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Time domain nonlinear lateral response of dynamically loaded composite caisson-piles foundations in layered cohesive soils

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ABSTRACT

A nonlinear Winkler model for composite caisson-piles foundation (CCPF) is proposed by joining the two components, the caisson and the pile group, in which the nonlinear four-spring Winkler model is utilized for the caisson and the axial-lateral coupled vibration equations are derived for the pile group. Then the nonlinear lateral dynamic response of CCPFs embedded in layered cohesive soils and loaded at its top center is investigated by a simplified time domain method based on the model. All the impedance functions of the foundations are frequency independent, which make it easy to conduct a standard time domain analysis. The results are compared with 3D finite element simulations and the consistence convincingly verifies the reliability of the simplified method. The nonlinear Winkler model is also extended to consider the gapping and the cyclic degradation, and it is shown to be capable of reproducing various important nonlinear features such as oval-shaped or s-shaped hysteresis loops. Finally, the lateral dynamic responses of CCPFs with three different configurations of pile group are analyzed. The results indicate that the configuration of pile group beneath the caisson plays an important role in the lateral dynamic response of the CCPF. The results also convincingly illustrate the important role of considering the soil nonlinearity, cyclic degradation and gapping in the dynamic analysis of the CCPF.

1. Introduction

For bridge crossing rivers or seas, pile groups and caisson are the most common forms of deep-water foundation. However, the construction of traditional pile groups is difficult due to its long length, while it was believed for many years that the performance of caisson foundation subjected to seismic loading is poor. Combining the advantages of pile groups and caisson foundation, the composite caisson-piles foundation (CCPF) was first proposed in the pre-construction investigation for the highway channel crossing the Qiongzhou straits in South China Sea and it shows better dynamic behavior when subjected to lateral and seismic loads [1]. Zhong and Huang [1,2] developed a dynamic Winkler soil model in the frequency domain for the lateral response of CCPF, as shown in Fig. 1. However, the major limitation of the approach is that the soil was assumed to be linear elastic and the important nonlinear soil behavior has not been taken into account. It also assumed that the CCPF remained in complete contact with the surrounding soil. Nevertheless, the actual interactions between CCPF and soil involve complicated material and geometric nonlinearities such as soil inelasticity, separation, slippage and strong interface nonlinearities when the foundation was subjected to moderate or strong seismic loading or other excitations. To obtain such nonlinear response, a more reasonable model should be proposed.

Since the CCPF is a composite of a caisson and pile groups, it is reasonable to divide the foundation into two parts, caisson and pile groups, for detailed analysis. Caissons are widely used in deep-water or offshore engineering [3]. However, until now only a few studies have been carried out on the caisson foundations. Gerolymos and Gazetas [3–5] proposed an efficient method to calculate the lateral response of caisson by idealizing the soil medium as a Winkler model with four-springs and further improved the method to capture the nonlinear behavior using the Bouc-wen model [6]. Varun et al. [7] calibrated the spring coefficients of the Winkler model in a multi-layered soil using 3D finite element method. Despite the lack of published researches about caissons, there are abundant references in terms of embedded foundations, which can enlighten the study of caissons, such as Wolf [8], Wolf and Somaini [9], Beredugo and Novak [10], and Gazetas [11].

Different approaches for dynamic response of pile groups have been proposed by researchers as well, such as finite element method (FEM) and simplified models. The FEM can analyze problems with complicated geometry and advanced soil constitutive models can be used to account for the complicated soil behavior under dynamic load [12,13].

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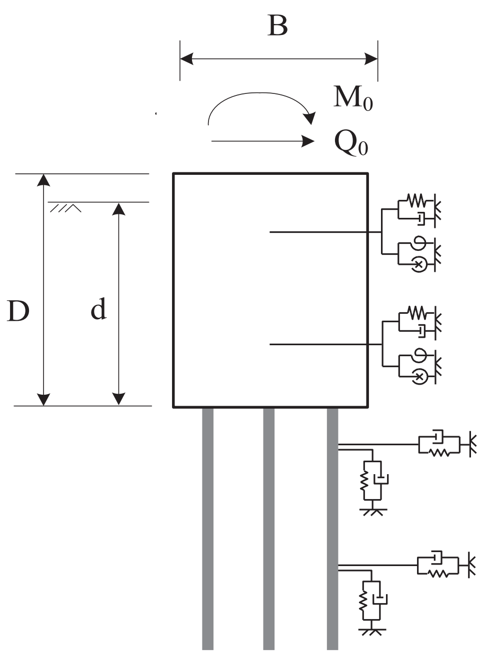

Fig. 1. Dynamic Winkler model of CCPF.

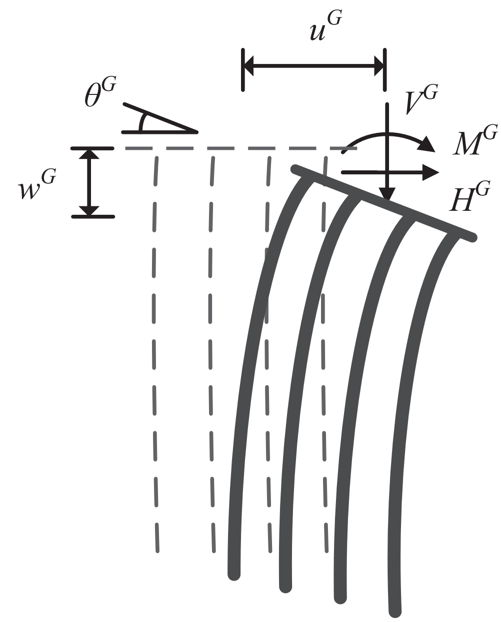

Fig. 2. Axial-lateral coupled vibration of the pile group.

However, FEM may costs large computational efforts during the analysis. On the other hand, simplified models, especially the Winkler model, had also been developed to analyze the axial, lateral, as well as the seismic responses of pile groups. In order to achieve reasonable nonlinear hysteretic behavior of soil and interface, the beam on a nonlinear Winkler foundation (BNWF) method became the most commonly used approach which is extended from the linear Winkler model [14,15]. Some researchers [16,17] also used a phenomenological constitutive model which called BWGG model to make an approximation for pile dynamic analysis. It should be noted that the BWGG model needs more parameters to define the *p-y* curves compared to the BNWF model during the analysis. Generally, all these simplified methods can be divided into two categories according to the selection of backbone curves: using the empirical *p-y* curves directly [18,19] and using the stress-strain curves to derive *p-y* curves [20,21]. It should be emphasized that the nonlinear dynamic response analysis using these simplified models must be conducted in the time domain, especially in analyzing the transient dynamic response or seismic response. However, all the analytical procedures of a single pile or pile groups mentioned above were not rigorously developed in the time domain due to the frequency-dependence of stiffness and damping parameters. For example, a time domain Winkler model was developed for analyzing the axial and lateral response analysis of a single pile subjected to dynamic transient loading by Nogami and Konagai [22,23]. Then it was extend to obtain the dynamic response of axially loaded pile group accounting for pile-soil-pile interaction by Konagai and Nogami [24]. Nevertheless, the calculations were based on the hypothesis that the pile displacement is in a polynomial form. It may be a crude approximation in terms of the actual deformation.

In this paper, a time domain simplified analysis approach is developed for analyzing the nonlinear lateral dynamic response of the CCPF. The developed model accounts for the nonlinear behavior of the soil adjacent to the CCPF. The presented approach enables the direct time domain computation of the dynamic response of the CCPF, and it can be directly utilized for the response analysis of the CCPF subjected to any type of dynamic loadings since the impedance functions are frequency-independent. In order to verify the proposed simplified method, a series of 3D finite element simulations have been developed, and the results agree well with the proposed simplified method. The model is also extended to consider the gapping, and the nonlinear cyclic behavior in a rational manner. Finally, the significance of the pile group configuration beneath the caisson in lateral dynamic analyses of CCPF was investigated.

2. Nonlinear lateral response of pile groups in layered soils

Although several studies have been carried out on the lateral vibrations of pile groups [15,19,25], only few of them are dedicated to the axial-lateral coupled excitation in time domain. However, pile deformations are accompanied with the vertical displacement, especially for a rigid cap or caisson at the top of piles. This will result in vertical force and additional moment on the pile top, as depicted in Fig. 2. According to the deformation mode, proper calculated models for the single pile and the interaction between two piles should be established to investigate the dynamic response of pile groups.

2.1. Nonlinear lateral dynamic response of the single pile

The beam on nonlinear Winkler foundation method (BNWF) is widely used because of its simplicity, and it can also account for the nonlinear behavior of soil and interface properly. In a BNWF model, pile is divided into a series of discrete elements with damper and stiffness springs along the pile shaft, as shown in Fig. 3. Soil is also divided into segments with the same number and length as the pile. Selection of the appropriate *p-y* properties is the major factors affecting the accuracy of the model. Several researchers have discussed and improved the properties of *p-y* curves based on the generalized BNWF model [18,19,26], while the patterns of the dynamic response obtained by these approaches are unlikely changed too much. In what follows, a classical hyperbolic stress-strain model which associated with basic physical parameters of soil is employed to derive the *p-y* curve used as the backbone curve of a generalized BNWF model.

2.1.1. Backbones

The backbone of hyperbolic stress-strain model is given by [27] :

$$c_m(\varepsilon_s) = \frac{G_0 \cdot \varepsilon_s}{G_0 \cdot \varepsilon_s / S_u + 1} \tag{1}$$

where ε_s is the shear strain of soil , $c_m(\varepsilon_s)$ is the yield stress that corresponds to ε_s, S_u is the undrained shear strength of soil, and G_0 is the initial shear modulus of soil.