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Numerical modeling of parallel seismic method for detecting existing piles in layered soil

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Abstract

For piles connected to superstructures, whose pile tops are inaccessible, a lateral horizontal impact on the side of the piles through the generation of a flexural wave of the pile shaft is a more feasible approach. This paper presents a parallel seismic (PS) method based on the flexural wave of the pile shaft that combines down-hole tests for the length and an integrity evaluation of existing piles in layered soil. It is suggested that two PS tests be conducted by horizontal striking on the side surface of the pile along and perpendicular to the pile-to-borehole direction, respectively. The first arrivals of the transmitted P-wave and S-wave at the pile-soil interface obtained in these two PS tests and the results of down-hole tests are combined to analyze the pile length and to distinguish the embedded defects for the pile integrity evaluation. A simplified theoretical model for PS tests in layered soil is established, and a correction formula is proposed to correct the initial estimated pile length accordingly. A three-dimensional finite element model is then established to verify the effectiveness and reliability of the proposed PS method in layered soil and the correction formula.

Keywords: Existing piles; Parallel seismic method; Integrity; Flexural wave; Nondestructive test

1. Introduction

Determining the length of piles and characterizing the possible defects of existing pile foundations are extremely necessary and important in some situations, such as when unplanned changes in loading must be applied to foundations, old foundations must be reused, and an integrity evaluation of the piles must be performed after earthquakes (Hertlein and Walton, 2000). However, due mainly to the lack of necessary design information and construction records, quality evaluations of pile foundations under existing superstructures for load capacity assessments remain a big challenge for civil engineers (Davis, 1995; Olson et al., 1995; Rix et al., 1996).

In terms of nondestructive techniques for existing pile foundations, Olson et al. (1996) emphasized that the parallel seismic (PS) test has been shown to have the broadest applications and greatest potential among these techniques. Kenai and Bahar (2003) and Lo et al. (2009) showed several cases of PS tests for practical applications. With these cases, the pile bottom was normally identified as an inflection point showing an evident change in the slope of the stacked trace plots (Davis, 1995). Owing to the existence of the pile-to-borehole distance, the pile length by this approach is often overestimated. To eliminate the effect of this distortion, Liao et al. (2006) proposed a correction formula based on the determined velocities of waves in piles and soil and the pile-borehole distance in order to improve the estimation accuracy. Huang and Chen (2007) presented a method by which the upper first arrival line beside the pile shaft is switched to pass through the origin

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point, and the location of the intersecting point of this new shifted line and the lower first arrival line was taken as the pile bottom. However, as the height of the location of the impact above the ground is not considered, this method usually yields a shallower estimation. In PS tests, the testing borehole should be strictly parallel to the pile. In their study, Ni et al. (2011) showed the influence of the borehole inclination on the pile length estimation and proposed a formula to correct this effect. Niederleithinger (2012) developed a new mathematical algorithm for data interpretation, which takes into account the soil layers and the borehole inclination. The applicability of the parallel seismic method was then extended to situations with greater pile-borehole distances.

These recent studies on PS tests were conducted based on the one-dimensional (1-D) longitudinal wave (P-wave) of the pile shaft. When piles are connected to superstructures, for which there is no access to the pile tops, a lateral horizontal impact on the side of the pile through the generation of a flexural wave of the pile shaft is a more feasible approach (Uncuoğlu and Laman, 2012; Wang et al., 2010). Investigations related to the flexural wave have mainly focused on exploring the dispersive characteristics and testing approaches for existing piles. Wang (2004) solved the governing equation for a pile embedded in homogeneous soil in terms of the flexural modes. It was difficult to excite high flexural modes $F(p, q)$ ($p > 1$, $q > 1$, p is the mode number and q is the branch number) due to the complex displacement patterns for higher modes and the existence of cut-off frequencies for higher branches (Wang, 2004; Lynch, 2007). The theoretical dispersion curves proposed by Wang (2004) were subsequently validated through experiments conducted by Lynch (2007). In these experiments, a typical model hammer was used and only branch F(1,1) was excited. Accordingly, in what follows, the flexural wave will refer particularly to the flexural mode wave on branch F(1,1).

The evaluation of the length and integrity of existing piles by PS tests is based on a comprehensive analysis of the first arrival time and waveforms. For piles embedded in layered soil, when the testing site is limited in such a way that the testing borehole cannot be located close enough to the pile to be tested, the changes in the first arrival time and waveforms may be individually or simultaneously caused by a defect in the pile or the soil layer interface. The distinction between these two cases is very important in the integrity evaluation.

The development of PS tests, wherein the receiver in the borehole does not always have to be coupled with water (Sack et al., 2004; Yu et al., 2010), makes the S-wave more easily received. In addition, the flexural vibration of an embedded pile in soil is more effective for exciting the S-wave of the surrounding soil (Wang, 2004). Although there are reports of receiving the S-wave in PS tests (Niederleithinger, 2012), it is considered for use in PS tests for the first time in this paper.

The aim of the present paper is to provide a combined PS method for detecting the existing piles in layered soil. This PS method includes two PS tests conducted by striking on the pile side along and perpendicular to the pile-to-borehole direction and down-hole tests in the same testing borehole. Both the transmitted P-wave and S-wave at the pile-soil interface are utilized in the two PS tests. A simplified theoretical model for PS tests in layered soil is established based on the ray path theory. A correction formula is proposed to correct the pile bottom depth. The effectiveness and reliability of this PS method is analyzed by a three-dimensional (3-D) finite element (FE) model.

2. Procedure of parallel seismic test

The procedure for the PS test is illustrated in Fig. 1. A small-diameter borehole is drilled as close as possible to the pile foundation, which is either lined with a plastic tube to retain water as an acoustic coupling for the hydrophone in the traditional PS test (Davis, 1995; Olson et al., 1995) or used for a cone probe system combining cone penetrometer and the PS test to enable the evaluation of both the soil properties and the embedded depth of the pile bottom in some recent PS tests (Sack et al., 2004; Yu et al., 2010). The receiver is first placed on the top (or bottom) of the borehole and then lowered (or elevated) in uniform increments to collect the waveforms induced by striking the cap or pile side at each depth. Finally, the waveforms generated at different depths are assembled to form stacked time-depth trace plots. The first arrival time at each depth is identified and used to analyze the length and integrity of the pile shaft.

3. Simplified theoretical model for PS test in layered soil

A simplified theoretical model of the PS test in layered soil is shown in Fig. 2. It is supposed that soil layer i is an arbitrary soil layer beside the pile shaft above the pile bottom, and that soil layer j is a soil layer into which the pile bottom is embedded. For refraction point A at depth

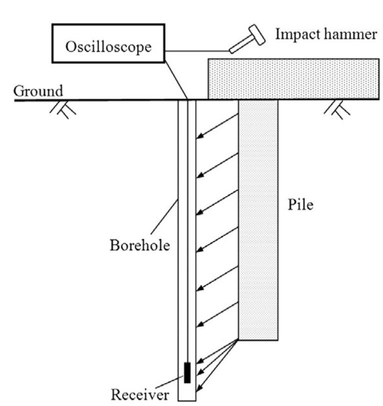

Fig. 1. Specifications for the PS tests.

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