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Theoretical basis and numerical simulation of parallel seismic test for existing piles using flexural wave

Jing-Yi Zhang [a,b], Long-Zhu Chen [a,*], Jinying Zhu [c]

[a] Institute of Engineering Safety and Disaster Prevention, Department of Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
[b] Sichuan Institute of Building Research, Chengdu 610081, China
[c] Department of Civil Engineering, University of Nebraska Lincoln, Omaha, NE 68118, USA

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ABSTRACT

This paper presents theoretical analysis of the parallel seismic (PS) method for evaluating existing piles using the flexural mode wave exited by a horizontal impact on the lateral surface of a pile. A simplified theoretical model of the flexural wave for PS method was established to elaborate the theoretical basis. A correction factor was then obtained and proposed to correct the pile depth obtained from the PS method, thus providing a more accurate estimation. A three dimension (3-D) finite element (FE) model was developed and the existence of the flexural waves on branch F(1, 1) in the pile shaft has been verified. Two time domain methods were used to calculate the flexural wave velocity in the pile. One was based on the pile tip reflection signal using a model where pile head reflection was minimized, and another method used the slope of the upper fitted line in the PS test. The flexural wave velocities from both methods match well with the predicted flexural wave group velocity determined from the dispersion curve of a 1-D rod embedded in the soil. The accuracy in estimation of pile tip depth is improved by applying the correction factor. A series of parametric studies were carried out to demonstrate the effectiveness of using flexural wave for PS test and the correction factor proposed in this study.

1. Introduction

As pile foundations are commonly used to provide support for a variety of structures, the importance of evaluation the length and integrity of a pile foundation has long been recognized. Nondestructive evaluation (NDE) methods provide a time-saving and cost-effective solution to pile testing. Among them the sonic echo (SE) [1,2] and impulse response (IR) [3] methods are the most popular NDE methods for new pile foundations when the top of piles is accessible to install testing equipment. Evaluation of existing pile foundations is still a challenge [4,5]. Many existing pile foundations lack necessary design information or actual as-built construction records. In some situations, such as a planned change in loading, rehabilitation, reusing foundations for new superstructures and evaluation integrity of pile foundation after the earthquake, knowing the length and integrity information becomes important [6–8].

A number of methods have been developed to investigate the unknown existing pile foundation depth. The SE/IR test from an existing pile cap or transfer beam is one important method [9–12]. The one dimensional (1-D) longitudinal wave theory is generally applied to interpret testing results. Sometimes data interpretation may be difficult, for example, when wave energy is reflected from the pile cap (or transfer beam) and little energy passes into the pile shaft. An axial impact on steel bracket mounted on the lateral surface of a pile is also an alternative [13]. The reflected waveform from the superstructure and the flexural waves from eccentric bending moment are often superimposed with the tip reflected wave, increasing the difficulties of interpretation. With the addition of two accelerometers mounted along the side of the pile, the reflections from the pile tip and those from the pile head and the overlying structure can be distinguished, therefore the velocity of the pile shaft and pile tip depth can then be possibly determined [14]. Normally, it requires enough exposed pile length to keep the two accelerometers at certain distance.

Olson et al. [15] have summarized various NDT techniques to test existing unknown pile foundations, pointing out that among those techniques the parallel seismic (PS) test has been shown to have broad applications and great potentials. Theoretical and experimental investigations are carried out based on longitudinal wave theory [7,8,16–18]. As seen in Fig. 1(a), using an axial impact on the transfer beam or steel bracket mounted on the side of the pile is the regular procedures. In most cases, when piles are connected to superstructures with lack of access to their tops, using

* Corresponding author. Tel.: +86 21 34208026; fax: +86 21 34206334.
E-mail address: lzchen@sjtu.edu.cn (L.-Z. Chen).

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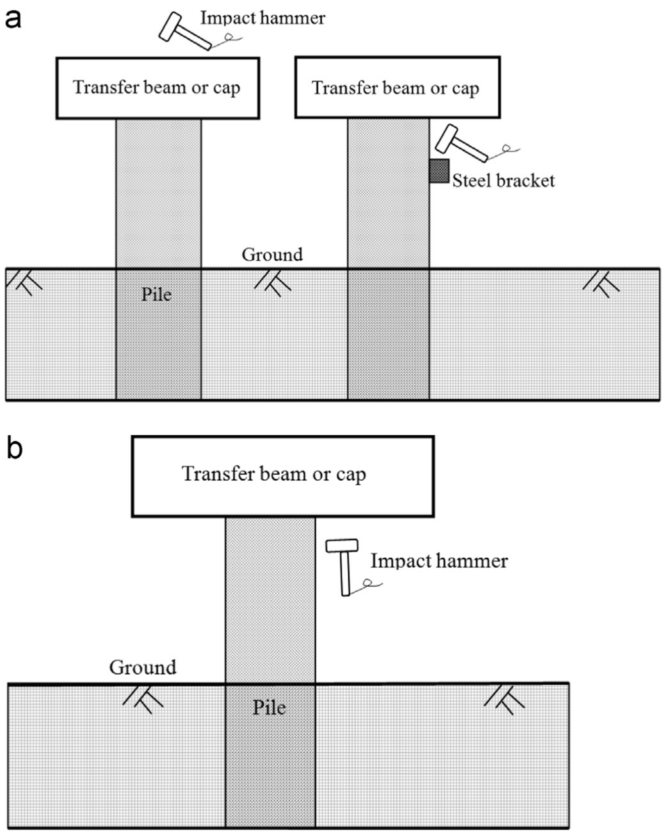

Fig. 1. Schematic arrangement for (a) longitudinal and (b) flexural wave testing.

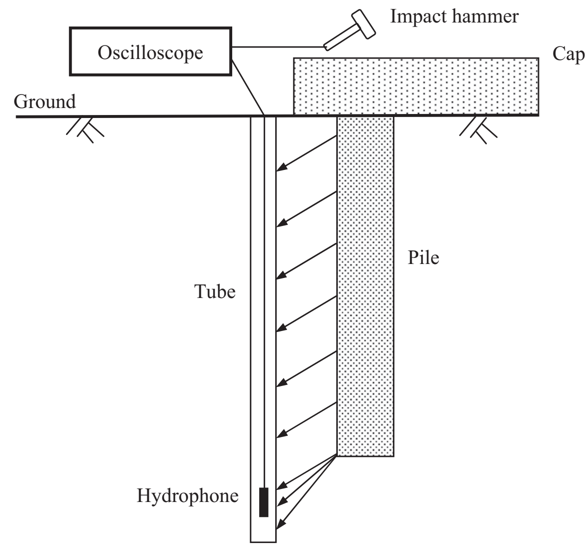

Fig. 2. Specification for integrity by PS test.

lateral horizontal impact on the side of the pile as shown in Fig. 1 (b) is a more economical and practicable way, and the flexural wave is thus induced.

The objective of this paper is to provide a pile testing approach by PS method using the flexural wave induced by horizontal impact on the lateral surface of a pile. A simplified theoretical model for PS method based on ray path theory was established to elaborate the theoretical basic. A correction factor was then obtained and proposed to correct the depth of pile tip. A 3-D finite element (FE) model was developed to verify the effectiveness of using flexural wave for PS method and the correction factor in this paper.

2. Flexural wave theory and testing method

Guided waves are produced by a combination of longitudinal and shear waves continually interacting with the boundaries. By using horizontal impact on the lateral side of partially exposed part of a pile, the flexural mode guided waves are induced [19]. Theoretical and experimental investigations have been conducted to explore the dispersive characteristics and testing approaches for pile integrity evaluation. The governing equation for a pile surrounding by the soil for the flexural modes has been solved by Wang [20]. Because of the complex displacement patterns for higher modes and existence of cut-off frequencies for higher branches, higher branch flexural mode F (p, q) $(p > 1, q > 1, p$ is the mode number, and q is the branch number) is not easy to be excited [20,21]. According to Hanifah [22], the dispersion curves are independent of soil properties, and depend only on the physical properties of the concrete. Lynch [21] designed experiments to verify the theoretical dispersion curves, and presented that for a typical model hammer only the branch $F(1, 1)$ will be excited.

For using flexural waves in the pile testing, Holt et al. [23] proposed an approach to identify tip depth of an existing pile based on modal analysis technique. By measurement of the frequency response functions between input of the hammer and output of the accelerometer at various source and receiver positions along the exposed length of the pile, the natural frequencies and mode shapes are obtained and used to back calculate the embedded length. However, Hughes et al. [24] later conducted a comprehensive experimental study and corresponding numerical analyses to investigate the feasibility of the modal analysis approach for identification of pile tip depth, showing a great variation with pile tip depth and no discernible trend to allow identification of the pile tip depth. Yu [25] considered of IR test based on flexural waves. By analyzing the mechanical mobility curves in frequency domain, the pile depth can be determined by:

$$L = \frac{V_{PF}}{2\Delta f} \quad (1)$$

where V_{PF} is the flexural wave velocity of the pile, Δf is the frequency spacing between two peaks. Since flexural waves are dispersive in low frequency, it is necessary to determine Δf where the flexural wave velocity V_{PF} approaches limiting flexural wave velocity, which is the Rayleigh wave velocity. For a typical model hammer, however, Rix et al. [5] designed a small-scale test of a pile, demonstrating that it is hard to excite peaks of higher order modes at high frequency.

3. Procedures of parallel seismic test

The PS test was initially developed by the CEBTP research organization headquartered in Paris, France. Later, Davis [2] and Olson [15] documented this method in details, reporting cases of practical applications to existing bridge foundations. In general, a small-diameter borehole is drilled close to the pile foundation, and is lined with a plastic tube to retain water as an acoustic coupling, as shown in Fig. 2. A hydrophone is placed in the tube at the top at first, and lowered in uniform increments to collect waveforms induced by impacting the cap or pile side at each depth. Finally, the waveforms with depths are assembled to form a stacked time–depth plot. The first arrival time at each depth is identified and used to analyze pile tip embedded depth and velocity of the pile.

Up to present, the PS testing procedures have made great progresses. A cone probe system combines the cone penetrometer