The Crosshole Sonic Logging (CSL) Measurement System to Measure the Quality of Physical Model of Bored Pile

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Abstract. The crosshole sonic logging measurement to measure the quality of bored piles is presented in this paper. The development of crosshole measurement system on physical bored pile modeling was carried out. The diameter of the concrete model was around 1 m and the height of the model was 1 m. In the model two holes were constructed to simulate the crosshole measurement system in the field. The two holes were filled with water and then two transducers were lowered in the holes. The transducers were built from audio speaker and microphone and they were sealed by rubber material so that the transducers were water proof. The speaker transducer acted as transmitter and the microphone transducer acted as receiver. The acoustic wave transmitted from the speaker penetrated in the concrete material and received by receiver. By analyzing the waveform arrived at the receiver by means of datalogger we determine the condition the concrete pile i.e. whether there were cavities in the concrete etc.

1. Introduction

In this modern era, tall buildings are common to be seen everywhere. Those buildings are built based on strong foundations. Without it, those buildings will be vulnerable to natural disasters such as earthquake, hurricane, tornado, tsunami, etc. Many of them use foundation that usually called deep foundation. Deep foundation is advancement from shallow foundation. Main difference between deep and shallow foundation is the depth from surface. Many geotechnical experts recommend deep foundation over shallow one. It because deep foundation has more endurance which is not affected by soil properties that surrounds it. One of the most frequently used deep foundations are bored piles. Bored piles (called drilled shafts in some countries) are deep, cylindrical, cast-in-place concrete foundations poured in and formed by a bored excavation. The quality assurance of bored piles must be done because they relatively have high probability of having anomalies and tasks to remake the shafts will be difficult to be done.

Non-Destructive Test (NDT) has big contribution in assuring a shaft to function properly with efficient cost. Engineers and NDT technicians have big role in determining whether the condition of a shaft is sufficient enough to be used as a foundation. Because some flaws in a shaft can make unwanted accident (the collapse of a building, bridge, etc.) happen. NDT is used in a way that is not affecting material's structure or anything that surrounds it. In other words, NDT works without destroying the main function of a shaft so it is an effective and efficient way to give an assurance for a foundation.

There are several kinds of NDT that already used world-wide, one of them is, which is going to be discussed in this paper, Crosshole Sonic Logging (CSL). The advantages and disadvantages as well as case history where the accuracy of CSL methods are presented in this paper.

2. Methods

CSL main principle is velocity of wave that is going through the concrete is varied proportionally with density of material and the elastic constant. In CSL, travel time of a signal between transmitter and receiver is measured. By doing so then the velocity approximation can be calculated as function of distance and time. First arrival time that is recorded in CSL is actually time travel of P-wave. P-wave has discrete motion that move along the same direction as the wave movement. The surface of the constant phase, or the surface on which particles are moving together at a given moment in time, is called the wavefront. An imaginary line perpendicular to the wavefront is called a ray path. It is often assumed that a beam of produced ultrasonic energy travels along the ray path (Robert E. Sheriff and Lloyd P. Geldart, 1995). Basic elements of waves through the concrete are described in Figure 1.
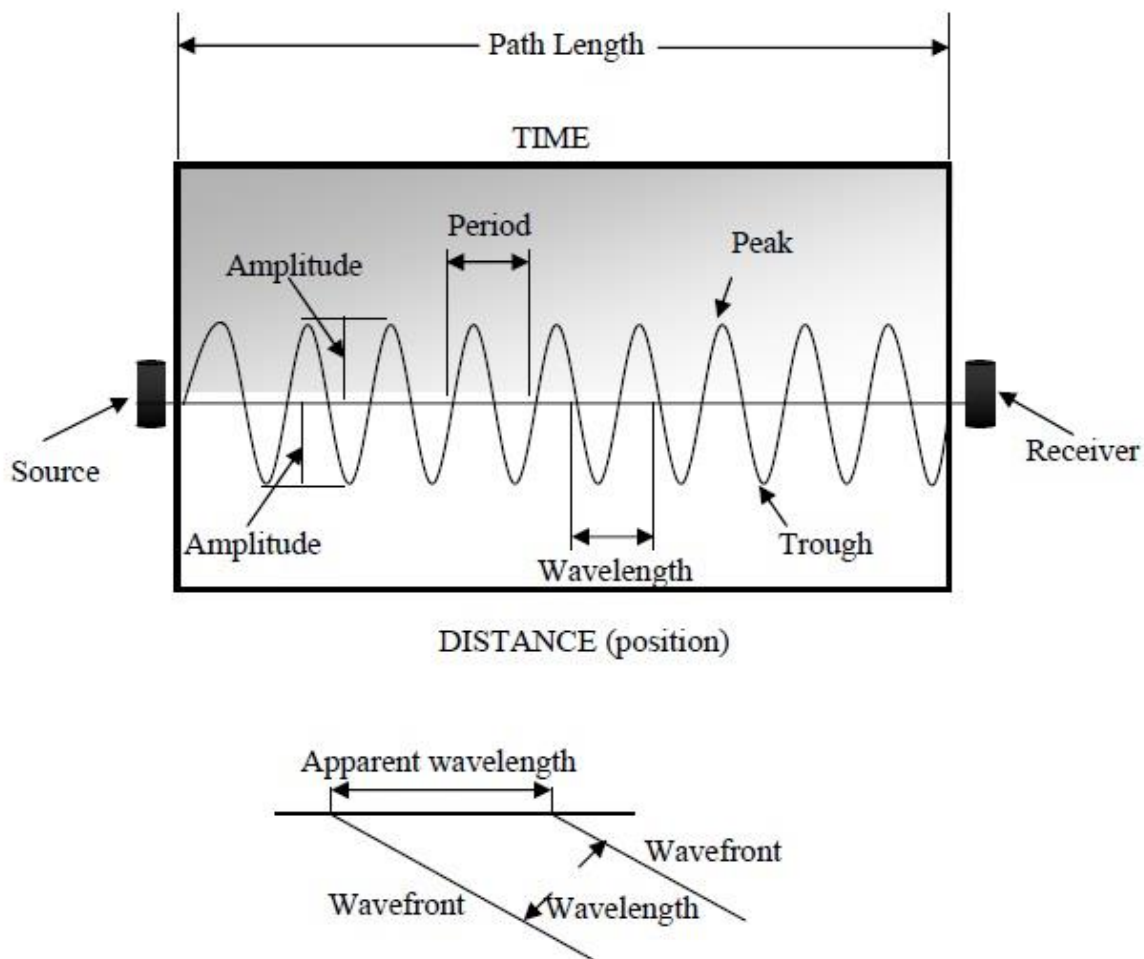
FIGURE 1. Basic elements of waves from transmitter to receiver

The following are definitions of terminology used with CSL analyses (Robert E. Sheriff, 1978):

- Wavelength (λ) – distance between successive repetitions of a wavefront.

- Amplitude (A) – maximum displacement from equilibrium.
- Period (T) – time between successive repetitions of a wavefront.
- Frequency (f) – number of waves per unit time.
- Velocity (V) – speed at which a seismic wave travels, proportional to frequency and wavelength.
- Apparent wavelength – distance between successive similar points on a wave measured at an angle to the wavefront.
- Apparent velocity – product of frequency and apparent wavelength.

Velocity of P-wave in isotropic homogenous media is related to density and the medium modulus where the wave travels is defined by:

$$V_p = \left(\frac{\frac{4}{3}\mu + k}{\rho} \right)^{1/2} \tag{1}$$

where:
- V_p – Velocity of P-wave
- μ – shear's modulus of the medium
- k – bulk's modulus of the medium
- ρ – density of the medium

with:

$$k = \frac{E}{3(1-2v)} \tag{2}$$

$$\mu = \frac{E}{2(1+v)} \tag{3}$$

where:
- E – Young's modulus
- v – Poisson's ratio of the medium

In CSL analysis, the signal velocity can be calculated with:

$$Signal\ Velocity = \frac{Distance}{First\ Arrival\ Time} \tag{4}$$

To get accurate results, distance and first arrival time should be recorded with accuracy greater than 1%. Although velocity of P-waves varies with different concrete mixes, the average velocity should refer to suggested wave velocity in concrete which are explained in Table 1.

TABLE 1. Suggested wave velocity rating for concrete from ultrasonic test (Malhorta, 1976, Harrell and Stokoe, 1984)

Wave Velocity, meter/second (by Malhorta)	Wave Velocity, meter/second (by Harrell and Stokoe)	General Conditions
> 4570	> 4120	Excellent
3660 – 4570	3300 – 4120	Good
3050 – 3660	2750 – 3300	Questionable
2130 – 3050	1920 – 2750	Poor
< 2130	< 1920	Very Poor

CSL was first developed by French National Construction Industry Research Center in the late 1960s. This method has been used to test the integrity of bored piles worldwide. The procedure is explained in

ASTM D6760 (ASTM 2008). The preparation for CSL testing is some access tubes (usually one for each 0.3 meter of shaft's diameter) that are tied to rebar cage before the casting is done. After few days of casting, one speaker transducer acted as transmitter and one microphone transducer acted as receiver are lowered in access tube across each other. Those transducers are set in the same height and pulled simultaneously from bottom to top then moved to another access tube combination afterward. This test is done with all access tube combination.

Data analysis is given in Likins et al. (2012). Figure 2 represents waterfall diagram which is raw data of CSL. On the left side are First Arrival Time (FAT) and probably the most important data in this test. Graphic intensity represents signal strength: white area in 30 feet (approximately 9 meter) shows flaw. The left graphic is the result of testing after few days prior to casting.
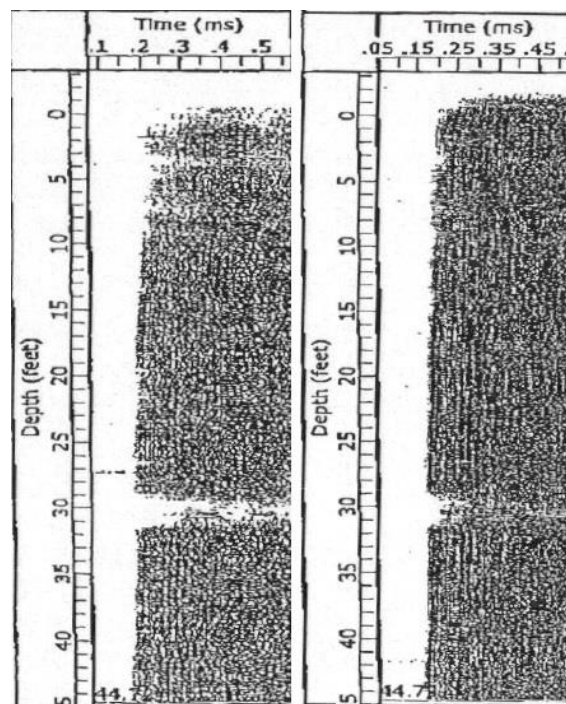
FIGURE 2. CSL testing result with flaw on 30 feet depth; left side is the first test and the right side after treatment is done (Likins, et.al., 2012).

Crosshole Sonic Logging (CSL) is indirect, low strain, non-destructive to detect flaws in bored piles. CSL has been standard test for many developed and developing countries, especially transportation and construction companies. Before CSL was popular, integrity tests were rarely done. Only few bored piles were tested, sonic echo or impulse response test was commonly used at that time. Gamma-gamma density logging also quite popular to support CSL test results. CSL has been acknowledged worldwide for successful and effective result.

3. Results

The physical model in this paper is built with a cube shaped model with 1 meter length for each side. It can be presented in Figure 3.

**FIGURE 3.** Bored pile model, (a) Before casting, (b) After casting

The application computer program used for recording the data is one that is written in LabVIEW software. In this application the user can vary the frequency of the sound produced by the speaker as the transmitter. The front panel of application can be seen at Figure 4.
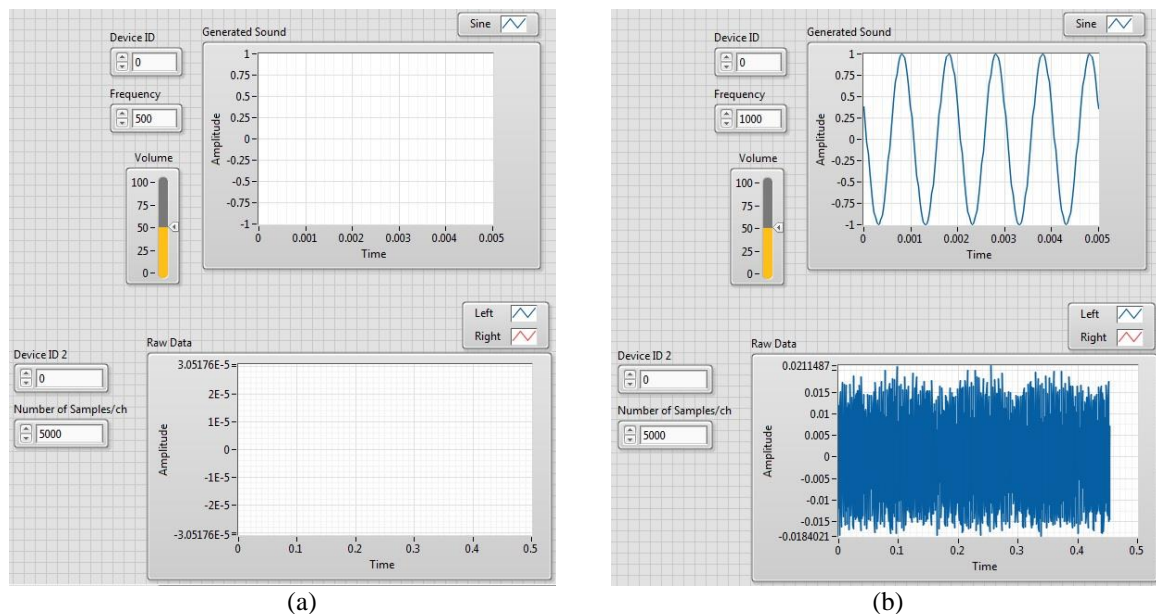
FIGURE 4. Front panel of application used in LabVIEW, (a) Before running, (b) After running

As can be seen in Figure 4, the upper display shows wave that is transmitted through the speaker and the bottom shows wave that is received by the receiver (microphone). The data then exported to Microsoft© Excel 2010 and then we can see the first of arrival time (FAT) of the wave. After obtaining the FAT then we can get the velocity of wave by using equation (4). In this case, the distance between access tubes is 0.78 meter. The measurement in this model is done every 5 cm depth of access tubes. The samples of analyzed data can be seen in Figure 5.
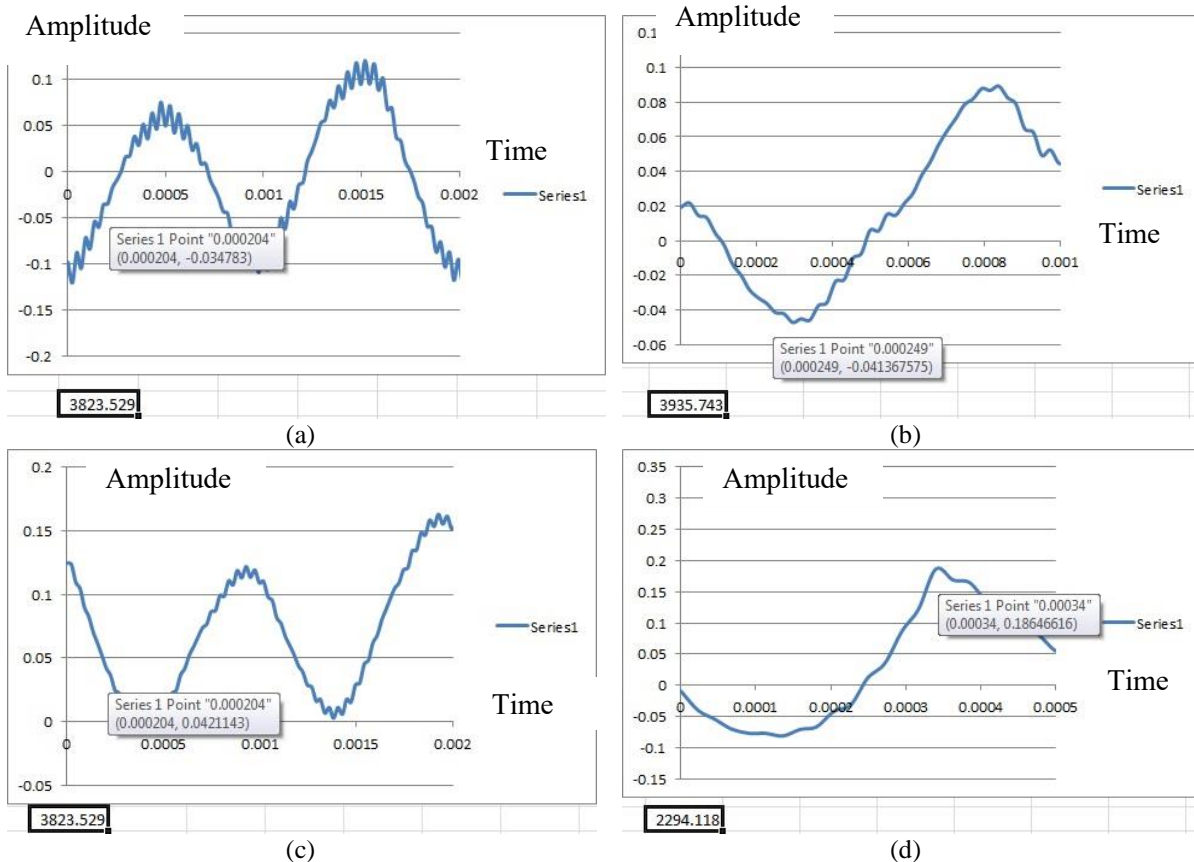
FIGURE 5. Samples of analyzed data, (a) V_p = 3823 m/s, (b) V_p = 3935 m/s, (c) V_p = 3823 m/s, (d) V_p = 2294 m/s

From Figure 5 above, it can be seen that by using acoustic wave to perform CSL testing we can also obtain accurate results. However the displacement of transmitter and receiver inside the access tubes can produce error in reading the data like shown in Figure 5(d) (in assumption that the concrete is homogenous).

4. Conclusion

The case study shows that using acoustic wave to perform CSL can also give accurate result. The results, if they are compared to Table 1 mean that the cube-shaped bored pile model has a good quality. However for the case of Figure 5(d), further measurement must be done to determine whether recorded signals of transmitter and receiver produce the graph in Figure 5(d) which has P wave velocity lower than it should be for good quality concrete.

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