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Simplified *p-y* curves under dynamic loading in dry sand

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ABSTRACT

The behavior of soil-pile systems subjected to dynamic loads in dry sand was investigated using experimental tests. The focus of this study was to quantify the simplified dynamic *p-y* curve for pseudo-static analysis from model tests under various loading frequencies. A framework for determining the *p-y* curve on the basis of 1 g shaking table tests was introduced. Based on the results of the model tests, the dynamic *p-y* curve is highly dependent on the relationships between the natural frequency of the soil-pile system and the loading frequency, the acceleration amplitude and the relative density of soil. The simplified dynamic *p-y* curve is a hyperbolic function. The initial slope and the ultimate soil resistance were proposed as functions of the properties of the pile and soil. The proposed *p-y* curves were determined to be more appropriate than the existing *p-y* curves for representing the soil-pile interaction for a single pile under dynamic loads in dry sand.

1. Introduction

Recently, the number of large-scale earthquakes of magnitude 6.0 or greater, and their resulting tsunamis, has increased worldwide, resulting in many human injuries and substantial property damage. Seismic design has become increasingly important to reduce the threat that earthquake-induced structural deformation and damage poses to communities and property. To analyze the performance of piles under dynamic loads such as earthquakes, a number of analytical and numerical approaches have been proposed based on either linear elastic or viscoelastic models [1–6]. However, pile foundations behave nonlinearly under dynamic loads due to the plastic deformation of the soil, soil-pile separation and slippage. Therefore, nonlinear analysis is required to analyze the behavior of piles under dynamic loads.

Lumped mass models, which feature nonlinear springs and dampers along the pile, as well as gapping mechanisms, were developed to reproduce strong nonlinear effects [7–10]; however, relating the characteristics of the discrete elements to the general soil parameters is difficult [11]. Alternatively, the lateral load transfer curve method, often referred to as the *p-y* curve method, has been studied to define soil stiffness at a particular depth. This method is based on a numerical solution of a physical model based on a beam with a Winkler foundation. *p-y* curves have been established based on full-scale pile head loading tests under static or cyclic loads [12–18].

Pseudo-static analysis, which is a method of converting dynamic loads into the equivalent static loads using inertial loads, is widely used in the seismic design of pile foundations. *P-y* curves, which were proposed by Reese et al. [14] and the API (American Petroleum Institute) [17], are most frequently used for pseudo-static analysis in practical engineering applications. However, *p-y* curves do not properly consider soil stiffness or soil inertia effects under seismic loads because the *p-y* curves are derived from field tests by applying static and cyclic loads at the pile head [19–25].

Considerable work has been conducted by many researchers on laterally loaded piles by considering the dynamic loading conditions to overcome the limitation of the existing *p-y* curves. Ting et al. [26] noted that the secant slope of the dynamic *p-y* curve is highly dependent on the loading frequencies in dynamic pile load tests. On the basis of the API *p-y* curve, Boulanger et al. [27] proposed that the *p-y* element equations can be conceptualized as elastic, plastic and gap components in series. However, the model is too complicated for pseudo-static analysis in practical engineering applications.

The NCHRP (National Cooperative Highway Research Program) [28] described that the dynamic behavior of the soil-pile interaction is closely associated with the pile diameters, shear wave velocities of the soil and loading frequencies. Additionally, the NCHRP suggested dynamic *p-y* curves by using a numerical analysis method that related the static *p-y* curves to the dimensionless frequency. However, the verification of the dynamic *p-y* curves was conducted under restrictive conditions by statnamic tests in which a lateral load was applied on a pile head. El Naggar and Bentley [29] observed that the soil resistance under dynamic loading increases due to the damping effect. They also noted that the dynamic *p-y* curves depended on the loading frequency. Yang et al. [21] and Yoo et al. [30] proposed dynamic *p-y* backbone

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