Soils and Foundations 2014;54(5):927–937

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Soils and Foundations

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# Horizontal impedance of pile groups considering shear behavior of multilayered soils

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Received 22 June 2013; received in revised form 13 April 2014; accepted 12 June 2014
Available online 14 October 2014

**Abstract**

The impedances and internal force distributions of a pile and pile groups subjected to horizontal harmonic pile-head loads have been studied. A layered Pasternak model, which overcomes the limitation of the Winkler model, that ignores the shear stiffness of the soil, is developed to describe the reaction of the soil on piles. The differential equation of the horizontal damped vibrations of a pile is solved by the initial parameter method, combined with transfer-matrix formulations, to deal with the layered property of the soil. The superposition approach, based on the interaction factors, is taken to estimate the effects of pile groups. The precision and the applicability of the method are demonstrated through this study. Comparing the results of the Pasternak model and the Winkler model, it is revealed that the role of soil shear has an influence on the impedances of a single pile and pile groups, especially in the case of a low pile–soil modulus ratio.


*Keywords:* Pile group; Pasternak model; Dynamic impedance; Transfer matrix method; Superposition approach

## 1. Introduction

Piles have been widely applied in deep foundations in various fields of engineering, such as high-rise buildings, bridges and offshore platforms, due to their high bearing capacity and good seismic performance. The dynamic impedance of a pile, which describes the force–displacement relationship including stiffness and damping, is a key issue when studying the soil–structure interaction (SSI) under seismic or impact excitations. In practical engineering, piles are commonly used in the form of closely spaced groups. Therefore, in addition to the loads transmitted from the pile caps, each pile in the group experiences the attached loads arising chiefly from the interference of wave fields coming from the adjacent piles. This phenomenon is called the dynamic group effect. The approaches to evaluate the dynamic impedance of pile groups can be classified into two main categories: (1) The direct method is generally realized by numerical methods, such as the finite element method (Tamura et al., 2012; Allani and Holeyman, 2013) or the boundary element method (Maeso et al., 2005); (2) The superposition method (Markis and Gazetas, 1992) is based on the interaction factors, rather than simply superimposed impedances, of every pile in the group. It is well known that the finite and boundary element models are far too complicated and time-consuming to solve a large practical project, while the superposition method is a simple, and yet, commonly effective approach to problem solving.

Poulos (1968) first presented the concept of "interaction factors" for the mechanical study of a statically loaded pile group, which was latterly extended to a dynamic analysis (Kaynia and Kausel, 1982; Ghazavi et al., 2013). The factors

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Peer review under responsibility of The Japanese Geotechnical Society.

http://dx.doi.org/10.1016/j.sandf.2014.09.001
0038-0806/

related to the frequency of the external load were obtained through the boundary integral approach (Gazetas et al., 1991). The dynamic response of a pile group embedded in homogeneous and non-homogeneous soil media was provided by the superposition method (Kaynia and Kausel, 1991; Miura et al., 1994). Dobry and Gazetas (1988) used the Winkler model to calculate the dynamic interaction factors in a pair of piles embedded in a uniform stratum, in which the interaction between the receiver pile and the surrounding soil was disregarded. The method was further refined to obtain the dynamic interaction of a single pile (Markis, 1994) and a pile group (Markis and Badoni, 1995) under Rayleigh-waves by considering the pile–soil–pile interaction. Mylonakis and Gazetas (1999) presented a simplified analytical formulation to estimate the interaction factors, dynamic impedances and internal forces of a pile group embedded in soil with linearly varying elasticity based on the Winkler model. Halabe and Jain (1996) showed the influence of a preloaded axial force on the natural frequency of a single pile using the Winkler model. Hasan and Mehraz (2011) analyzed the interaction factors between two adjacent piles with an inclination angle (less than 30°). It is well known that in the Winkler model, the pile is treated as a beam imbedded in an elastic foundation and the reaction of the soil against the pile deformation is modeled by the closely distributed springs and dashpots along the pile shaft. Due to its clear physical concept and low computational complexity, the Winkler model has been the subject of detailed researches and has experienced widespread applications.

However, the Winkler model assumes that the foundation pressure at any point is only proportional to the deflection at that point. Therefore, it cannot represent the continuous deformation of a practical foundation. To overcome the limitations of the Winkler model, the Pasternak model, which considers the shear behavior of soil, has been introduced to investigate the mechanical behavior of foundations (Rosa and Maurizi, 1999; Zhou et al., 2006). Rosa and Maurizi (1999) solved the differential equation of motion for a Pasternak foundation pile with a piecewise constant cross-section, in the presence of elastically flexible ends and axial tip force. Filipic and Rosalesa (2002) presented the solutions, stated by means of the extended trigonometric series, for the natural frequencies and critical buckling loads of a pile embedded in soil simulated by two elastic parameters. Dogan and Mesut (2011) studied the free vibration of a graded pile embedded in a uniform Pasternak foundation. The variation in the non-dimensional frequency of a single pile was analyzed with respect to the two elastic parameters. To the best of the authors' knowledge, there have been no reports of studies on the dynamic impedance of pile groups based on the Pasternak model.

In this paper, the horizontal vibrations of a pile group in a layered Pasternak foundation are investigated. The differential equation of horizontal damped vibrations for a pile is solved by the initial parameter method. The horizontal impedance of a single pile and the interaction factor between two adjacent piles are obtained by using the transfer matrix method. The horizontal impedance of a pile group and the distribution of internal forces along each pile shaft are finally obtained by the superposition method. The effects of various structural and soil parameters on the impedance of the pile group are analyzed in detail.

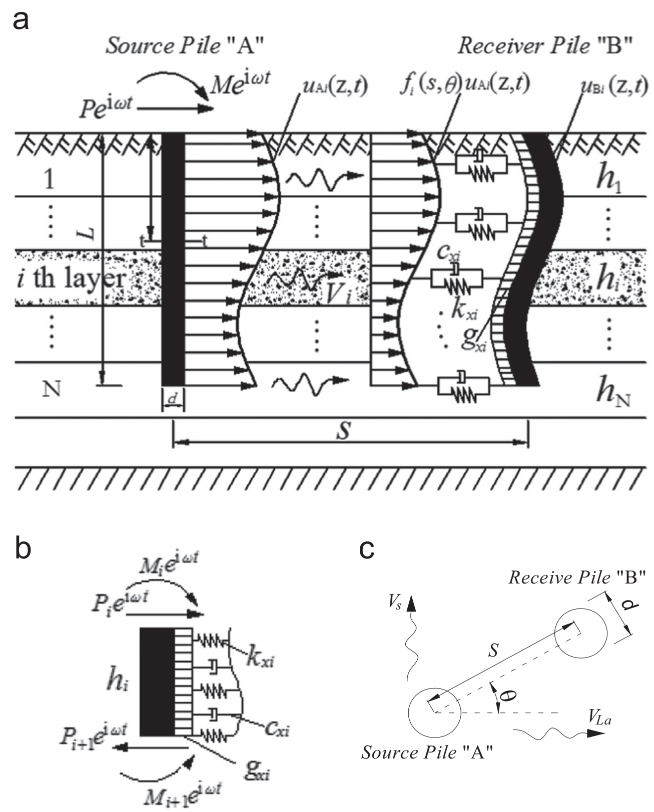


Fig. 1. Model description. (a) Horizontal vibration of piles in Pasternak layered foundation; (b) pile element in soil layer; and (c) relative position of two piles.

## 2. Formulations

### 2.1. Horizontal vibration of a pile

Consider a cylindrical elastic pile excited by a horizontal harmonic force or moment acting on the pile head, as the source pile shown in Fig. 1(a). The foundation is taken into account as a system composed of infinitely close linear springs and dashpots, which are connected through an incompressible shear layer. According to the specific distribution of the stratum, the pile is divided into $N$ segments along its shaft with the origin at the head, so that the soil in each segment has uniform mechanical properties. The Euler–Bernoulli beam theory is used to describe the transverse vibration of the pile. The Pasternak model is used to describe the reaction of the soil on the pile. The governing dynamic equation of the $i$th segment embedded in a uniform soil, shown in Fig. 1(b), can be expressed as

$$E_pI_p\,\frac{\partial^4 u_{Ai}(z,t)}{\partial z^4}+\rho_pA_p\,\frac{\partial^2 u_{Ai}(z,t)}{\partial t^2}+c_{si}\,\frac{\partial u_{Ai}(z,t)}{\partial t}-g_{si}\,\frac{\partial^2 u_{Ai}(z,t)}{\partial z^2}+k_{si}u_{Ai}(z,t)=0 \tag{1}$$