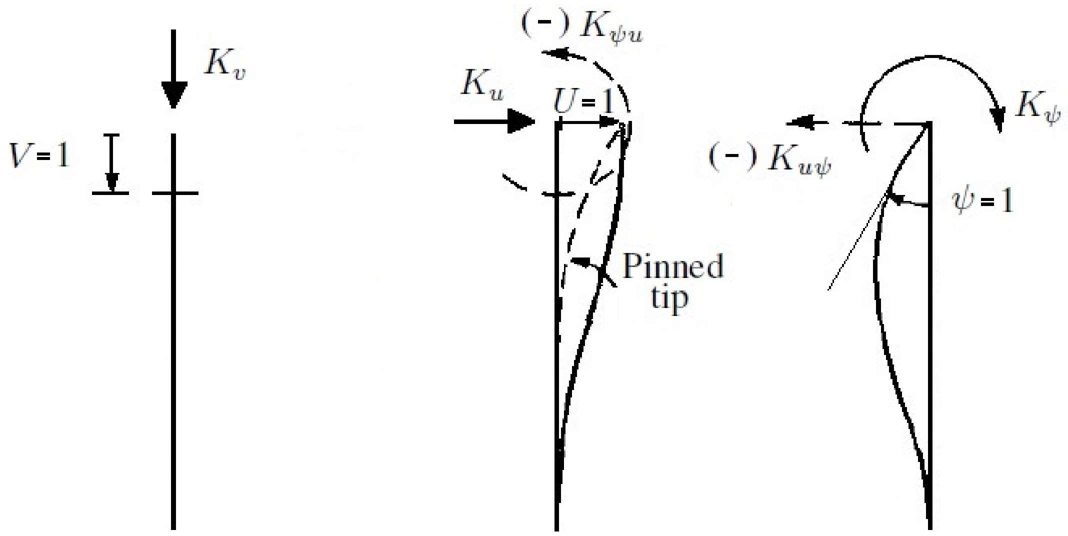

Figure 1: Introduction of Stiffness & Damping Constants for Individual Directions [4]

The stiffness and damping constants in different degrees of freedom are mentioned in Equation 1 to Equation 4.

$$K_v = \frac{E_p.A}{R}.f_{v1}, C_v = \frac{E_p.A}{V_s}.f_{v2} \tag{1}$$

$$K_u = \frac{E_p.I}{R^3}.f_{u1}, C_u = \frac{E_p.I}{R^2.V_s}.f_{u2} \tag{2}$$

$$K_\psi = \frac{E_p.I}{R}.f_{\psi 1}, C_\psi = \frac{E_p.I}{V_s}.f_{\psi 2} \tag{3}$$

$$K_c = \frac{E_p.I}{R^2}.f_{c1}, C_c = \frac{E_p.I}{R.V_s}.f_{c2} \tag{4}$$

where E_p, A, R and I represent, respectively, the pile's Young's modulus of elasticity, cross-section area, radius and moment of inertia, and $V_s = (G_s/\rho)^{0.5}$ is the characteristic shear wave velocity of the soil, with G_s being the soil's shear modulus and ρ representing its density. Index c represents ψu and $u\psi$, i.e. the coupling terms between horizontal translation and rotational degrees of freedom.

In their work, Novak neglects the torsional behavior around the pile's axis since he states that this motion is not only strongly frequency dependent, but also consequential just for caisson foundations or groups of massive piles.

The coefficients f_{ij} (with i representing the direction and $j = 1$ for stiffness and $j = 2$ for damping) are extensively introduced and studied in their research for various cases examined with different assumptions in the mentioned survey. Novak argues that excitation frequency does not considerably influence the coefficients for slender piles, and the relative mass ratio of soil to pile is only important for extremely heavy piles. Furthermore, he claims relative stiffness of pile to soil and also the soil's profile to be of major importance for determination of the factors f_{ij} in general, while the pile's slenderness and bottom conditions (floating or end-bearing) are decisive in its vertical behavior. Parabolic variation of soil's shear modulus, versus a constant modulus in the entire soil profile, represents the physically homogeneous soil stratum with its shear modulus increasing downward as the confining pressure enlarges. It is worth noting that for non-circular cross sections, utilization of an equivalent pile radius is possible [4].

3 EXAMPLE

3.1 Case study

The 2-DOF system with first and second eigenfrequencies of $4.0217Hz$ and $10.563Hz$ (fixed case), illustrated in Figure 2, is modeled when put on a pile resting in a homogeneous soil stratum. The rotation DOF is fixed in the lumped mass levels, so that the structure represents the behavior of a small-scale 2-storey steel frame. The circular cross section of the columns has a diameter of $7mm$. Table 3.1 exhibits the exact dimensions and material properties of the pile, the structure and the soil which, in the Holistic approach, is modeled as a linear elastic homogeneous material.

The system is modeled once with a full 3D continuum FE method (Holistic) as a reference (REF). The soil stratum together with the pile is then replaced by the springs proposed by Novak, assuming once a constant (C1) and once a parabolic (C2) soil profile as mentioned in section 2. The same procedure with the models using springs is repeated with the columns simulated by 2D beam elements (B1 for constant and B2 for parabolic soil profile).

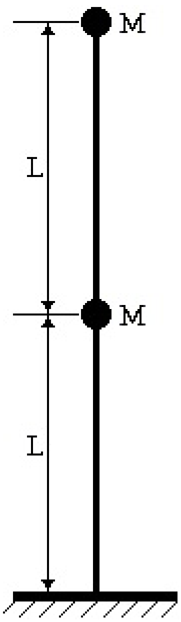

Figure 2: The Structural System

Property	Unit	Value
	Pile	
Young's modulus	Pa	$1.89 * 10^{11}$
Radius	m	$5.00 * 10^{-3}$
Length	m	0.15
	Soil	
Young's modulus	Pa	$4.74 * 10^{8}$
V_s	m/s	$3.2 * 10^{2}$
ρ	Kg/m^3	$1.85 * 10^{3}$
Poisson ratio	-	0.25
	Structure	
Young's modulus	Pa	$2.0 * 10^{11}$
L	m	0.45
M	Kg	1.7

Table 1: The Problem's Parameters

Direction	Stiffness	Damping
v	$5.95 * 10^{7}$	$2.62 * 10^{3}$
u	$1.76 * 10^{7}$	$6.73 * 10^{2}$
ψ	$6.96 * 10^{3}$	$7.55 * 10^{-2}$
c	$-2.48 * 10^{5}$	$-5.72 * 10^{0}$

Table 2: Springs' Stiffness & Damping Properties for Constant Soil Profile (SI Units)

Direction	Stiffness	Damping
v	$4.46 * 10^{7}$	$2.09 * 10^{3}$
u	$6.40 * 10^{6}$	$3.52 * 10^{2}$
ψ	$5.58 * 10^{3}$	$7.26 * 10^{-2}$
c	$-1.49 * 10^{5}$	$-4.28 * 10^{0}$

Table 3: Springs' Stiffness & Damping Properties for Parabolic Soil Profile (SI Units)

The five cases undergo an eigenfrequency calculation, accompanied by a 1-second forced vibration ($F(t) = 10\sin(31.4t)$) followed by 10 seconds of free vibration, while the structure experiences a damping ratio of 2%. Keeping in mind the required calculation time and modeling complexity, together with examining the responses in different cases, will finally lead to a qualitative comparison between different modeling techniques which address this problem.

3.2 Results

Based on the theory and problem dimensions explained in previous sections, the calculated stiffness and damping constants are presented in Table 2 and Table 3 for the constant and parabolic soil profile respectively.

Firstly, the error (here defined as the percentage of difference between a model's specific output and that of the reference model) in eigenfrequencies calculated by the four modeling approaches (C1, C2, B1 and B2 as previously defined in subsection 3.1) are presented in Figure 3. As can be seen, the C1 (3D elements for the beam and constant soil profile) model has a relatively more accurate prediction capability for both modes. It is also worth mentioning that both modes are most accurately predicted by C1, followed by C2 and finally B2 followed by B1 (beam elements and constant soil profile).

Finally, Figure 4 demonstrates the horizontal displacement of the top level of the structure in the first 8 seconds when excited by the load mentioned in subsection 3.1, comparing the reference (Holistic) and the B1 models. Fitting on the response of the reference model at almost every point, C1 proved to have the highest capability in simulating the problem. When compared to the REF, C2 model tends to predict lower displacement values in the excitation phase (the first second), and higher values in the free vibration phase, while a slight phase difference is also detectable. In contrast, B2 approach calculates higher displacement values in the excitation phase and lower values in the free vibration phase compared to the reference model. The phase difference is also intensified compared to the C2 model.

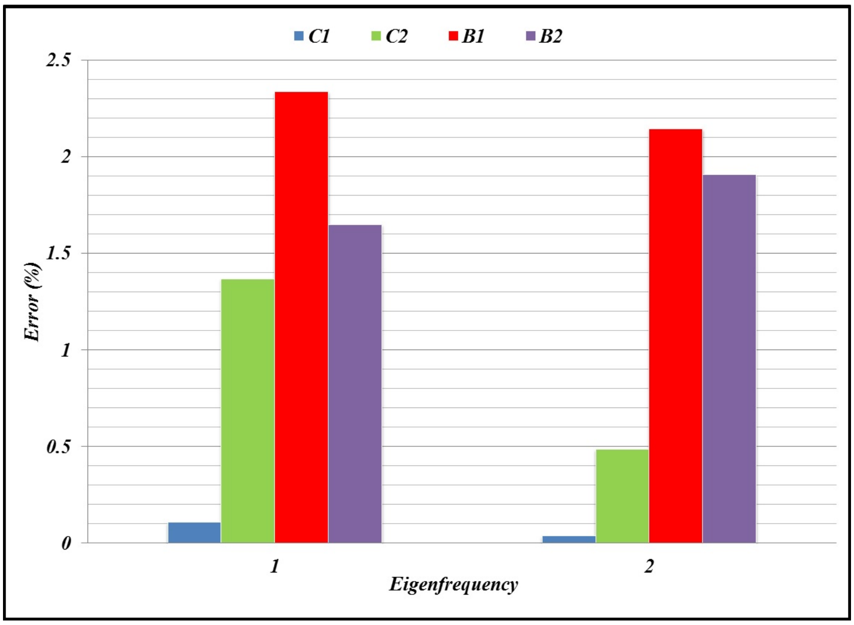

Figure 3: The Error of the Modeling Methods in Predicting the Eigenfrequencies

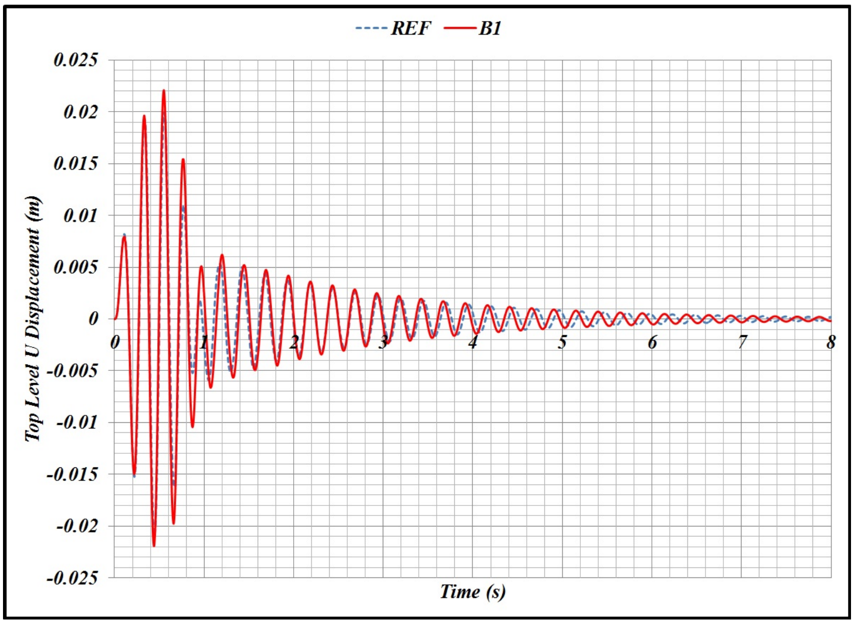

Figure 4: The Structure's Response Calculated with REF and B1 Models

4 CONCLUSION & REMARKS

Based on this study, it can be deduced that the substructure part of the full 3D FE model (Holistic) of a 2-DOF structure illustrated in Figure 2 resting on a pile embedded in a homogeneous elastic soil stratum can be best replaced by springs proposed by Novak [4], when the soil is assumed to have a constant profile and the columns are modeled with 3D (volume) elements. This approach, when compared with the Holistic model, predicts reasonably precise eigenfrequencies and structural response when excited by a 1-second harmonic load followed by a free vibration.
By performing an uncertainty analysis, however, a more accurate comparison between the methods could be made, leading to quantitative measures rather than qualitative comments.

Substitution of the soil layer and the pile with certain springs and dampers drastically reduces the computational effort and modeling complexity; however, one should keep in mind that a major drawback of application of such impedance functions is their incapability of capturing plastification and other phenomena not accounted for in an elastic modeling technique.

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