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Evaluating the Height of Cantilever Earth Retaining Walls by Sonic Echo Non-Destructive Testing Method

Jiunnren Lai *, Shu-Tzu Yang, and Tzyy-Shiou Chang

Department of Construction Engineering, Chaoyang University of Technology, Wufeng District, Taichung, Taiwan

Abstract: In recent years, failures of several earth retaining structures caused severe damage in property and loss of life in Taiwan. Therefore, evaluating the safety condition of existing earth retaining structures becomes an important task for the civil engineers. The objective of this research is to investigate the feasibility of applying Sonic Echo non-destructive testing technique for the evaluation of the height of existing cantilever earth retaining structures. Numerical modeling was performed to study the 3-dimensional (3D) effects on the measured signal. Field tests were also performed on two earth retaining walls to verify the correctness of numerical modeling. Results of this study indicate that, in comparison to 1-dimensional structure such as piles, 3D effects reduce the intensity of signal reflected from the bottom of the structure, thus increase difficulty in determining the arrival time of the reflected wave. However, the error resulting from these 3D effects is less than 10%. Therefore, it is concluded that the sonic echo method is a promising technique for the evaluation of the height of existing earth retaining structures.

Keywords: Diacetone alcohol; refractive indices; surface tension.

1. Introduction

Taiwan is located on the Pacific Seismic Rim and the path of Southeast Asia Typhoon. In recent years, failures of several earth retaining structures induced by earthquakes and typhoons caused severe damage in property and loss of life. Therefore, evaluating the safety condition of existing earth retaining structures becomes an important task for the civil engineers. However, many of these retaining structures were built long time ago. The design drawing of these structures are no longer available. It becomes necessary to access the dimensions of these retaining structures through nondestructive testing (NDT) techniques for their safety evaluation. The objective of this research is to investigate the feasibility of applying Sonic Echo (SE) NDT technique for the evaluation of the height of existing earth retaining structures. Numerical modeling was performed to study the 3D effects on the measured signal (velocity waveforms). Field tests were also performed on two earth retaining walls to verify the correctness of numerical modeling.

2. Background

Evaluating the integrity of drilled shafts or driven piles with NDT techniques has long been recognized as an important means for quality control in the construction industry [1,

* Corresponding author; e-mail: jrlai@cyut.edu.tw

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2]. Among these NDT techniques, the Sonic Echo method is often used to evaluate the integrity and determine the length of deep foundations [3, 4]. In an SE test, the foundation top is struck by a hammer and the response (particle velocity) of the foundation is monitored by a receiver as shown schematically in Fig. 1 [5]. The induced stress wave travels down in the pile shaft and reflected waves from significant changes in pile shaft acoustic impedance are registered by a transducer held against the pile head. An idealized (based on 1-dimensional wave propagation) velocity waveform of a pile which contains a bulge and a neck is illustrated in Fig. 2 [5].

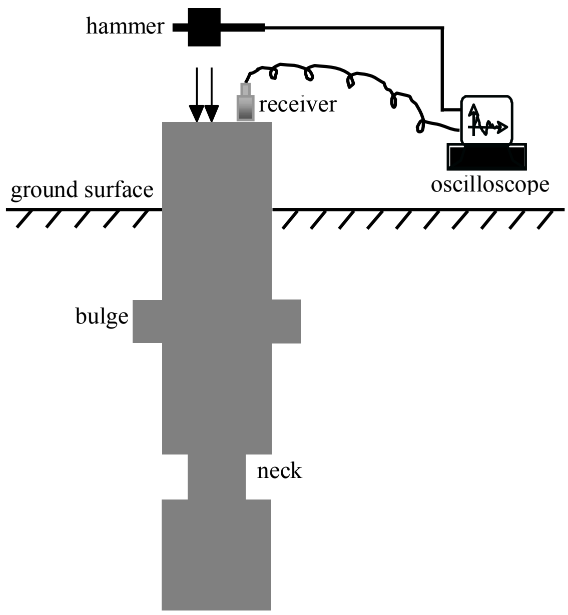

Figure 1. Schematic drawing of the setup for an SE test [5]

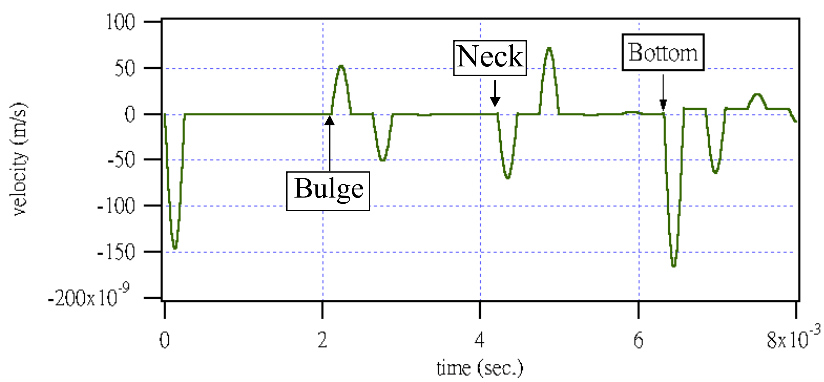

Figure 2. Idealized waveform of an SE test on a pile with a bulge and a neck [5]

The recorded waveform from an SE test can be used to determine the length or location (L) of a defect in the foundation based on the travel time (△t) of the first arrival and the first reflection events or between any two consecutive reflection events according to the following equation:

$$L = (C \times \triangle t)/2 \quad (1)$$

where C is the propagation speed of stress wave in that medium (about 3800 m/s for concrete with a compressible strength of about 28.5 MPa, or 280 kg/cm^2).

The SE NDT technique has been successfully used to evaluate the integrity and determine the length of slender foundations such as drilled shafts or driven piles [3, 4], and was adapted as a standard procedure by the American Society for Testing and Material (ASTM) [6]. However, the shape of earth retaining structures is quit different from that of piles and shafts. Experience on integrity testing of piles and shafts may not applicable to earth retaining structures. Therefore, it becomes necessary to investigate the feasibility of applying this technique for the evaluation of the height of existing earth retaining structures.

3. Methodology

In this study, numerical simulations were performed to investigate the 3D effects on the signal of an SE test using commercial finite element software (ANSYS). A dynamic module (LS DYNA) was used to simulate the velocity waveforms of a 3-meter height earth retaining structure (Fig. 3) with various wall lengths (*l*), base width (*B*), key depths (*d*) and surrounding soil properties. In order to study the 3D effects, numerical modeling was performed using both 2D plan strain element and 3D solid element provided by the FEM software.

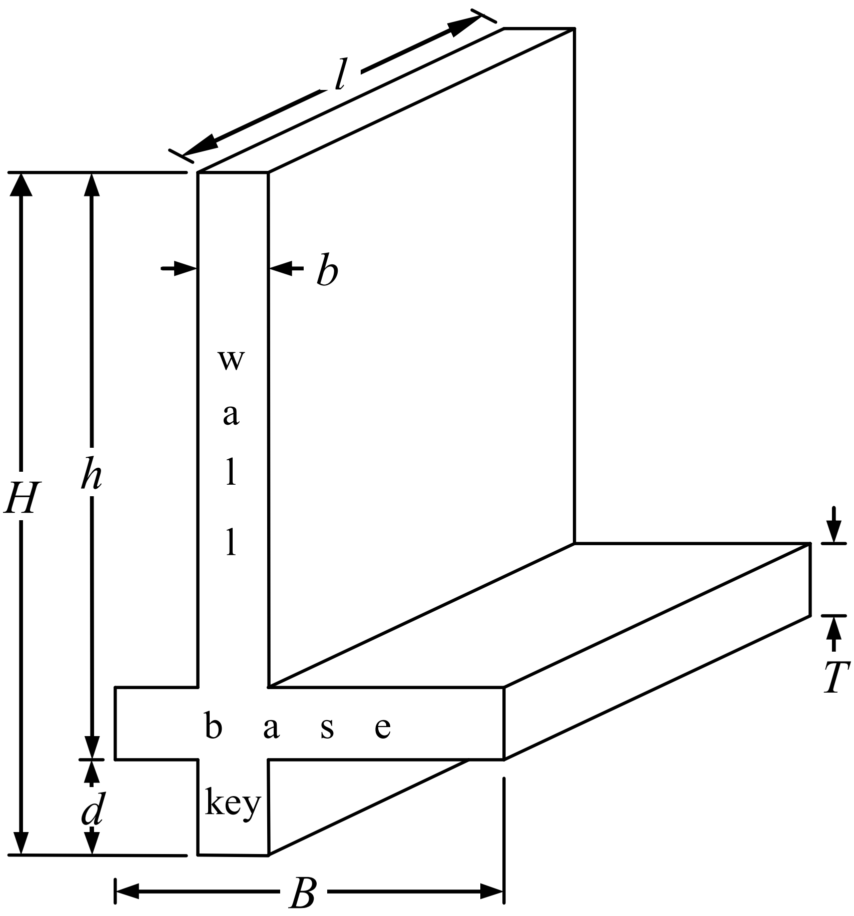

Figure 3. Definition of the dimensions of a cantilever earth retaining structure

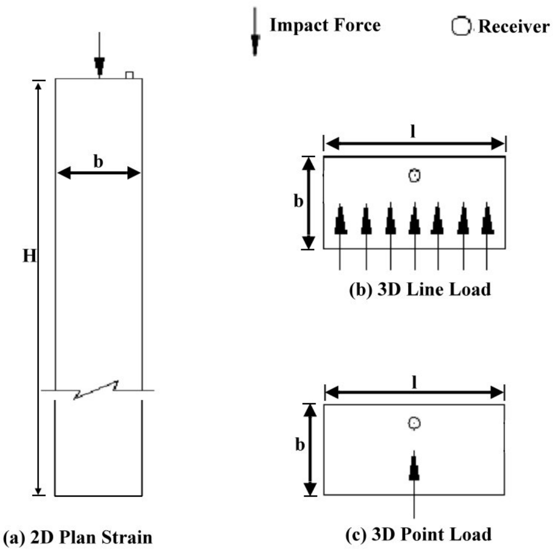

Figure 4. Schematic drawing of the test configuration in the numerical simulation

The impact force was simulated by a half cycle of square sinusoidal function ($\sin^2$) with duration of 500 μs. A schematic drawing of the test configuration used in the numerical simulation is shown in Fig. 4.

The height (*H*) of the retaining structure calculated by Eq. (1) were compared with the real value to investigate the extent of errors resulted from the 3D effects. Field tests were also performed on two earth retaining walls to verify the results from numerical modeling.

4. Results and Discussions

4.1. Numerical modeling

The main difference between a cantilever earth retaining structure and a pile is in their lateral dimension. The diameter of a pile is relatively small in comparison to its length. Therefore, the 1D stress wave theory works fine with this type of structure. For the cantilever earth retaining structures, the wall length is usually greater than their height. The 3D effects are expected to be more significant for this type of structure. The 3D effects on the waveforms of SE tests form numerical simulation are presented first. As shown in Fig. 5a, for short wall length (*l* = 0.3m), the simulated waveforms from 2D plan strain and 3D line load are almost identical. In contrast, there is a little spike after the incident wave in the waveform of 3D point load, and the spike becomes more significant for longer wall length (Fig. 5b; *l* = 8m)

To study the extent of 3D effects, numerical simulation was performed by varying the wall lengths from 0.3m to 8m while the height and the thickness of the wall were kept constant at 3m and 0.3m, respectively. As shown in Figs. 6a ~ 6f, the lateral dimension of an earth retaining wall generates an abnormal spike in the incident wave of the velocity waveform due to the point load effect. It also decreases the amplitude of the wave reflected from the bottom of the wall. However, as shown in Table 1, the point load effect is not the major factor which produced the most significant error in estimated wall height. The largest error (9.7%) comes from the wall with a length of 1 meter. As shown in the Fig. 6c, the error is resulted from surface wave reflected form the edge of the lateral dimension which offsets the primary wave reflected from the bottom the wall.

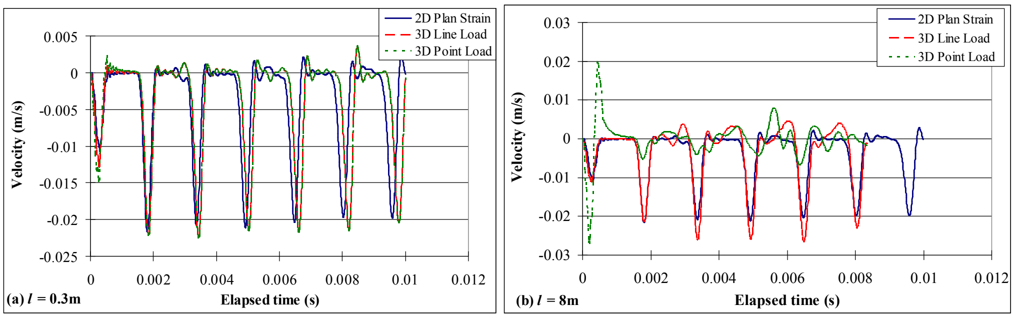

Figure 5. 3D effects on the waveform of SE tests(H=h= 3m, B=b= 0.3m, T=d= 0m)

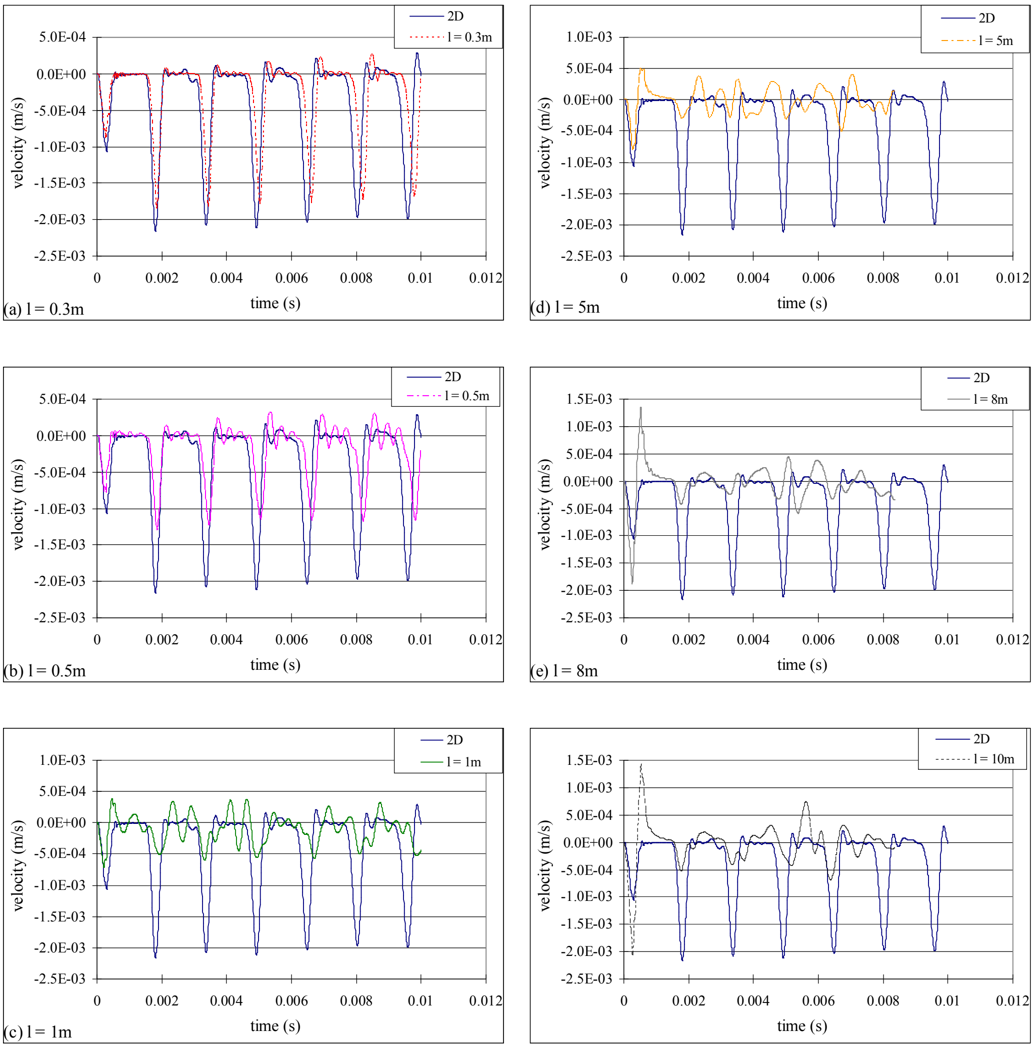

Figure 6. Effects of wall length on the waveform of SE tests(H=h= 3m, B=b= 0.3m, T=d= 0m)

Table 1. Effects of wall length on evaluated wall height

l (m)	Δt (s)	H (m)	Error (%)
0.3	1.57×10^{-03}	2.98	-0.7
0.5	1.58×10^{-03}	3.00	0.0
1	1.72×10^{-03}	3.26	9.7
3	1.52×10^{-03}	2.88	-4.0
5	1.60×10^{-03}	3.03	1.0
8	1.54×10^{-03}	2.92	-2.7

Another parameter which may influence the evaluated height is the width of base. As shown in Figs. 7 and 8, the existence of the base creates another spike as the stress wave travels downward along the wall when it hits the top of the base. In addition, it further decreases the amplitude of the wave reflected from the bottom, thus making identification of the travel time more difficult. However, it does not increase the error in the evaluated height as show in Table 2.

The effects of key depth on the evaluated height were also studied and the results are shown in Fig. 9 and Table 3. It can be seen that the errors for the evaluated height are within the tolerable range (less than 4%).

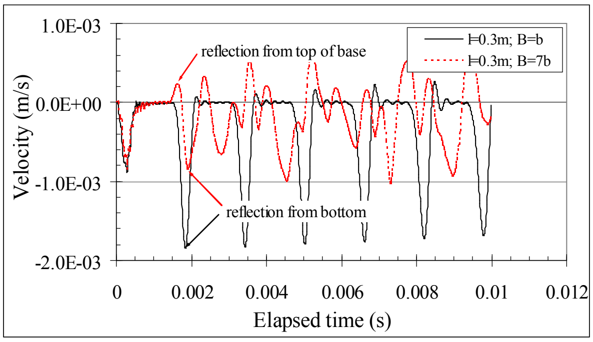

Figure 7. Effects of base width on the waveform of SE test for l = 0.3m (H=h= 3m, b= 0.3m, T= 0.3m, d= 0m)

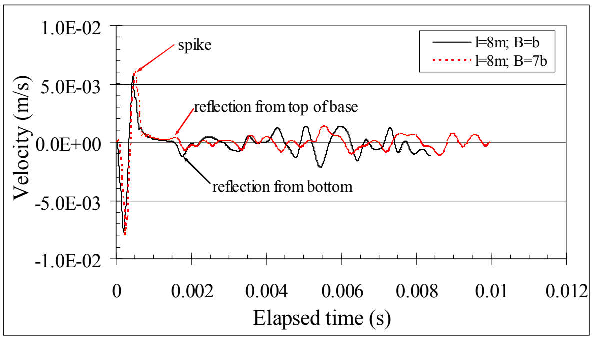

Figure 8. Effects of base width on the waveform of SE test for l = 8m (H=h= 3m, b= 0.3m, T= 0.3m, d= 0m)

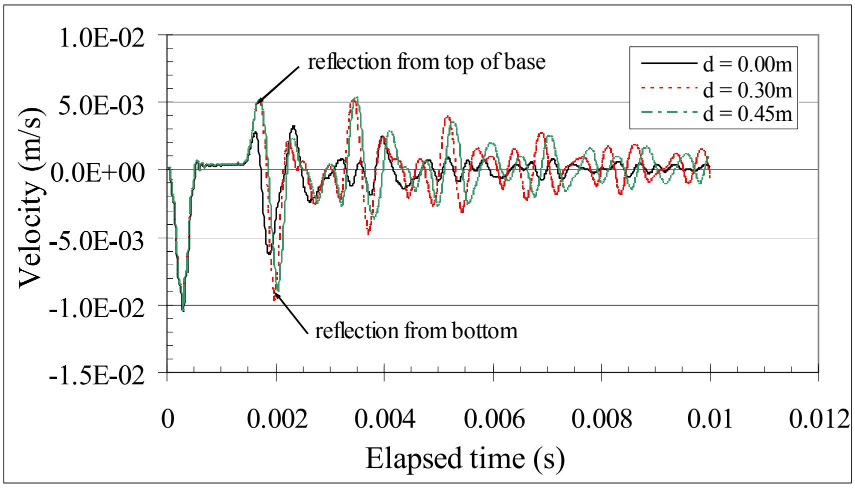

Figure 9. Effects of key depth on the waveform of SE test for *l* = 0.3m (*h*= 3m, *b*= 0.3m, *B*= 2.1m, *T*= 0.3m)

Table 2. Effects of base width on evaluated wall height

l (m)	*B*/*b*	Δ*t* (s)	*H* (m)	Error (%)
0.3	1	1.57×10^{-03}	2.98	-0.7
8	1	1.54×10^{-03}	2.92	-2.7
0.3	7	1.63×10^{-03}	3.09	3.0
8	7	1.66×10^{-03}	3.15	5.0

Table 3. Effects of key depth on evaluated wall height

d (m)	Δ*t* (s)	*H* (m)	Error (%)
0	1.60×10^{-03}	3.03	1.0
0.3	1.70×10^{-03}	3.22	-2.4
0.45	1.76×10^{-03}	3.34	-3.2

Since the earth retaining structures are backfilled with soil, the effects of soil properties such as Young's Modulus (E), Poisson's ratio (ν), and mass density (ρ) on the signal of the SE test were also studied. It was found that the ρ and ν of typical soils do not have significant influence on the signal of an SE test as shown in Figs. 10 and 11. However, the stiffness of soil does affect the waveform of the SE test. As shown in Fig. 12, the reflected wave from the bottom of the wall can barely be identified when the stiffness of the back filled soil is equal to the stiffness of concrete, i.e. E_s=E_c. However, as shown in Table 4, the height of the wall can still be evaluated without significant error as long as the stiffness of the back filled soil is less than 1/10 of the stiffness of concrete, i.e. E_s/E_c <0.1.

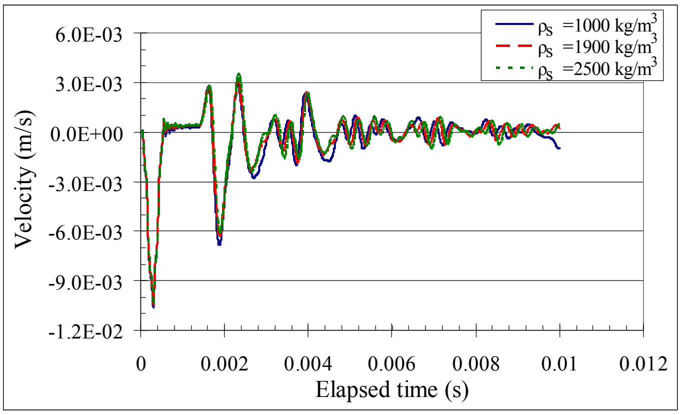

Figure 10. Effects of soil density on the waveform of SE test ($\sqrt{s}$ = 0.2; $E_s = 0.001E_c$)

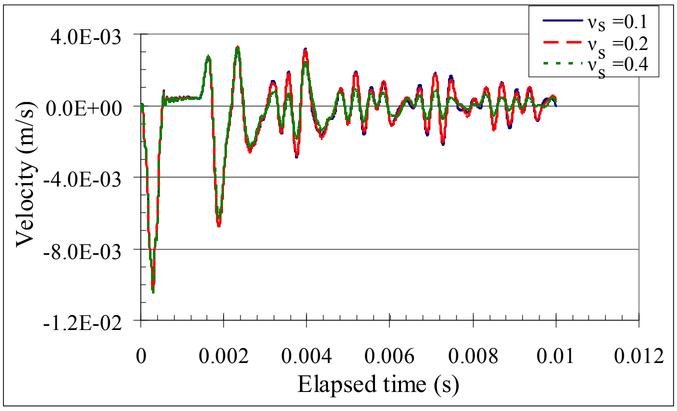

Figure 11. Effects of Poisson's ratio of soil on the waveform of SE test (ρ_s = 1900 kg/m^3; $E_s = 0.001E_c$)

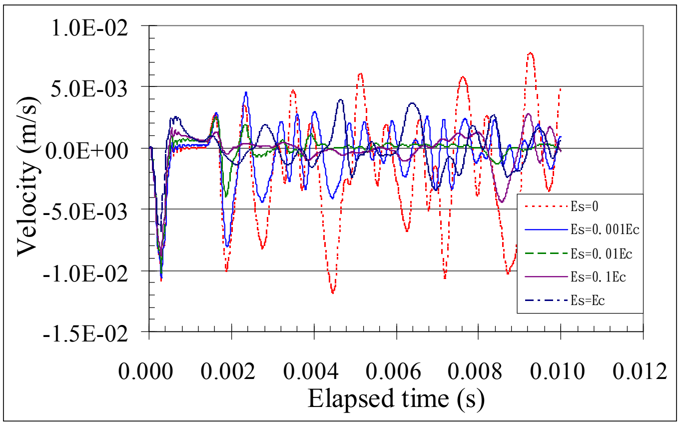

Figure 12. Effects of soil stiffness on the waveform of SE test (ρ_s = 1900 kg/m^3; $\sqrt{s}$ = 0.2)

Table 4. Effects of soil stiffness on evaluated wall height

E_s/E_c (m)	Δt (s)	H (m)	Error (%)
0	1.58×10^{-03}	3.00	0
0.001	1.60×10^{-03}	3.03	1
0.01	1.56×10^{-03}	2.97	-1
0.1	1.60×10^{-03}	3.03	1
1	1.84×10^{-03}	3.39	13

4.2. Field test

In order to verify the correctness of numerical modeling, two earth retaining walls as shown in Fig. 13 were tested using the SE NDT method. Wall-A has a length of 8.7 meters while Wall-B is 2.0 meter long. Both walls are 7.5 meter high and have a base width of 2.3m and thickness of 0.4m with no key. Results of the SE test on these two walls are shown in Fig. 14. It can be seen that, similar to results from numerical modeling, the abnormal spike of the longer wall is more significant than that of the shorter wall. The evaluated wall height is 7.1 meters for Wall-A and 7.6 meters for Wall-B, respectively. The error of the estimated height is only about 5%.

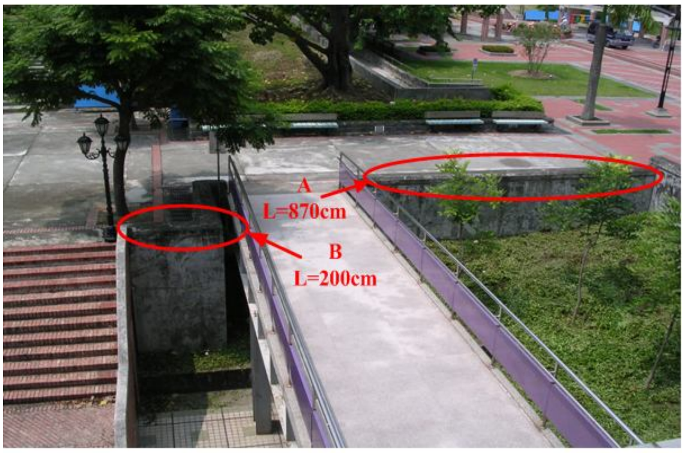

Figure 13. Photograph of the earth retaining walls tested

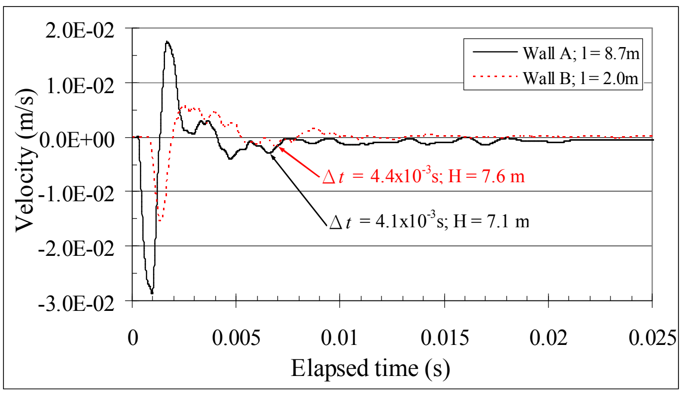

Figure 14. Results of field SE tests on the earth retaining walls

5. Summary and Conclusion

Based on the results of this study, the following conclusions can be drawn:

a) Three dimensional effects generate an abnormal spike in the incident wave and reduce the amplitude of reflected wave in the velocity waveform.
b) Existing of the base in a cantilever earth retaining wall further decreases the amplitude of reflected wave.
c) Results of numerical modeling and field test indicate that, despite of the reduction in the amplitude of reflected wave, the SE NDT technique still can evaluate the height of earth retaining walls with tolerable accuracy.

It is thus concluded that the Sonic Echo method is a promising technique for the evaluation of the height of existing earth retaining structures.

Acknowledgements

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