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Measurement of frozen soil–pile dynamic properties: A system identification approach

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ABSTRACT

A free-decay response signal approach is proposed for reliable estimation of frozen soil–pile dynamic properties of a partially embedded pile. Theoretical consideration and approximations are given for the free vibration of pile structures, with 20% of the pile cantilevered aboveground and the remaining embedded in Fairbanks silt. Winter measurements were taken for free-decay response of the pile. A comprehensive frequency spectrum analysis that includes fast Fourier transform, power spectrum density, and spectrograms is used to evaluate the system's vibration properties. Empirical mode decomposition is then used to decompose the signal to extract specific components for parameter identification. Results show that the response exhibits time-variant and nonlinear characteristics in the time–frequency domain. Experimental data show that the tested system exhibits weak nonlinearity. Dominant system parameters, used to characterize frozen soil–pile interactions, are identified. Two dominant frequencies for a stiff pile embedded 20 ft (6.096 mm) deep in frozen Fairbanks silt are 97 Hz and 1080 Hz. Damping was found to be approximately 0.016.

1. Introduction

Dynamic measurements of the vibration spectrum of piles embedded in frozen soils are used to estimate pile integrity or stiffness for deep pile foundations. That is, the vibration spectrum is used to estimate the integrity or interaction stiffness of a pile in deep soil foundations (Chau et al., 2009; Chau and Yang, 2005; Hua et al., 2008; Ku et al., 2003; Maheshwaria et al., 2004; Masoumi et al., 2009; Naggar and Novak, 1995; Ni et al., 2008; Puri and Braja, 1993; Tahghighi and Konagai, 2007; Takewaki, 2005; Teguh, 2008; Xiong and Yang, 2008). When piles in deep soil foundations are subjected to an earthquake, response depends on stiffness and damping. In the past, most studies have focused on the behavior of piles in unfrozen soils. The response of such structures subjected to earthquakes is influenced by the season. Seismic loading can cause strains in the soil to increase to a point where the soil shear modulus and stiffness decrease while damping increases. A change in modal parameters is dependent on structure boundary condition, material deterioration, or damage. Modal parameter identification is a well-known method for system identification and condition monitoring. Traditional methods for modal parameter identification are commonly used to fulfill general identification tests in the laboratory or in well-controlled field tests. In classical experimental modal analysis, the modal parameters (resonance frequencies, damping ratios, etc.) for a structure are identified via forced excitation experiments. However, for many structures, implementation of measured input is not conveniently available. Impact response measurements in these circumstances are probably the most popular method of modal parameter identification. For a soil–pile structure with little or no lumped mass, the test signals acquired from the soil–pile system tend to be complicated. Many factors—for example, the nonlinearity of the soil–pile structure—affect the captured signal, resulting in nonlinear stiffness and nonlinear damping. A hysteresis condition occurs for a pile and soil that interacts as an inelastic material. For example, when the pile pushes against the soil, a gap will likely form between the soil and the pile at ground line. So, the response is changed by soil hardening or weakening as the soil deforms and a gap occurs between the pile and soil at the ground surface. This interaction affects the soil–pile deformation or stiffness.

Analytical and experimental procedures that account for nonlinear soil behavior are described in the literature (Chau et al., 2009; Chau and Yang, 2005; Hua et al., 2008; Naggar and Novak, 1995; Tahghighi and Konagai, 2007). Generally, pile response under dynamic loads can be analyzed using spring-mass models. Soil springs are obtained from the shear modulus of the soil. Soil nonlinear effects can be accounted for by using strain-dependent values from laboratory shear modulus data. To account accurately for soil nonlinearity, seismic response analysis for the pile foundation should be conducted in the time domain. The proper representation of damping and inertia effects for the adjacent continuum (soil media) is needed, and the effects of plasticity and soil hardening or softening are usually required. Seasonally

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frozen soil causes significant change in the stiffness and damping ratio of the soil–pile system (Xiong and Yang, 2008). Despite previous related research, an effective method does not appear available for describing actual in situ dynamic properties and nonlinear response for frozen soil–structure interaction systems. Therefore, a high level of uncertainty in characterizing frozen soil adjacent to the pile continues, causing the prediction of structure system integrity to be elusive.

We propose an approach to reliable estimation of the dynamic properties of a partially embedded pile in frozen soil. The proposed method relies on using the free-decay response signal of the pile. Theoretical considerations and approximations of the free vibration of the frozen soil–pile structure interaction are presented. Measurements are taken for the free-decay response of the pile, and a comprehensive frequency spectrum analysis is conducted. Conventional spectrum results such as fast Fourier transform (FFT), power spectrum density, and spectrograms are used to give preliminary evaluation of the system's vibrational properties in the context of a linear system. Besides employing conventional approaches for identification of system response, the empirical mode decomposition (EMD) method (Huang et al., 1998, 1999; Yang et al., 2004; Yang and Lei, 1999) is adopted to enhance the characteristics of the testing signal, which is done to improve identification. Empirical mode decomposition is a method of decomposing a nonlinear, nonstationary signal into a series of zero-mean amplitude modulation-frequency modulation (AM-FM) components that represent the characteristic time scale of the observation.

Based on this approach, the nonlinearity of the frozen soil–pile system is estimated. An analysis of the acquired data shows that the tested frozen soil–pile system exhibits weak nonlinearity and that the dominant portion can be approximated by a linear model. A system identification approach is used to extract modal and damping parameters, which are used to characterize the frozen soil–pile interactions under varied conditions. A distinct linear phenomenon between pile and soil is observed in a specific frequency range. Nonlinear effects are within a wide frequency range. Bouncing phenomena, caused by the development of ground surface separation (gap) between the frozen soil and the pile, are observed.

2. Test setup and measurements

Full-scale pile dynamics tests were conducted on a 16 in. (406 mm) diameter steel-jacketed reinforced concrete pile (Davis, 2010). A 20 ft (6.096 mm) pile was imbedded in a soil profile of uniform Fairbanks silt, with 5 ft (1,524 mm) of the pile exposed aboveground. The horizontal acceleration of the top end of the pile was measured by applying a horizontal impulse load. Fig. 1 is a schematic diagram of the test setup.

Free horizontal vibration tests were conducted by first applying incremental static loads to about 5000 lb (22 kN). During incremental loading, pile strains, displacements, and applied load were monitored. An accelerometer was used to monitor free vibrations that occurred after suddenly removing the applied load using a quick release. An accelerometer was also used to record free-decay response. A data acquisition system was used to store the data. The resultant information was transferred to a computer for processing. The soil at the site is classified as Fairbanks silt; its properties were determined by conducting in situ and laboratory tests. Others have conducted laboratory tests for the soils at this test site to evaluate the soil properties such as dynamic shear moduli were determined by laboratory tests (Czajkowski and Vinson, 1980; Wilson, 1982). Details of the soil properties, described in the research reports, are not included in this paper. Field experiments were conducted during December and January (the winter season).

3. Spectrum analysis

Fig. 2(a) shows the FFT of a measured acceleration signal. Two specific peaks are visible, corresponding to $f_1 = 98$ Hz and $f_2 = 1080$ Hz. Fig. 2(b) and (c) show the FFT of three measured acceleration signals recorded on the same day. Fig. 3 shows the power spectrum density of three measured acceleration signals for the same day. Note in Fig. 3 that the first specific frequency is less sensitive to test history and the first specific peak of all three tests is identical, whereas the second specific frequency is sensitive to test history and the second specific peak of the three tests is within the range of $f_2 = 1065$–1080 Hz. These data suggest that tests conducted on the same day could slightly change the soil boundary condition, which is reflected by the change in the second specific frequency.

If the system is idealized as a linear system, then we may presume that the two peaks correspond to the first two modes of the system. Thus, the first-order natural frequency is a horizontal vibration of $f_1 = 97$ Hz, and the second-order natural frequency is a horizontal vibration of $f_2 = 1080$ Hz. The validity of this assumption will be demonstrated later in the paper. Fig. 4 shows a spectrogram of one of the measured acceleration signals determined from the field test. Fig. 4(a) is a contour plot showing that four kinds of components exist. The first component is the dominant one, corresponding to the specific frequency of $f_1 = 97$ Hz. The second component consists

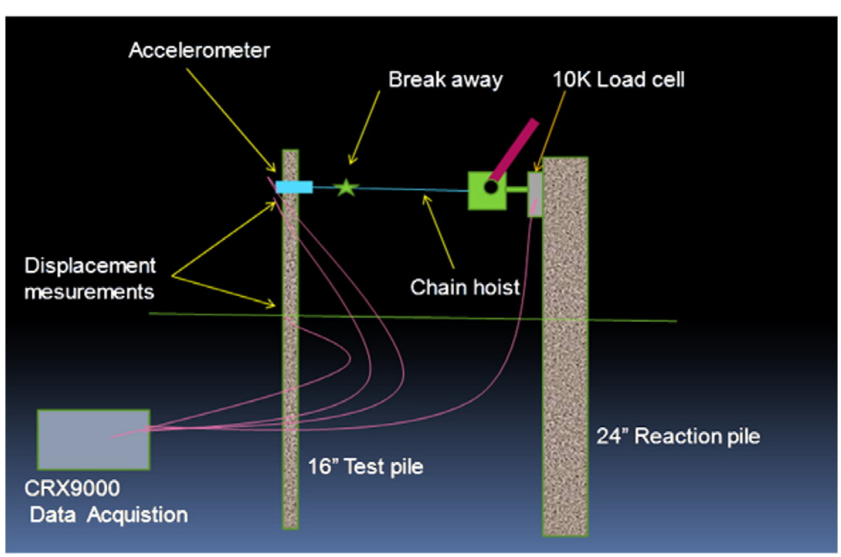

Fig. 1. Schematic diagram of the test setup.