Characterization of timber piles using guided waves

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ABSTRACT: Timber piles have been widely used in Canada. The pile length is an important index for structural health monitoring (SHM) and pile length estimation for existing unknown pile foundation can help make correct strategies for pile foundation reuse. Therefore, in this paper, a novel technique based on the periodic analysis of the phase difference and the 3-dimensional (3D) guided wave theory was developed to effectively estimate the embedded depth of unknown timber pile foundations. In this method, the guided wave model of a cylindrical pile is built by the spectral element method to determine the dispersion relation. A modified Ridders' algorithm is proposed for root-searching. According to the phase difference of the responses collected by at least two sensors located on the top or the lateral side of the pile, and the dispersion relation obtained by the spectral element method, the dispersion analysis diagram can be obtained to show the relationship between the phase difference and the wavenumber. By the periodic analysis of the dispersion analysis diagram, the pile length can be estimated.

KEY WORDS: Timber piles; Guided waves; Spectral element method; Dispersion relation; Ridders' algorithm; Pile length estimation; Unknown pile foundation; SHM; Pile foundation reuse.

1 EXTENDED ABSTRACT

Timber has been widely used in civil engineering applications. In Canada, a country with rich wood resources, timber structures have attracted much attention because of their low cost, easy transportation, and long-life service. Timber piles have been widely utilized in different applications, such as manufacturing plants, marines' structures, commercial buildings, highway bridges and so on [1]. As such, developing novel technique to assess the health condition of timber piles is of great importance. Pile length is an indicator of importance for the SHM of pile foundations, and it can be used to indicate the scouring level. Therefore, this paper aims to develop a new pile length estimation method.

The detailed process of the proposed method for the estimation of pile length based on the guided wave model is shown in Figure 1 and 2. The method is developed for two configurations. One configuration is when the sensors are placed on the lateral side, which is corresponding to Figure 1; the other case is that the sensors are placed on the top surface, which is corresponding to Figure 2. The schematic diagram of the experiment setup using the lateral-side responses and the top-surface responses is shown in Figure 1(a) and Figure 2(a), respectively. These two configurations are discussed in detail in the following sections.

1.1 The pile length estimation based on the lateral-side signals

The process of the method using lateral-side signals is shown in Figure 1. For a pile under investigation, if there is an exposed part, the lateral-side signals can be used. In this case, two sensors, denoted by S_1 and S_2, are placed on the lateral side of the exposed part of the pile. The distance between S_1 and the pile toe, and the distance between S_2 and the pile toe, are denoted by L_1, and L_2, respectively. The test pile is impacted by a hammer or another source of excitation on the top of the pile. The vibration responses acquired by the sensors S_1 and S_2 are denoted by R_1 and R_2 respectively (As shown in Figure 1(a)).

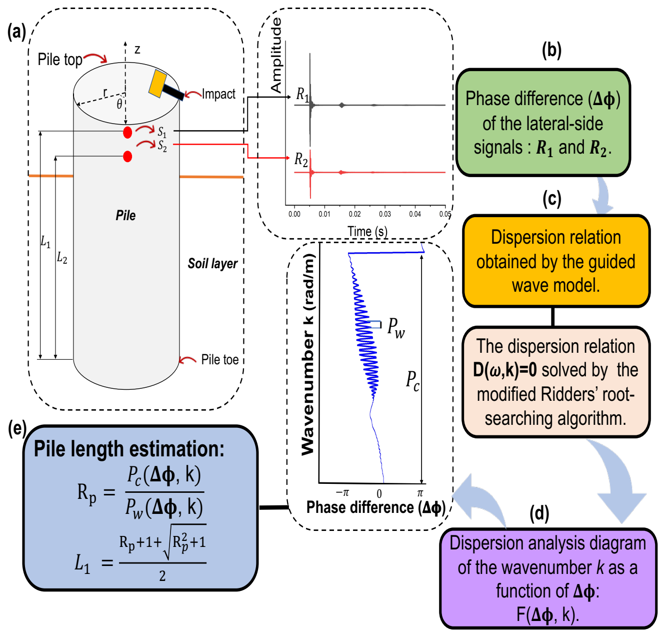

Figure 1. The graphic abstract of the proposed method using the lateral-side signals. (a) The setup of data acquisition on the test pile where the response pair R_1 and R_2 are collected from the sensor S_1 and S_2 on the lateral side. (b) The calculation of phase difference using the response pair R_1 and R_2. (c) The dispersion relation D(ω, k) = 0 between the wavenumber k and the frequency ω obtained by Helmholtz's decomposition method-based guided wave model can be solved by a modified Ridders' algorithm. (d) The dispersion analysis diagram F(ΔΦ, k) of the wavenumber k and the phase difference ΔΦ can be

plotted. (e) Pile length estimation is based on the information obtained from the plot F(ΔΦ, k) of the lateral-side signals.

In Figure 1(b), the phase difference ΔΦ can be calculated based on the response pair R_1 and R_2 recorded on the lateral side. The signal $R_1$and R_2 in the time domain can be transferred into the frequency domain by the Fast Fourier transform, and the corresponding signals in the frequency domain are denoted by $R_1(\omega)$, and $R_2(\omega)$. The phase difference of the signals collected on the lateral side can be calculated as,

$$\Delta\phi = Imag\ (\log\ (R_1(\omega) - \log(R_2(\omega)), \quad (1)$$

where *Imag (.)* means the imaginary part of the input signal and *log (.)* is the logarithmic function; the phase difference can be transferred into the range $[-\pi, \pi]$.

Then, as shown in Figure 1(c), a 3D guided wave model for a cylindrical pile is built based on Helmholtz's decomposition method [2]. The dispersion relation between the wavenumber *k* and the frequency ω, denoted by D(ω, k) = 0, can be obtained by the developed 3D guided wave model. The related root-searching function can then be solved by the modified Ridders' algorithm [2]. According to the phase difference ΔΦ and dispersion relation, the dispersion curve of the wavenumber *k* as a function of phase difference ΔΦ, denoted by F(ΔΦ,k) (called as the dispersion analysis diagram) can be obtained by using either the lateral-side (as shown in Figure 1(d)).

When the sensors are placed on the lateral side, using the equation in Figure 1(e), the pile length (indicated by the distance L_1 between the upper sensor (S_1) and the toe of the pile) can be estimated by the cycle period P_c, the wiggle period P_w obtained from the dispersion analysis diagram F(ΔΦ,k) of the signals from the lateral side, and the distance ΔL of the two sensors (ΔL= $L_1 - L_2$).

1.2 The pile length estimation based on the top-surface signals

The process of the method using the top-surface signals is shown in Figure 2. If the pile is fully buried in the soil and there is no exposed part, two sensors, denoted by S_3 and S_4, can be placed on the position r_1 and r_2 on the top surface. The vibration responses acquired by the sensors S_3 and S_4 are denoted by R_3 and R_4, respectively (as shown in Figure 2(a)). The recorded responses (R_1,R_2, R_3 and R_4) can be in terms of accelerations, velocities, or displacements.

As shown in Figure 2(b), the phase difference ΔΦ can be calculated based on the response pair of R_3 and R_4 recorded on the top surface as,

$$\Delta\phi = Imag\ (\log\ (R_3(\omega) - \log(R_4(\omega)). \quad (2)$$

$R_3(\omega)$ and $R_4(\omega)$ are the response R_1 and R_2 in the frequency domain respectively. Then, according to the 3D guided wave model for a cylindrical pile and the modified Ridders' algorithm, the dispersion relation D(ω, k) = 0 can be obtained (as shown in Figure 2(c)). The dispersion analysis diagram F(ΔΦ,k) of the top-surface signals can also be plotted (as shown in Figure 2(d)). For the sensors are placed on the top surface, using the equation in Figure 2(e), the pile length L can be estimated by the wiggle period P_w recognized from the dispersion analysis diagram of the responses recorded on the top surface.

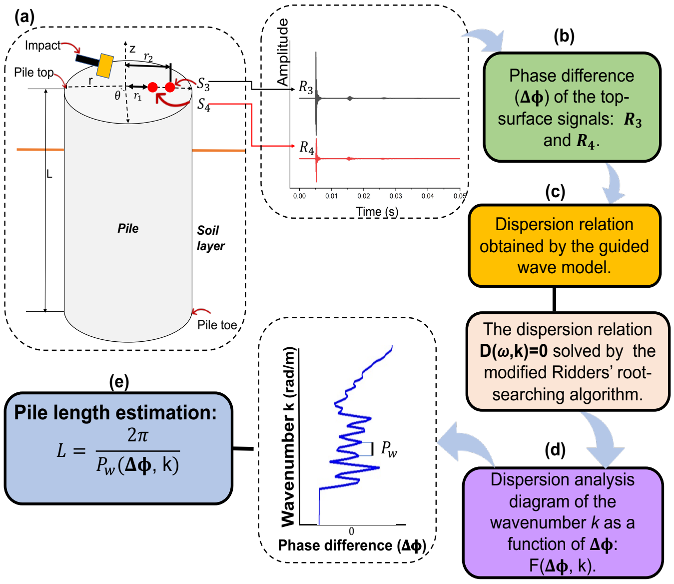

Figure 2. The graphic abstract of the proposed method using the top-surface signals. (a) The setup of data acquisition on the test pile where the response pair R_3 and R_4 are collected from the sensor S_3 and S_4 on the top surface. (b) The calculation of phase difference using the response pair R_3 and R_4. (c) The dispersion relation D(ω, k) = 0 between the wavenumber k and the frequency ω obtained by Helmholtz's decomposition method-based guided wave model can be solved by a modified Ridders' algorithm. (d) The dispersion analysis diagram F(ΔΦ, k) of the wavenumber k and the phase difference ΔΦ can be plotted. (e) Pile length estimation is based on the information obtained from the plot F(ΔΦ, k) of the top-surface signals.

Using synthetic data for validation, it was shown that the proposed method based on the 3D guided model can achieve an average accuracy of less than 5% error.

REFERENCES

[1] C. James, E. Edward, S. Rubin and M. Jeanie. Timber Pile Design and Construction Manual 2016, 2016.

[2] S. Cui, H. Liu and P. Maghoul, Pile length estimation based on guided wave theory and dispersion analysis for reuse of foundations (under review), 2022.