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Assessing physical mechanisms related to kinematic soil-pile interaction

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ABSTRACT

The kinematic soil-pile interaction is a cornerstone in developing seismic design procedure for piles. How to mathematically quantify this interaction has received intensive research efforts. However, to date, there is no consensus among researchers on the optimal mathematical model with sufficient accuracy and mathematical simplicity. Specifically, existing idealized models are frequently criticized as missing some important physical mechanisms, e.g., shear stresses in soil or continuity. It remains elusive to what extent these physical mechanisms contribute to the overall kinematic response. Herein, the contribution of each physical mechanism is singled out of the overall kinematic response of end-bearing piles with the aid of a continuum solution. Then, a series of parametric study shows that the contribution of each physical mechanism highly depends on the frequency, and the shear stresses in soil may contribute appreciably to the overall kinematic response.

1. Introduction

Kinematic soil-pile interaction originates from the seismic waves scattered by the pile embedded in soil and is important to understand how much resistances piles need under seismic wave excitations and how much seismic energy is transmitted to the superstructures. Therefore, kinematic soil-pile interaction should be included in the seismic design of piles and superstructures (e.g., Mylonakis and Gazetas [1]; Anoyatis et al. [2]). To fully describe the kinematic soil-pile interaction, numerous numerical methods have been developed, e.g., boundary element method [3] and dynamic finite element method [4–12]. In contrast to numerical methods, the analytical solutions directly reflect the physical nature and are easily implemented in engineering practice by idealizing the soil-pile interaction with a series of springs, dashpots, and shear layers. Among them, the Beam on Dynamic Winkler Foundation approach (BDWF) utilizes a series of springs and dashpots to describe soil-pile interaction, and has been frequently employed in seismic assessment of piles (e.g., Flores-Berrones and Whitman [13]; Makris and Gazetas [14]; Sica et al. [15,16]; Anoyatis et al. [17,18]; Di Laora and Rovithis [19]; Di Laora et al. [20]). Wang et al. [21] introduced the Pasternak foundation model to soil-pile interaction. Recently, Ke and Zhang [22] extended the Pasternak foundation model to kinematic soil-pile interaction, referred as Beam on Dynamic Pasternak Foundation model (BDPF), and concluded that the shear stresses in soil neglected by the BDWF model may contribute significantly to kinematic soil-pile interaction.

To date, it still remains elusive to what extent the kinematic soil-pile interaction can be simplified [23], and there are no quantitative methods on how each physical mechanism contributes to the overall response. The main objectives of this study are two-fold: (1) summarizing and identifying physical mechanisms underlying soil-pile interaction; (2) proposing a quantitative way to assess the impact of each physical mechanism on kinematic soil-pile interaction.

2. Physical mechanisms

Five physical mechanisms potentially contribute to dynamic equilibrium of piles under vertically-incident S waves, as shown in Fig. 1. In engineering practice, the piles are sufficiently slender such that they can be accurately captured by the Euler-Bernoulli beam. Therefore, the lateral resistance of pile is almost fully provided by the pile bending. As shown in Fig. 1a, the pile bending enables the pile to resist external loadings or the reaction pressure brought by surrounding soil. Physically, the pile bending dictates the seismic wave propagating in the pile body.

Generally, the lateral resistances of pile and soil are distinct, suggesting different response patterns under S wave excitations. The displacement compatibility generates interacting forces between soil and pile. Conventionally, these interacting forces are simplified as the reaction soil pressure produced by a series of springs, referred to as Winkler beam model, as shown in Fig. 1c. Subsequent researchers (e.g, Pasternak [24]; Kerr [25]) indicated that the Winkler beam model is

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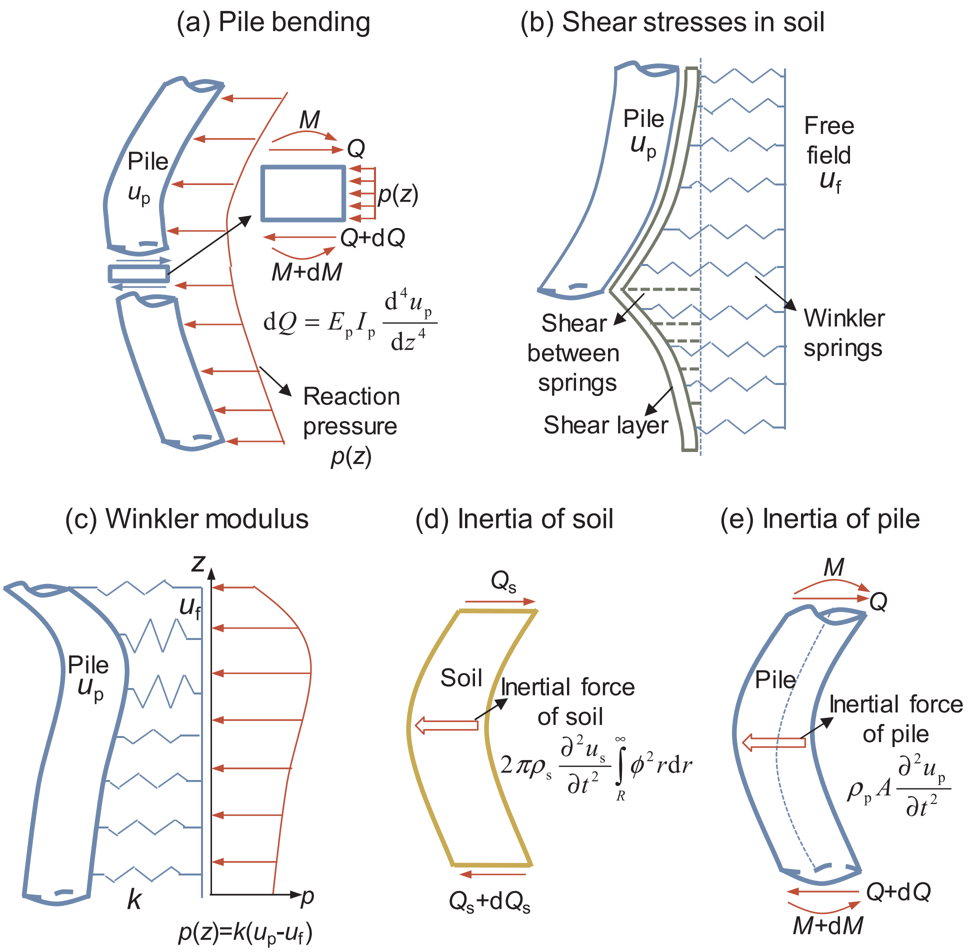

Fig. 1. Illustration of five physical mechanisms underlying kinematic soil-pile interaction.

incomplete due to its dissatisfaction with continuity in soil. Precisely, the interaction between springs is overlooked, and the underlying shear stresses in soil is neglected. To accommodate this shear behavior, a shear membrane is proposed to represent the shear stresses in soil, frequently referred to as Pasternak model, as shown in Fig. 1b.

Under seismic wave excitations, the inertial forces caused by the acceleration of soil and pile also contribute to the dynamic equilibrium of the soil-pile system, as illustrated in Fig. 1d-e. The inertia force of pile is essentially proportional to the mass and acceleration of pile body, which has been included in the BDWF model. However, the inertia force of soil represents the reaction pressure of soil to pile generated by the inertia of soil, which is frequently neglected. The mathematical formulations of these physical mechanisms will be derived with the aid of a modified Vlasov beam model below.

3. Mathematical model

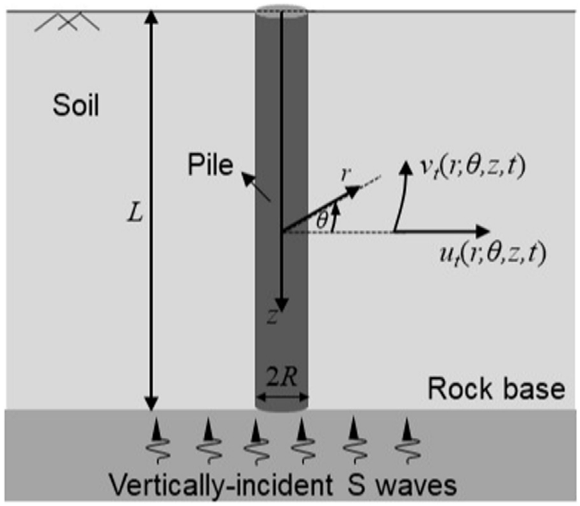

Fig. 2. Kinematic soil-pile system of interest.

An end-bearing pile is considered to showcase the proposed method as its ubiquitous application in routine practice, shown in Fig. 2. The pile of interest exhibits a length of L and a radius of R, and is embedded in a soil layer with a thickness of L. The soil is assumed to be linear viscoelastic, isotropic and homogeneous with physical properties: density ρ_s; Young's modulus E_s; damping ratio β_0; and Poisson's ratio ν_s. The pile is modeled by a linear elastic Euler-Bernoulli beam with physical parameters: density ρ_p; Young's modulus E_p; area $A_p = \pi R^2$; and area moment of inertia $I_p = \pi R^4/4$. The vertically-incident S waves exhibit a circular frequency of ω and an amplitude of u_g. The other parameters to simplify the derivation are defined as: shear modulus of soil $G_s = E_s/[2(1 + \nu_s)]$; complex elastic modulus of soil $E_s^* = E_s(1 + 2i\beta_0)^{0.5}$; and complex shear modulus of soil $G_s^* = E_s^*/[2(1 + \nu_s)]$.

3.1. Modified Vlasov model

The modified Vlasov model is selected to describe the kinematics of soil-pile system because it can maintain both displacement continuity and analytical nature. The modified Vlasov model [26] has been successfully implemented to model static soil-pile interaction [27–31] and