Application of High Frequency Parallel Seismic Pile Test to Determine the Unknown Length of Piles Supporting Retaining Wall and Low-rise Building

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ABSTRACT

The parallel seismic pile test (PSPT) is currently considered as one of the most reliable near-surface geophysical methods for assessing the length of buried piles. Similar to seismic refraction method, PSPT relies on analyzing the first arrival time of the P-wave to determine the depth of the pile tip. When conducting a PSPT on the limited compounds of existing buildings, it is challenging to identify the first arrival of P wave for data analysis due to the connection of the foundation structure with the superstructure and other foundations. This paper presents the results of a PSPT conducted to determine the unknown depth of piles supporting the retaining wall and multi-story reinforced concrete buildings located in Pathum Thani, Nakorn Sri Thammarat, Chiang Mai, and Phetchaburi, respectively. At these study sites, boreholes were drilled with installation of 2-inch diameter PVC casings to conduct PSPT. The tests were performed within 10-15 meters from the target foundation. The survey results revealed an indistinct slope of the primary wave arrival, characterized by noise and multiple variations. Through a careful signal analysis, it was observed that high-frequency waves (higher than 190 Hz) have experienced significant attenuation when passing through the soil layer, which is clay. To mitigate this issue, a high-cut frequency filter was applied. The processed results displayed a clearer waveform along the pile depth, enabling identification of the pile tip depth in range of 4 to 18 m based on PSPT results. One important outcome of this study is a chart displaying the correlation between the H/D ratio and the low-cut frequency, where H is the structure height and D is the depth of the supporting pile. This H/D-f chart can be used for the design of new PSPT test at other locations.

Keywords: near-surface engineering geophysics, parallel seismic pile test (PSPT), pile foundation, pile depth, pile length

1. INTRODUCTION

At the construction sites, one of the most common seismic test methods for construction engineers to apply is seismic integrity testing [1, 2] for pile quality assessment. This method, unfortunately, cannot work well for determination of the buried pile tip depth, which is in fact one of most challenging problems facing near-surface engineering geophysics to date. The seismic parallel pile test (PSPT) is now emerging as the most accurate pile tip assessment method [3-5]. Adapted from the seismic refraction method that is commonly performed on the ground surface, the PSPT is performed in the borehole [3], requiring a drilled borehole that can also be used for groundwater observation or inclinometer casing installation [6]. The procedure of PSPT is similar to that of a uphole seismic survey, in which first arrival of waveform recorded from each depth is identified to determine the change of slope, and then the seismic velocity (see Fig. 1).

This study presents the results of PSPT that was conducted in several provinces in Thailand, and namely, Pathum Thani, Nakorn Sri Thammarat, Chiang Mai, and Phetchaburi (see Fig. 2). The objective of this study is to determine the length of the piles supporting the retaining wall and concrete buildings found at the mentioned study sites. The PSPT data were processed and interpreted for identification of pile length.

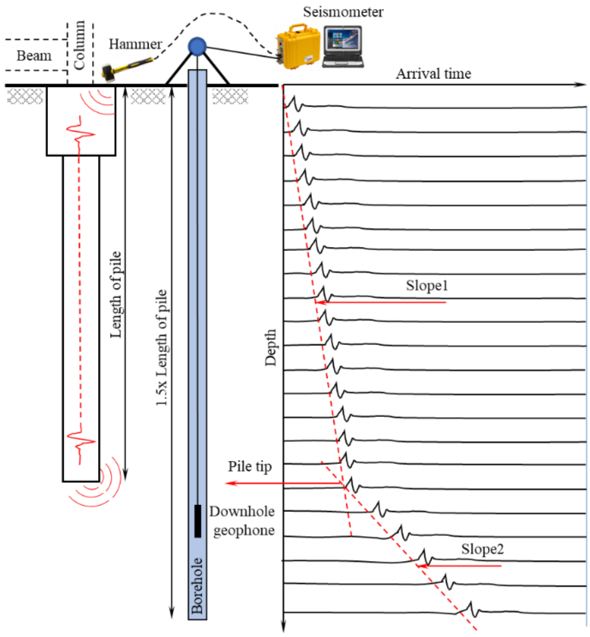

Fig. 1 Sketch of parallel seismic pile test (PSPT)

Fig. 2 Locations of target concrete structures tested by PSPT at four study sites

1.1 Parallel seismic pile test method

The PSPT lies in the principles of seismic wave propagation through the concrete structure and the ground [7-8]. Seismic waves are generated by a hammer strike hit on top of the tested pile located at the ground surface (see the setup in Fig. 1). The travel time of the primary wave depends on the properties of the concrete structure and the surrounding soil. The seismic sensor (geophone or accelerometer) is placed at specifically designed locations along the newly drilled PSPT borehole, located at some distance, within 15 to 20 m, from the target pile.

The P-waves are the first to arrive at the seismic sensors placed at a desired depth in the PSPT borehole. By analyzing the first arrival time of the P-waves at the sensors, it is possible to determine the depth at which the pile tip is located. The travel time of the seismic waves is directly related to the velocity of the waves through the subsurface materials. The velocity of the P-waves can vary depending on the properties of the soil or rock layers [9].

1.2 Seismic signal degradation phenomena

The attenuation of seismic waves as they propagate through the subsurface is caused by several wave phenomena, each contributing to the loss of energy and changes in the characteristics of the seismic waves. Some of the main phenomena causing the degradation of seismic waves include:

1) Geometric spreading or spherical divergence: Seismic waves spread out radially away from the seismic source [10-11]. This geometric spreading leads to a reduction in wave amplitude with increasing distance from the source. As the waves cover a larger area, the energy is distributed over a larger volume, resulting in weaker seismic signals further away from the source.

2) Intrinsic attenuation or absorption: The additional of spherical divergence, elastic energy is absorbed by the subsurface materials as a result of the friction between particles moving against one another, which is converted to heat [10-11]. This form of wave attenuation varies depending on the type of material. The intrinsic attenuation of seismic waves can be quantified using the exponential decay equation, which is similar to the equation used to describe the global attenuation of seismic waves owing to multiple factors. Seismic waves with high-frequency components are more susceptible to absorption and scattering, resulting in a decrease in overall energy and a change in waveform. The equation can be expressed as follows:

$$A(x) = A0 * \exp(-\beta x) \quad (1)$$

Where: A(x) is the amplitude of the seismic wave at a distance x from the source, A0 is the initial amplitude of the seismic wave at the source (x = 0), β is the intrinsic attenuation coefficient, which represents the rate at which energy is attenuated due to the material's internal properties, and exp (-βx) is the exponential term that governs the decay of the amplitude with distance x.

3) Scattering: when seismic waves encounter geological heterogeneities or boundaries between different rock layers, they can scatter in various directions. Scattering causes the waves to change direction and lose coherence, leading to a reduction in energy in specific directions and affecting the overall quality of seismic data [10].

2. METHODOLOGY

2.1 Borehole preparation

Four concrete structures, including one retaining wall and three low-rise buildings, were selected for PSPT in this study are shown in Fig. 3. These structures are supported by piles of different lengths with the pile depth (D) to building height (H) ratios are shown in Fig. 4 and Table 1. The boreholes were drilled within a 5-meter range from the closest building's foundation. To ensure accurate measurements, the minimum depth of the boreholes was set at 150% of the pile length [5]. PVC casings were installed to prevent the boreholes from collapsing. Following the installation of the PVC casings, the space between the borehole and PVC casing was filled with sand to minimize coupling. This approach guarantees reliable and precise data collection during the seismic tests.

a) Retaining wall, Pathum Thani b) 5-story building, Nakorn Sri Thammarat

c) 2-story building, Chiang Mai b) 2-story building, Phetchaburi

Fig. 3 Views of concrete structures tested by PSPT in this study: (a) The concrete retaining wall No. 1; (b) The five-story building No. 2; (c) The two-story building No. 3, and (d) The two-story house No. 4

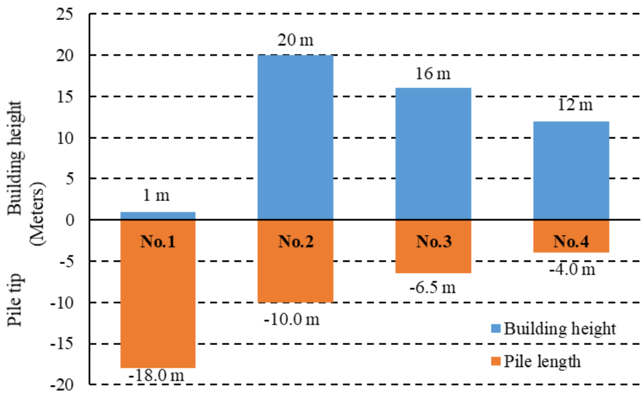

Fig. 4 Heights and depths of four concrete structures tested by PSPT

Table 1 Structures' information

Structure No.	Number of floors	Height, H (m)	Approximate pile tip depth, D (m)	H/D ratio
1	0	1	18.0	0.05
2	5	20	10.0	2.00
3	2	16	6.5	2.46
4	2	12	4.0	3.00

2.2 Data Acquisition

Utilization of the Geometrics Geode 24 seismometer with a single-channel downhole sensor. The downhole sensor contains a 30-Hz vertical geophone. The seismometer sampling rate was set to 0.25 milliseconds, and the seismic record was collected at a distance of 0.25 meters from the surface of the ground to the bottom of the borehole [1,3]. The seismic signals were generated by striking a column, ground beam, or floor adjacent to the pile with a nylon mallet [13-14]. The record length has been set to 1 second, and the average of three stacks has been selected. The collected dataset was stored in the SEGY format for analysis purposes.

2.3 Data processing and analysis

Firstly, collected data were normalized for enhancing the data visualization. After that, the bandpass filter was applied for noise attenuation and signal enhancement [12].

In seismic data analysis, identifying the arrival time of the direct wave, and/or first arrival, at each record depth is a critical step [13-15]. The seismic data is carefully and visually examined to spot the waveforms associated with the first arrivals. These waveforms exhibit distinct characteristics, including the initial onset of the seismic wave, setting them apart from later arrivals. After picking the arrival times of the first arrivals, a thorough review is conducted to ensure their consistency and accuracy. Any inconsistencies or erroneous picks are carefully corrected or removed from the dataset, maintaining the integrity of the analysis [13].

If the acquired dataset is noisy and identifying the first arrival is very difficult, the bandpass filtering can be used to target a specific range of frequencies within a signal while suppressing frequencies outside that range [14]. Its purpose is to extract desired frequency components while eliminating unwanted high and low-frequency noise from the signal. In this study, bandpass filtering has been applied to a dataset to mitigate low-frequency noise. The filtering process involves setting the low-cut frequency at 0 Hz and incrementally increasing the low-cut frequency by 25 Hz up to 500 Hz. At each step, the attenuation of low-frequency data is observed. The optimal low-pass frequency is determined by identifying high-frequency seismic traces along the depth of the pile. At depths above the pile tip, high-frequency seismic traces are evident, while at depths below the pile tip, there are no high-frequency signals. As a result, the depth of the pile can be accurately interpreted by analyzing the high-frequency traces recorded at the final depth-specific trace.

3. RESULTS AND DISCUSSION

Figs. 5 to 8 show the examples of raw and filtered data for four studied structures, respectively. In the raw data sets, low-frequency dominance poses significant challenges in identifying and picking the first arrivals, with only Fig. 7 exhibiting clear first arrivals. Structure No.1 (the retaining wall) shows a H/D ratio closed to zero, indicating minimal structure above the piles. For the other buildings, identification of the first arrivals was challenging. However, after applying low-cut filter and incrementally increasing the low-cut frequency, some improvement in first arrival identification is observed, although clarity remains limited. Optimizing the low-cut filter reveals high-frequency seismic traces along the recorded depth, which corresponds to the length of the pile. However, seismic traces below the pile tip depth display only spikes of high frequency, distinct from the traces within the pile length (see the filtered data in Figs. 5 to 8). This indicates that there is no longer period of high-frequency activity in the seismic trace beyond the pile length.

Fig. 9 shows the raw signal spectrum of the investigated buildings. It indicates that 100 Hz dominates all structures. Fig. 10 illustrates the correlation between the H/D ratio and the optimized low-cut frequency. The graph illustrates the relationship between these parameters by demonstrating that the H/D ratio of the low-cut filter varies directly with frequency. The height of structures above the pile is one of the most significant factors that can produce resonance, ringing, or multiple on the unpredicted first arrival data that was recorded. This relationship is beneficial for future PSPT data interpretation and analysis.

Table 2 Pile depths detected by PSPT for the piles under four buildings in this study

Structure No.	Depth of Pile Tip (m)	H/D ratio	Optimized Low-Cut Frequency (Hz)
1	18.0	0.05	5
2	10.0	2.00	150
3	6.5	2.46	200
4	4.0	3.00	250

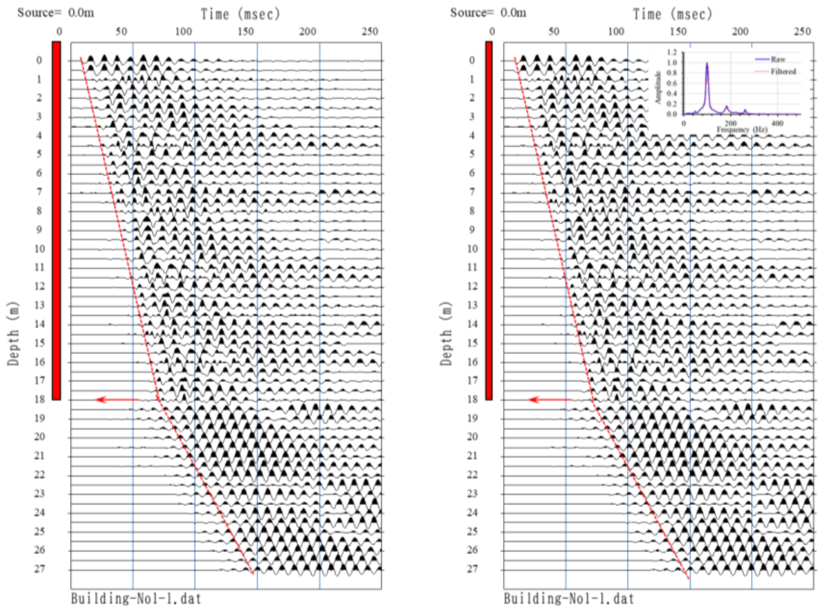

Fig. 5 PSPT result of building No.1: raw data (left) and filtered data (right)

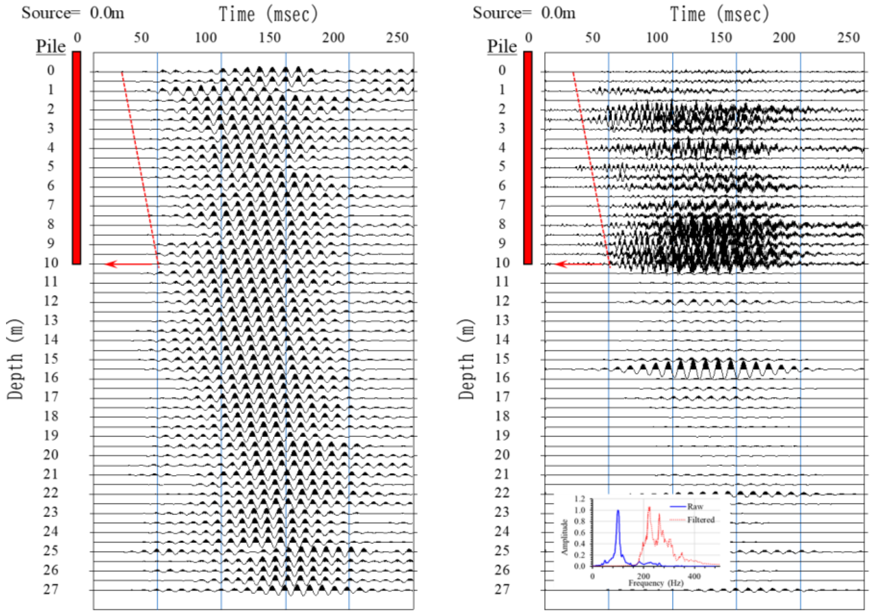

Fig. 6 PSPT result of building No.2: raw data (left) and filtered data (right)

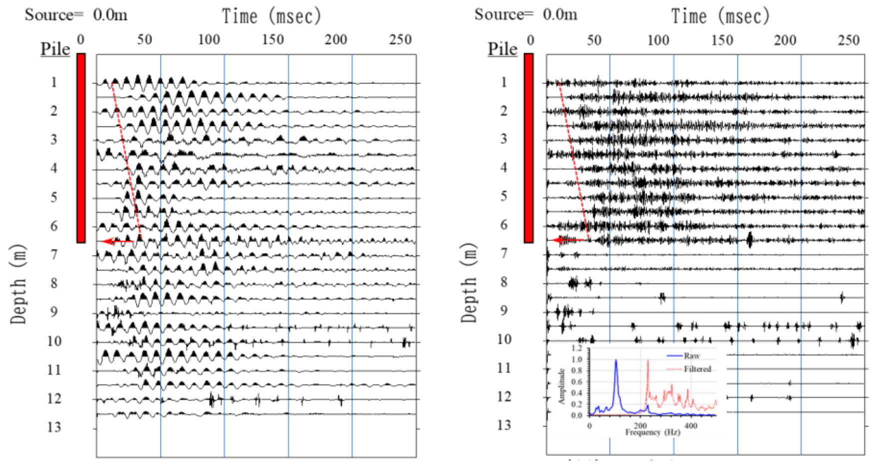

Fig. 7 PSPT result of building No.3: raw data (left) and filtered data (right)

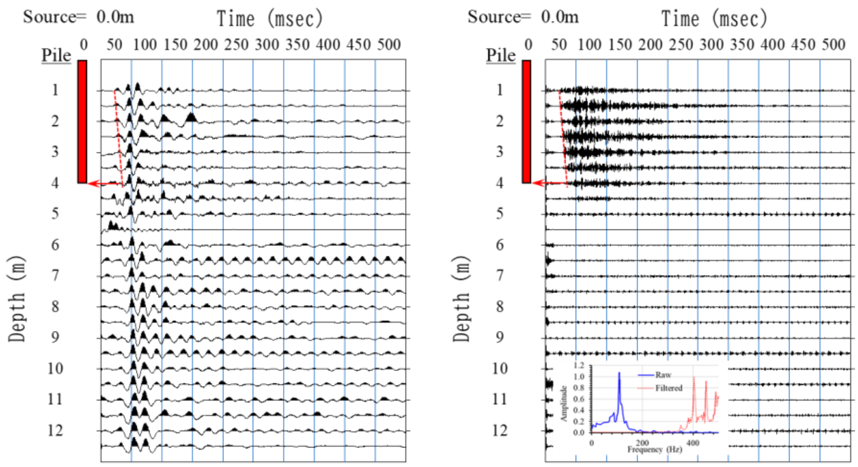

Fig. 8 PSPT result of building No.4: raw data (left) and filtered data (right)

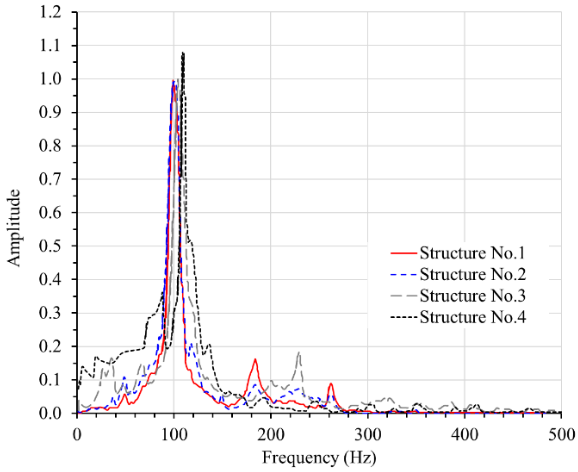

Fig. 9 Amplitude spectra

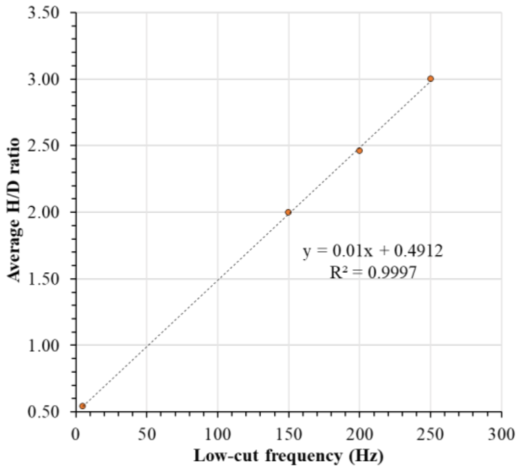

Fig. 10 Relationship between the H/D ratio and the optimized low-cut frequency

4. CONCLUSIONS

The seismic data analysis for four buildings presented in Figs. 5 to 8 highlights the challenges posed by low-frequency dominance in identifying and picking first arrivals. Only structure No.1 of retaining wall exhibited clear first arrivals, indicating a low H/D ratio with minimal structure above the piles, except for the interconnecting beams. Table 2 shows the pile depths detected by PSPT for the piles under four structures tested in this study, varying from 4 to 18 m deep.

For the other buildings, identifying first arrivals was more challenging. However, applying bandpass filtering with incremental increases in the low-cut frequency showed some improvement in first arrival identification [16], although clarity remained limited. Optimizing the low-cut filter revealed high-frequency seismic traces along the recorded depth, corresponding to the pile length. Nevertheless, seismic traces below the pile tip depth displayed only spikes of high frequency values, distinct from the traces within the pile length, suggesting no longer period of high-frequency activity beyond the pile length.

Fig. 9 revealed that structures with the highest H/D ratios have the lowest frequency spectra, demonstrating a relationship between building height above the pile and low-cut frequency as shown in Fig. 10 that can be used for design of low-cut frequency for a new PSPT location.

The PSPT results confirmed the clear identification of first arrivals for cases with low H/D ratios. However, higher H/D ratios were affected by low frequency, possibly due to the structure above the pile, multiple reflections, ringing, or random noise. The study further confirmed the varying H/D ratio's influence on low-frequency spectra.

By effectively employing bandpass filtering and isolating relevant seismic frequency ranges, this study successfully enhanced the clarity of the seismic data, enabling precise depth interpretation of the pile. The elimination of unwanted noise ensured a more accurate and reliable assessment, significantly contributing to a comprehensive understanding of the subsurface structures and properties.

The selection of appropriate cutoff frequencies for the bandpass filter allowed geophysicists and seismic analysts to focus on specific frequency ranges relevant to the seismic data analysis while suppressing noise or unwanted components outside the selected band [17]. This method enhanced the interpretation of seismic data and facilitated the extraction of valuable information about subsurface structures and properties. Overall, this research sheds light on the importance of bandpass filtering in seismic data analysis and its implications for subsurface characterization and engineering applications.

The variation of cutoff frequency can be attributed to inconsistencies in the energy of seismic sources, as well as differences in the distances from the borehole to the pile location and the source location to the pile. In our testing sites, we encountered certain locations that were inaccessible, which required us to use the closest available area to the pile location for generating seismic sources. These factors contribute to the observed variations in the cutoff frequency during the study.

In the case of building No.2 and No.3, test locations have foundations consisting of multiple piles. Consequently, the test results might mimic those obtained from a single pile foundation. However, it is important to note that the PSPT cannot distinguish between a single pile foundation and a multiple pile foundation [18]. As a result, additional complementary information and data is required for more accurate interpretation of PSPT results and classification of foundation types.

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