Flexural wave impulse response evaluation of pile bent foundations

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ABSTRACT

The transient-state flexural waves impulse response tests are alternatively introduced to the integrity evaluation of piles where the tops are inaccessible for conventional longitudinal wave testing. The conventional constant velocity-based one-dimensional wave theory is no longer suitable to interpret such testing results. In this research, linking the guided wave theory and resonance concept is a simple and efficient method to describe the dispersive wave velocity and precisely evaluate the on-site length of pile bents supporting a rail viaduct in central Taiwan.

Keywords: pile bent foundation; flexural wave impulse response; guided wave theory; resonance frequency; phase velocity; non-destructive testing

1 INTRODUCTION

The conditions of substructures directly affect the serviceability and performance of superstructures of infrastructures or buildings. Several non-destructive testing techniques, including visual inspection, stress wave propagation, and electrical resistivity tomography, have been applied to integrity evaluation in deep foundations. Amongst, the wave-based technique, such as impulse response, is the most commonly-used method due to its economy and operation feasibility.

2 CONVENTIONAL IMPULSE RESPONSE

The instrumentation arrangement for a conventional (longitudinal wave) impulse response testing in a single pile is plotted in Fig. 1. An impact on pile top is generated with a modal hammer instrumented with a load cell. The excitation transient-state longitudinal waves move downward and upward between the pile top and bottom. The reflected longitudinal waves from the pile bottom or gross anomaly are measured by a geophone or accelerometer installed atop the pile surface. The force and vibration response histories are transformed into the frequency domains or spectra by a fast Fourier transfer (FFT).

The one-dimensional wave propagation theory is assumed to be valid when interpreting the results of the conventional impulse response tests conducted on a pile. In a given pile, the propagation velocity of the stress waves is regarded as a constant. The distance between reflection sources, either the pile bottom or a gross defect and the sensing transducer is computed by

$$L = C_{bar} / 2 / \Delta f \tag{1}$$

where L is the distance between sensing transducer and reflection source, C_{bar} is the bar wave velocity, and Δf is the averaged equal-span resonant frequency, as shown in Fig. 2 at low frequencies (Davis and Dunn 1974). In addition, the induced wavelength is generally postulated as much larger than the pile diameter.

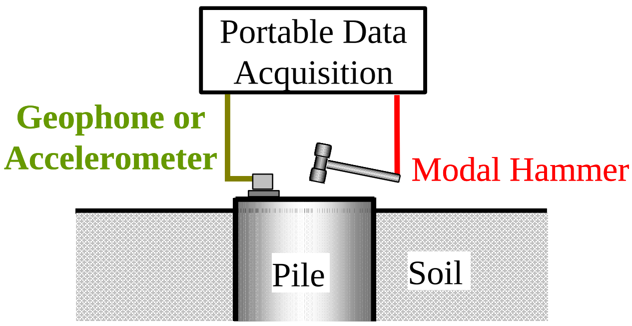

Fig. 1. Conventional impulse response conducted on a pile.

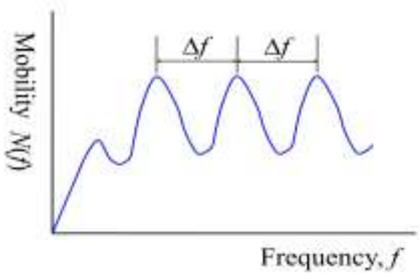

Fig. 2. Mobility response in a cylindrical pile.

3 FLEXURAL WAVE IMPULSE RESPONSE

Being modified from the traditional impulse response method, the flexural wave impulse response approach enables to non-destructively evaluate in the integrity of pile foundations supporting bridges or wharves, where the shaft tops are inaccessible for conventional testing (Figure 3). The transient-state flexural waves, induced by lateral impact on the free side of a shaft, travel downward and upward along the shaft and the surface vibration responses are directly measured with two accelerometers installed on the periphery of the shaft.

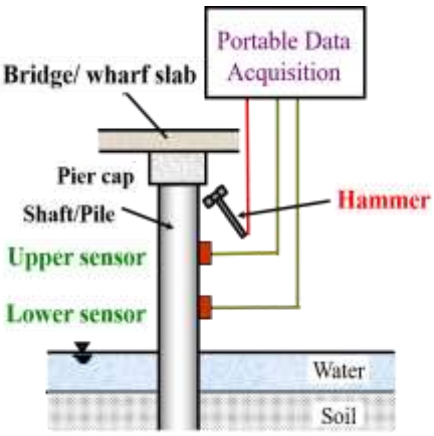

Fig. 3. Flexural wave impulse response testing conducted on a pile connected to a superstructure.

The constant velocity-based one-dimensional wave theory is implicitly assumed to interpret the results of longitudinal wave inspection. However, several experimental results show that the flexural wave velocity is dispersive and various with frequency in the low frequency range (Finno et al. 2005; Rix et al. 1995; Wang et al. 2010). A numerical analysis based on the Timoshenko beam theory suggested that one-dimensional wave theory is acceptable in the flexural wave impulse response testing for the resonance frequency modes higher than eight only such that the wave velocity is approaching a constant value (Yu and Roesset 1995). This indicates that Eq. (1) is not suitable to be applied to the interpretation on the flexural wave impulse response testing results.

4 METHODOLOGY

When the flexural waves are triggered by a hand-held hammer on piles, the most excited flexural waves scatter within a low frequency range, up to 2~6 kHz, as that with the conventional impulse response method. Treating a pile as a waveguide, the lowest flexural mode guided wave branch F(1,1) overlaps the most possible induced frequency range in the flexural wave testing (Finno et al. 2005). The dispersion relation between phase velocity and frequency can be explicitly defined and is associated with shear wave velocity, Poisson's ratio, and pile diameter only.

Figure 4 shows a typical dispersive phase velocity curve of branch F(1,1) for flexural waves traveling in a 1-meter diameter pile. At low frequencies, the velocity value increases monotonically from zero with frequency. For frequency beyond 2,500 Hz, the flexural wave velocity will approach the Rayleigh wave velocity. For such a frequency range, the flexural wave velocity becomes apparently constant and non-dispersive with frequency, instead.

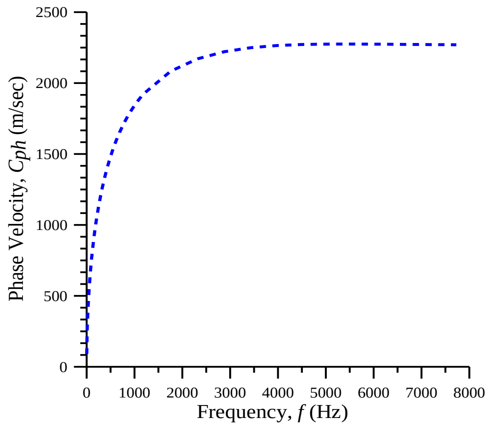

Fig. 4. Phase velocity curve of F(1,1) in a 1-m diameter pile with shear wave velocity of 2,500 m/sec.

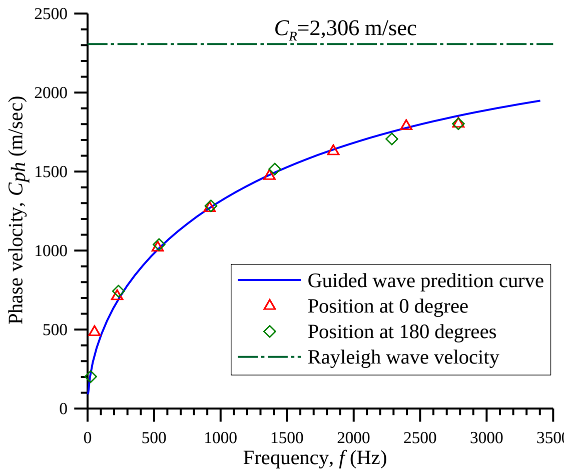

Fig. 5. Phase velocities at resonance frequencies superimposed on the flexural guided wave theoretical curve (after Wang et al. 2010).

Resonance concept is introduced as a simple way to link the flexural mode guided wave theory and flexural wave impulse response results (Finno et al. 2005; Lynch 2007; Wang et al. 2010). When the pile length is known, the phase velocity of flexural waves can be derived from the guided wave theory. The resonance solution is expressed as

$$C_{ph-n} = \frac{2L}{n} \times f_n \qquad (2)$$

where $C_{ph\text{-}n}$ is the experimental phase velocity, L is the pile length, n is the positive integer resonant number, and f_n is the measured resonant frequency. The experimental phase velocity are superimposed on the theoretically-determined flexural mode guided wave curve F(1,1). The testing results are expected to lie along the theoretical prediction curves. Figure 5 indicates that the phase velocities at resonant frequencies have a good trend with the flexural mode guided wave theoretical prediction curve.

5 FIELD TESTING

In this research, the flexural wave impulse response technique is applied to depth evaluation on the pile bents supporting a rail viaduct, consisting of the north and south bound viaducts, in central Taiwan (seen in Fig. 5). The individual pier is composed of 4 pile bents, 3~4 m exposure portion, with a diameter of 1 meter each. The detailed design-phase vertical view chart on the target pier is re-plotted in Figure 6.

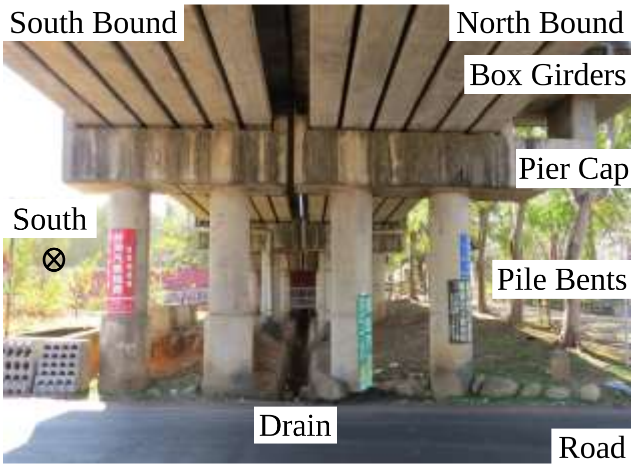

Fig. 5. Pile bents supporting a rail viaduct.

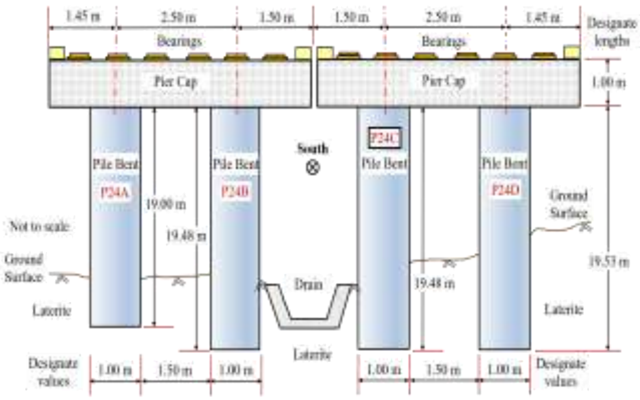

Fig. 6. Pile bent dimension on the target pile bent (not to scale).

The geophones are installed on the top of the pier cap supporting the north bound viaduct (as shown in Figure 7). The flexural waves, traveling downward and upward along the pile bent, are induced by lateral impact on the free side of the concrete pile bent due to limited space for operating impact between box girders and pier cap. The velocity signals in the time domain are stored in a seismogram (i.e., a portable data acquisition) on site and converted to the frequency domain with the fast Fourier transfer for further analysis.

Fig. 7. Flexural impulse response conducted on a pile bent.

6 ANALYSIS

Figure 8 shows the typical flexural wave impulse response spectra in the radial (horizontal) direction for 3 lateral impacts. A number of resonant peaks are found at frequencies below 1,100 Hz. Unlike the longitudinal wave (conventional) impulse response testing, more concentrated resonant frequencies are significantly found at low frequencies, below 300 Hz. The resonant frequency becomes more regular for frequency beyond 400 Hz.

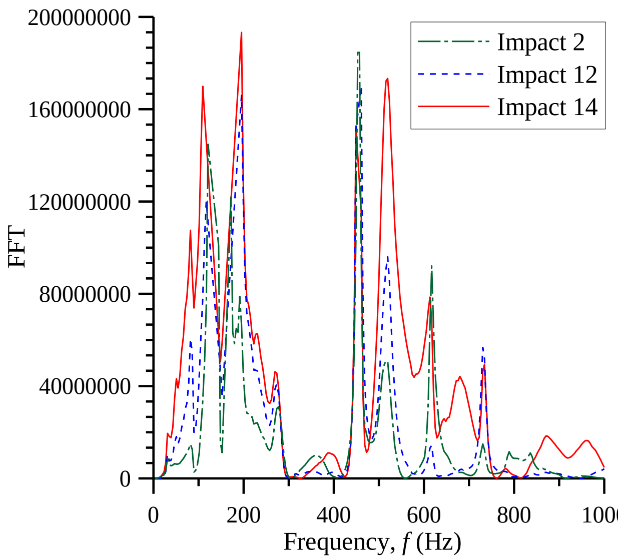

Fig. 8. Flexural wave impulse response spectra for 3 impacts.

Using Eq. (2) can compute the experimental phase velocity at corresponding resonant frequency. When the experimental phase velocities are superimposed on the theoretically-determined flexural mode guided wave curve, the corresponding phase velocities at resonant frequencies measured in the flexural wave impulse response tests have good matches with the theoretical predictions at frequencies below 1,100 Hz, as shown in Figure 9. Their phase velocities monotonically increase with frequency and have similar velocity trends with the flexural mode guided wave theoretical prediction.

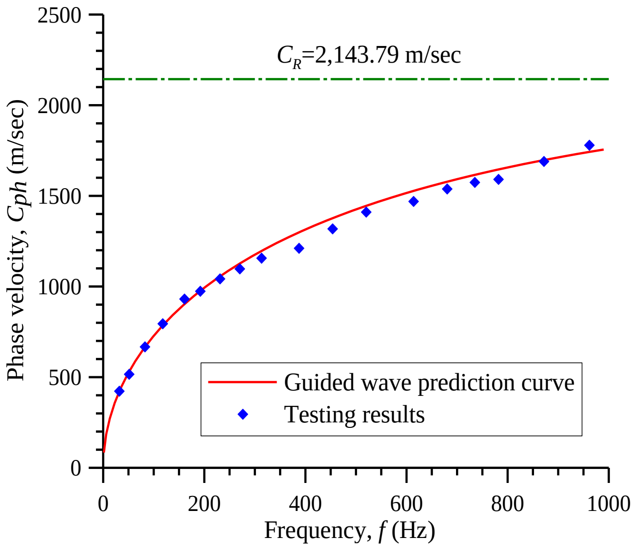

Fig. 9. Phase velocities at resonant frequencies superimposed on the flexural guided wave theoretical curve (impact 14).

Table 1. Length estimate for individual resonant frequency.

Resonant number, n	Resonant frequency, f_n (Hz)	Theoretical phase velocity, C_{ph} (m/sec)	Length estimate, L_n (m)
1	N/I	N/A	N/A
2	N/I	N/A	N/A
3	31.2500	416.063	19.97
4	50.7813	527.700	20.78
5	82.0313	663.531	20.22
6	117.1875	747.702	19.14
7	160.1563	901.306	19.70
8	191.4063	974.169	20.36
9	230.4688	1,054.768	20.59
10	269.5313	1,125.853	20.89
11	312.5000	1,194.902	21.03
12	N/I	N/A	N/A
13	386.7188	1,297.821	21.81
14	453.1250	1,374.849	21.24
15	519.5313	1,444.232	20.85
16	N/I	N/A	N/A
17	613.2812	1,526.759	21.16
18	679.6875	1,577.478	20.89
19	734.3750	1,615.250	20.90
20	781.2500	1,645.179	21.06
21	871.0937	1,696.762	20.45
22	960.9375	1,742.115	19.94
23	1,066.4060	1,788.590	19.29

Note: N/I and N/A indicate not identified and not available, respectively.

The resonant number, n, and identified twenty-three measured resonant frequencies, f_n, are listed in the first and second columns of Table 1, respectively, from Fig. 8. The theoretical phase velocities, C_{ph}, corresponding to resonant frequency are listed in the third column of Table 1. The individual pile length estimates can be computed with Eq.

$$L_n = \frac{nC_{ph}}{2f_n} \tag{3}$$

where L_n is the pile length estimate, n is the resonant number, C_{ph} is the theoretical phase velocity, and f_n is the measured resonant frequency. When all the resonant frequencies are expected to lie on the guided wave theoretical curve, F(1,1), Eq. (3) provides an inverse computation to estimate the individual pile lengths, which are listed on the remaining column of Table 1, for each resonant frequency. The averaged pile bent length (excluding pier cap height) is around 19.54 m with a 0.8% error to the nominal length, 19.39 m. Using an inverse computation can effectively find the pile bent length.

7 CONCLUSIONS

Using the guided wave theory and resonance concept provides not only the phase velocity trend for dispersive flexural waves, but also a reliable length estimate on pile bents in the flexural wave impulse response testing. In future, when knowing the *in-situ* shear wave velocity and pile diameter of pile bents only, one can use inverse computation to effectively and precisely determine unknown pile bent lengths.

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