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# Numerical and experimental study on evaluating the depth of caisson foundation with Sonic Echo method

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**Abstract.** Using nondestructive testing techniques to evaluate the length or depth of an existing foundation is an important issue with potential high application values. One of these is to evaluate whether the foundation is broken after severe earthquakes. In this aspect, academic research related to nondestructive evaluation for caisson foundations is rarely reported. The objective of this paper is to study the feasibility of using Sonic Echo method to evaluate the depth of caisson foundations. Two types of caissons, simple cylindrical caisson and compound caisson with chambers, were studied for their responses to the Sonic Echo tests. The study was carried out in numerical simulation with finite element method and experimental way with in-situ tests. A bridge system which spans over Sofong Brook in Taiwan was selected for the tests in situ. The bridge system is still under construction and therefore the effect of different construction stages on the testing results may be studied. In this paper, the parameters to be varied for the studies include the testing locations and the existence of chamber plates, the bottom plate and the top plate. Finally some preliminary conclusions can be reached for a successful test.

**Keywords:** nondestructive test; caisson foundation; Sonic Echo method; finite element method

## 1. Introduction

A severe earthquake, the Ji-Ji Earthquake, struck central Taiwan on September 21, 1999. The magnitude of the earthquake is 7.3 in Richter scale. Casualties and damages include more than 2505 persons killed and 10000 buildings totally damaged. The post-earthquake evaluation on the integrity of many infrastructures played an important role in the success of the later retrofitting work (Liao *et al*. 2006). In this aspect, the determination of the substantial depth of a foundation exhibits a high value in practical application. To achieve this goal, the nondestructive testing (NDT) methods were frequently used as a rapid and economic way. Among the most frequently used NDT methods, the Sonic Echo (SE) method has long been recognized as a direct and reliable method (ASTM 2004, Olson *et al*. 1995). Many successful cases have been reported with this method. However, these cases were applicable only to a very specific type of foundations, i.e., uncapped piles (Davis 2003, Chow *et al*. 2003, Kim *et al*. 2002, Finno and Gassman 1998, Liao and Roesset 1997, Rausche *et*

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*al*. 1991, Baker *et al*. 1991). Rare reports on predicting the depth of caisson foundations can be found. However, the need for evaluating the depths of existing caissons grows as people's requirement for safe infrastructures increases. In Taiwan the government launched a country-wide evaluation on existing bridges for the past years so that dangerous bridges may be repaired, retrofitted or replaced before disasters occur. It was found from the investigation that the paper data for original design and plans of many old caisson foundations were lost. Obtaining the geometric information for these old caissons plays a key step to design the later repairing or retrofitting work. In this aspect, the depth of existing caissons is among the most important data for the design. In this paper, the SE method will first be introduced and an in-situ test on a pile is illustrated as an example. A bridge system which is still under construction in eastern Taiwan is then introduced as a study case since it contains two types of caissons as the foundation. They are simple cylindrical caisson and compound caisson with chambers. Numerical simulation, as well as in-situ experiments, for these two types of caissons subjected to SE tests is then used to study the effect of chamber plate, bottom plate, top plate and testing locations on the SE testing results.

## 2. Sonic Echo method

To carry out a SE test on a foundation, the top surface of the foundation is usually struck by an instrumented hammer and the response of the foundation is recorded with a receiver placed at a nearby location, as shown in Fig. 1. The next step is to identify the signal associated with the stress wave that travels from the impacted point, is reflected at the bottom and travels back to the receiver. Once the traveling time $\Delta t$ of the reflected wave is determined, the depth $L$ of the foundation can be determined through the following equation

$$L = \frac{V_L \times \Delta t}{2} \tag{1}$$

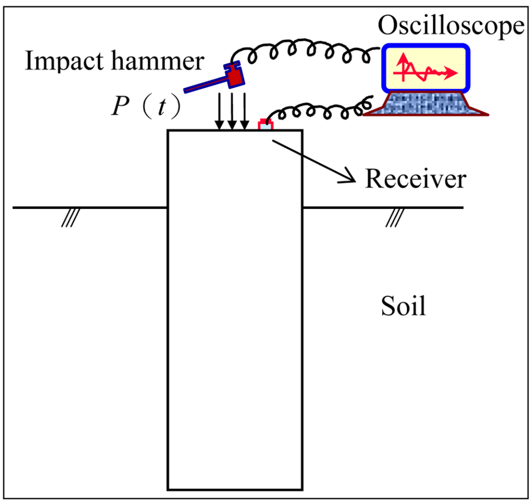



Fig. 1 Schematic showing Sonic Echo test on a foundation

Table 1 Elastic properties of concrete and corresponding wave velocities

| Concrete | | | Unit |
|---|---|---|---|
| Young's modulus | $E_c$ | $3.31 \times 10^{10}$ | N/m$^2$ |
| Mass density | $\rho_c$ | 2300 | kg/m$^3$ |
| Poisson's ratio | $\nu_c$ | 0.2 | - |
| Shear wave velocity | $V_S$ | 2450 | m/s |
| Bar wave velocity | $V_L$ | 3800 | m/s |
| Rayleigh wave velocity | $V_R$ | 2230 | m/s |

where $V_L$ is the longitudinal stress wave velocity in the structure. In most cases when one-dimensional wave propagation prevails, the velocity is calculated by

$$V_L = \sqrt{\frac{E}{\rho}} \tag{2}$$

where $E$ and $\rho$ are the Young's modulus and mass density of the structure. Listed in Table 1 are the elastic properties and associated stress wave velocities used in this research for normal concrete in the foundation. With the properties listed in the table, the longitudinal wave velocity can be calculated to be $V_L = 3800$ m/s. The velocities of shear stress wave and Rayleigh wave are also listed as $V_S$ and $V_R$ in the table.

Using this method, the depth of the foundation can be evaluated in a very straightforward way. This kind of NDT methods is also categorized as the surface reflection methods for the signals to be studied are the reflections of the induced stress waves and the receivers are located at accessible areas.

The time history of the velocity amplitude obtained from a SE test on an in-situ pile is presented with a solid curve in Fig. 2 as an example. The result from numerical simulation with finite element method is also shown with a dashed curve. In analyzing the results of a SE test, a rule is usually utilized to identify the signals of the reflected waves. The rule is to trace the response curve and the attenuation trend implied in the oscillations of the curve until a sudden amplitude rise is

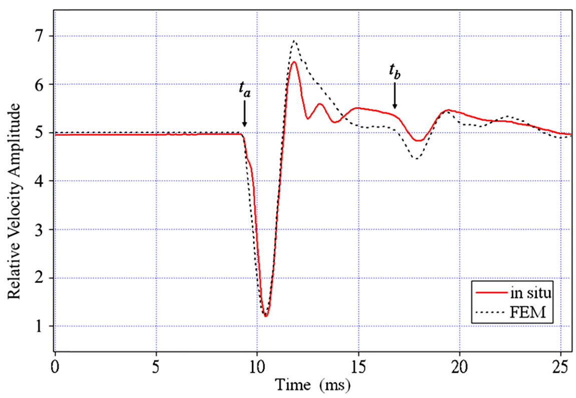



Fig. 2 Velocity amplitude responses of a pile to SE tests from finite element simulation and in situ test

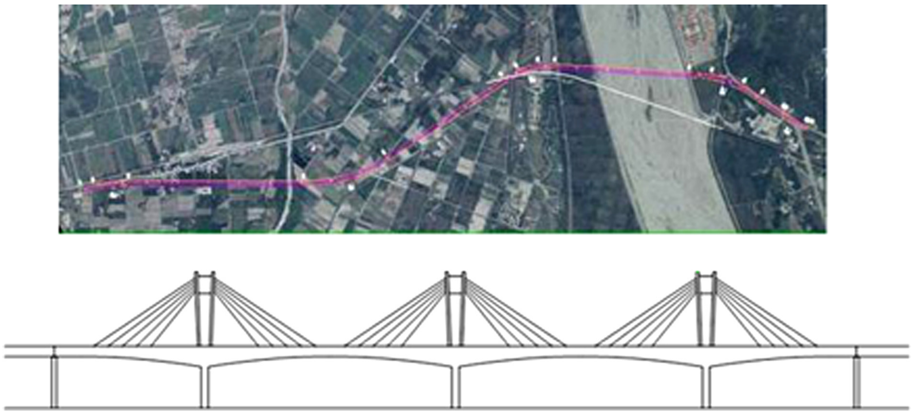


Fig. 3 Schematic overlook of the planned bridge over Sofong Brook

encountered. The oscillations usually attenuate evenly with time as a result of the geometric damping effect when the stress waves propagate out into the whole structure system. Therefore a sudden rise in the oscillation amplitude usually implies the arrival of a reflected wave, which may be used to retrieve the distance to a boundary, interface or abnormality. Using this useful rule, it is straightforward to identify in Fig. 2 that the first arrival time of the stress waves reflected at the pile toe and traveled back to the receiver at the pile head is about 0.0168 s, which is marked with $t_b$ in the figure. Consider that the stress waves leave the pile head at a time of 0.0092 s (marked with $t_a$ in the figure). The pile length can be determined to be $L$ = 14.4 m if $V_L$ = 3800 m/s.

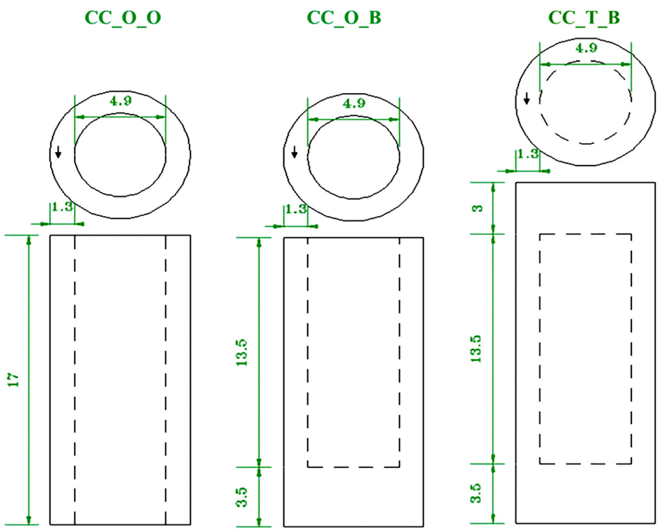
## 3. Geometric configuration of example caissons for study

To study the feasibility of applying SE test for evaluating the depth of caisson foundations, a bridge system under construction is chosen. As shown in Fig. 3, the bridge system is located in the eastern part of Taiwan and spans a total length of 4934 meters over the Sofong Brook. The construction of this bridge started in October 2009 and is expected to finish in June 2012. Two types of caissons were adopted as the foundations for this bridge system. They are cylindrical caisson and compound caisson with chambers. This in-built bridge was chosen for study for the reasons that it has two types of caissons and comparative study may be carried out among different stages of construction. For cylindrical caisson, the SE tests may be carried out at different construction stages so that the effects of the bottom and top plates of the caisson on the response of the SE tests may be studied. For compound caisson with chambers, the effects of chamber plates on the SE tests may be studied. Of course the effects of the bottom and top plates of the compound caisson may also be explored through the comparative studies over construction stages.

### 3.1 Cylindrical caisson

Shown in Fig. 4 are the geometric configurations of the cylindrical caisson of Sofong Brook Bridge at different stages of construction. The inner and outer diameters of the cylinder are 4.9 m and 7.5 m, respectively. The lateral surface of the cylindrical caisson was first constructed to a depth of 17 m before the bottom and top plates were poured. The symbol "CC_O_O" is used to denote this case, as shown in Fig. 4(a). Then concrete was poured to fill the bottom part of the cylinder to form a bottom plate of 3.5 m in height. This case is denoted by "CC_O_B", as shown in Fig. 4 (b). Finally a concrete plate of 3 m in thickness was constructed atop the cylinder to cover the caisson, as denoted by "CC_T_B" in Fig. 4(c).

At each of these three construction stages, the SE tests were carried out so that the effects of the bottom and top plates on the response of the caisson can be evaluated. The impacting force of the SE test was applied on the top surface of the caisson within the region projected by the underneath




(a) (b) (c)

Fig. 4 Geometric configuration of cylindrical caisson: (a) without bottom and top plates, (b) with bottom plate and (c) with bottom and top plates

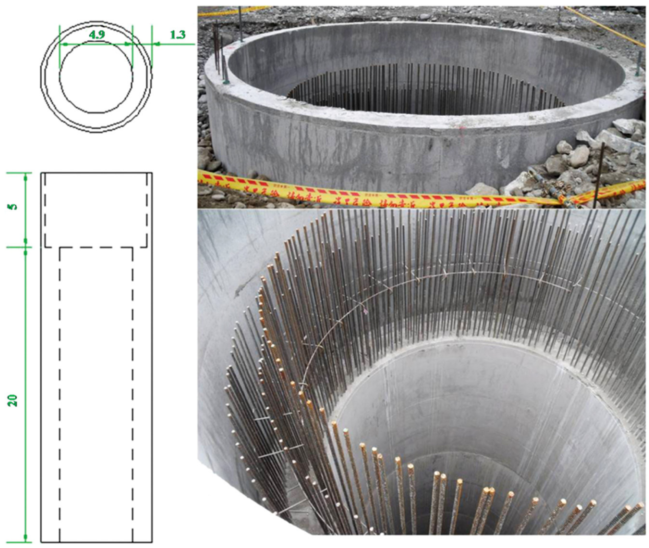


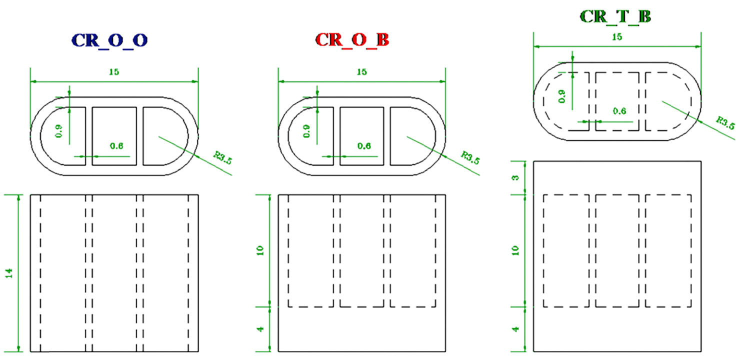

Fig. 5 In-site photo of the cylindrical caisson under construction

cylinder, as shown in Fig. 4 with the arrows. The receiver was placed about 10 cm around the impacting force.

In the site, a water wall of 5 m high was constructed over the top of the cylindrical caisson during the construction, as shown in Fig. 5. It should be noted that the SE test for this case was carried out over the top surface of the water wall.

### *3.2 Compound caisson with chambers*

Shown in Fig. 6 are the geometric configurations of the compound caisson of Sofong Brook Bridge at different stages of construction. The cross section of this type is composed of a rectangle and two half circles which form three chambers with two chamber plates. The lateral surface of this compound caisson was first constructed to a depth of 14 m before the bottom and top plates were poured. The symbol "CR_O_O" is used to denote this case, as shown in Fig. 6(a). Then concrete was poured to fill the bottom part of the cylinder to form a bottom plate of 4 m in height. This case is denoted by "CR_O_B", as shown in Fig. 6(b). Finally a concrete plate of 3 m in thickness was constructed atop the caisson to cover it, as denoted by "CR_T_B" in Fig. 6(c). In this case, the




(a) (b) (c)

Fig. 6 Geometric configuration of compound caisson: (a) without bottom and top plates, (b) with bottom plate and (c) with bottom and top plates

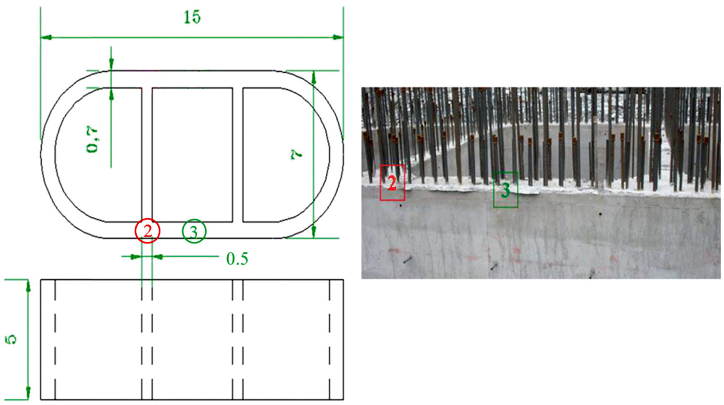



Fig. 7 In-site photo of the compound caisson under construction

cross section of the caisson is no longer axisymmetric and the locations for the impacting force and the receiver may affect the results of the SE test. What is the good location for the test becomes an important issue in this study.

In the site, the caisson was constructed segment by segment of a depth of 5 m, as shown in Fig. 7. It is noted that the cross section of this compound caisson is no longer axisymmetric and therefore the parameters for study should include the location for applying the SE test. It is also noted that the caisson is composed of multiple chambers and thus the effect on the SE test due to the existence of chamber plates can also be evaluated.

## 4. Results of numerical simulation for cylindrical caisson

The cylindrical caisson at different stages of construction shown in Fig. 4 is now modeled with finite elements to simulate its response to SE tests. The finite element meshes corresponding to the caisson without bottom and top plates (case CC_O_O), with bottom plate (case CC_O_B) and with bottom and top plates (case CC_T_B) are presented in Fig. 8. The top surface of the cylindrical caisson is struck with a hammer at a location indicated in Fig. 4 with an arrow. The velocity response amplitudes associated with the caisson at three stages are presented as a function of time in Fig. 9. The response curves associated with cases CC_O_O and CC_O_B are first compared to study the effect of the bottom plate. The two curves coincide totally with each other until a time of 7.1 ms, corresponding to a travel distance of 27 m, a distance for the stress wave to travel from the

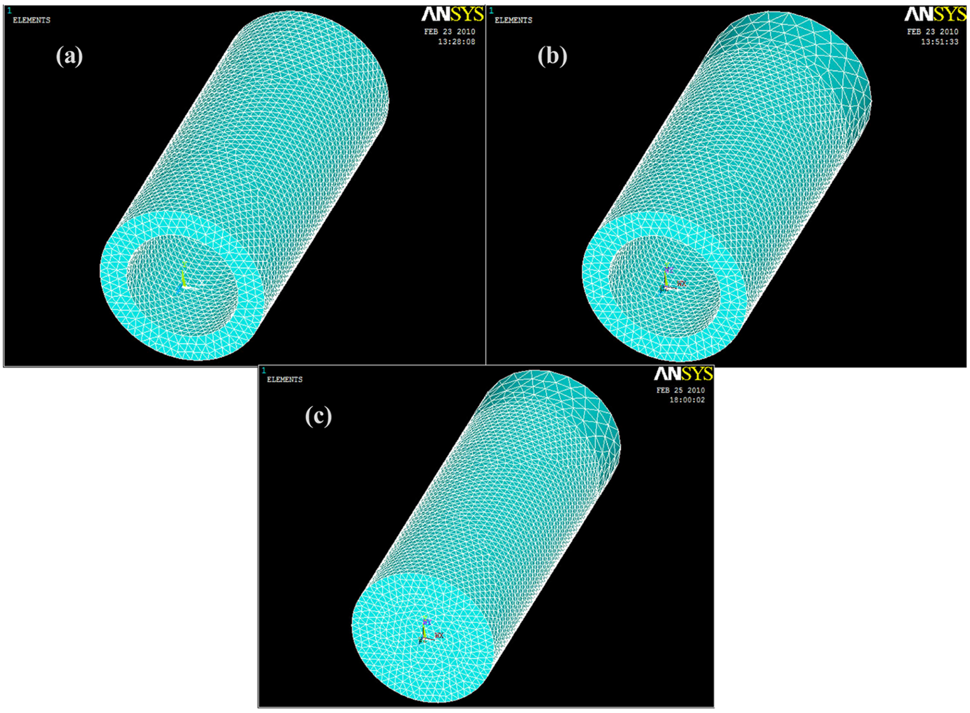



Fig. 8 Finite element meshes for cylindrical caisson: (a) without bottom and top plate, (b) with bottom plate and (c) with bottom and top plates

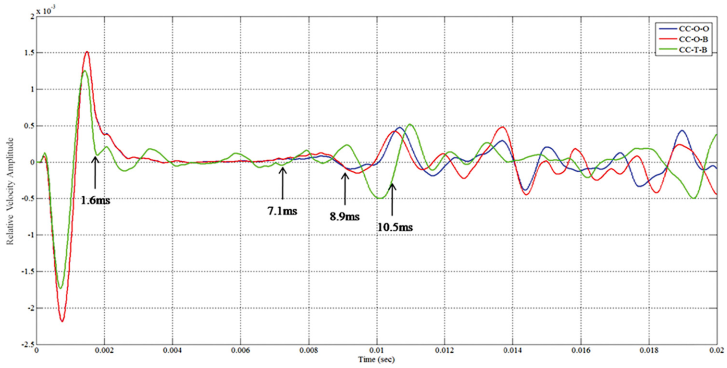



Fig. 9 Numerical velocity response of SE test on cylindrical caissons without bottom and top plate, with bottom plate and with bottom and top plates

top of the caisson and reflect back from hitting the bottom plate. Since that time, the two curves deviate from each other. The total travel time for a round trip through the cylinder depth is 8.9 ms. If the third response curve (case CC_T_B) associated with the caisson with bottom and top plates is considered, it can be seen that the effect on the response due to the existence of top plate is evident. In the response, the first reflection should reveal the depth of the top plate, which is 3 m with a round trip travel time of 1.6 ms. The other two reflections, corresponding to the travel distances 33 m and 40 m (with round trip times 8.7 ms and 10.5 ms), should reveal the depth of the bottom plate, ranging from a depth of 17.5 m to 20 m. It is noted that the main target of this study is the depth of the caisson, which is 17 m for cases CC_O_O and CC_O_B and 20 m for case CC_T_B. The round trip travel times are 8.9 ms and 10.5 ms, respectively. From the figure, identifying the arrival times associated with the depth of the caisson seems feasible, especially for cases when there is no top plate. However, it is noted that the travel time for Rayleigh wave to finish a round trip on the circular top surface of the cylinder is about 8.7 ms. The signals associated with these arrivals of stress waves may interfere with each other so that identifying work becomes obscure and uncertain.

## 5. Results of numerical simulation for compound caisson with chambers

For compound caisson with chambers, the results of SE tests depend not only on the existence of

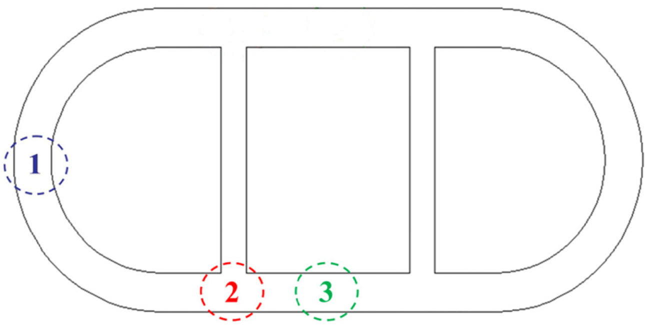


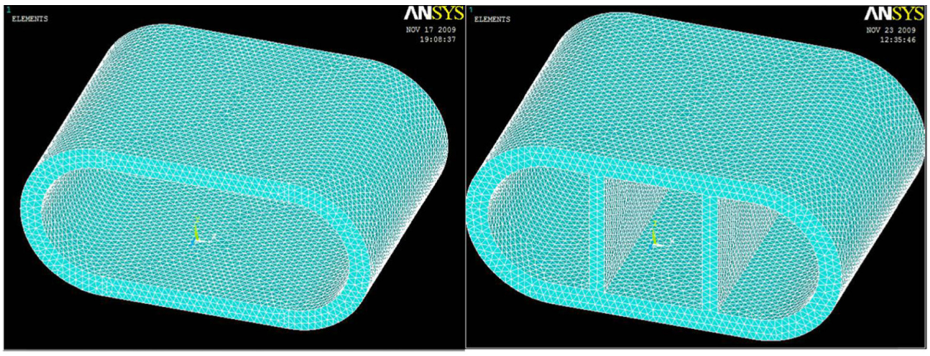

Fig. 10 Planned locations for SE tests on compound caisson

bottom and top plates but also on the testing locations. In this study, three locations were considered to carry out the SE test. As denoted by circled 1, 2 and 3 in Fig. 10, these locations are designated for they may be representative of testing performance. It is one of the main purposes of this research to reach a conclusion for suggesting optimal locations for SE tests on compound caissons.

### *5.1 Effect of chamber plate*

The compound caisson shown in Fig. 6(a) is now considered and simulated using finite element method. The first parameter to vary for studying the effect on the response of SE test is the existence of chamber plate. The finite element meshes for caissons without and with chamber plates are shown in Figs. 11(a) and (b), respectively.

The responses of the caissons with and without the chamber plates as the hammer impacts at position 1 on the top surface are presented in Fig. 12. It is very interesting to note that in both cases the arrivals of stress waves reflected at the caisson bottom (at a depth of 10 m with a round trip travel time of 5.26 ms) can be clearly identified. Another observation is that the arrival of Rayleigh wave after finishing a round trip on the top surface can be seen clearly when there is no chamber plate. Once the chamber plates exist, there are multiple paths on the top surface of the caisson for




(a) no chamber plate (b) with chambers

Fig. 11 Finite element meshes for compound caisson: (a) without and (b) with chamber plates

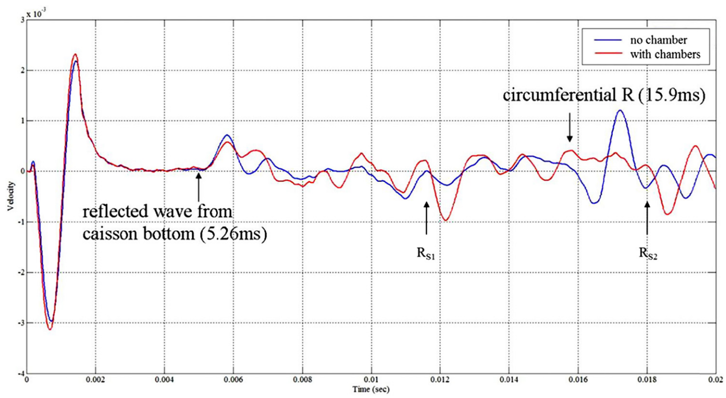



Fig. 12 Numerical velocity responses of compound caissons with and without chambers subjected to SE test

Rayleigh wave to travel and therefore the waves diverse into these paths. In such case, the arrival of Rayleigh wave going for a round trip on the top of caisson's lateral surface becomes obscure. However, a shortcut passing through the top of the nearby chamber plate is taken by Rayleigh wave. The arrivals associated with this kind of shortcut paths are marked by "$R_{S1}$" and "$R_{S2}$" etc. in the figure.

### *5.2 Effect of testing locations*

The effect of testing locations on the response of the compound caisson to SE tests is now explored. First consider the compound caisson without bottom and top plates as shown in Fig. 6(a). The velocity responses corresponding to the SE tests on locations 1, 2 and 3 are presented in blue, red and green ink in Fig. 13. The theoretical arrival times of the stress waves reflected at caisson's bottom is also marked in the figure at the time $t = 7.37$ ms. Comparing the curves with this theoretical arrival time, it can be seen that using the response curve obtained at location 3 to identify the reflection signal of caisson bottom is easier than using those at locations 1 and 2. At location 3, the reflection signal associated with the caisson bottom stands clearly as the first surge in the response curve. This is not true for the other two curves because the reflections associated with

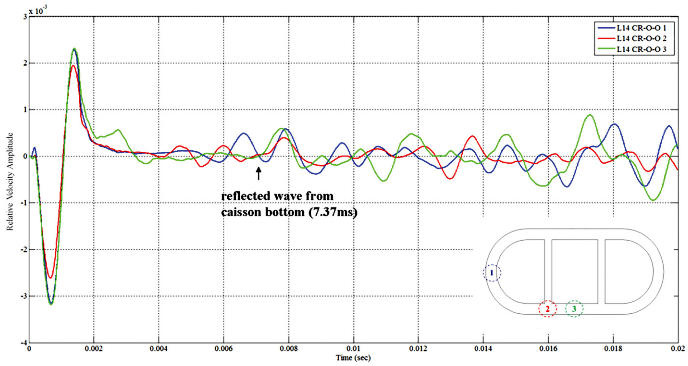



Fig. 13 Numerical velocity responses of SE test performed at locations 1, 2 and 3 on compound caissons without bottom and top plates

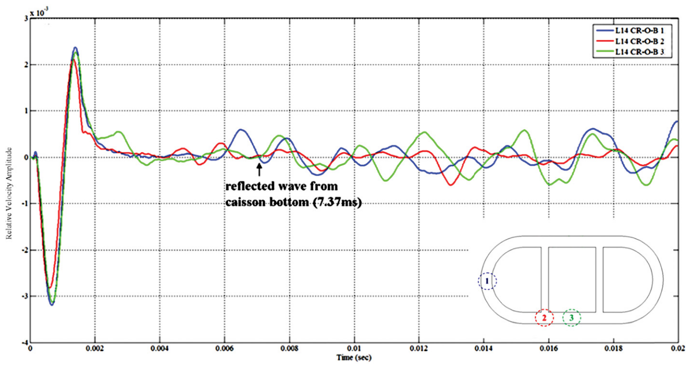



Fig. 14 Numerical velocity responses of SE test performed at locations 1, 2 and 3 on compound caissons with bottom plates

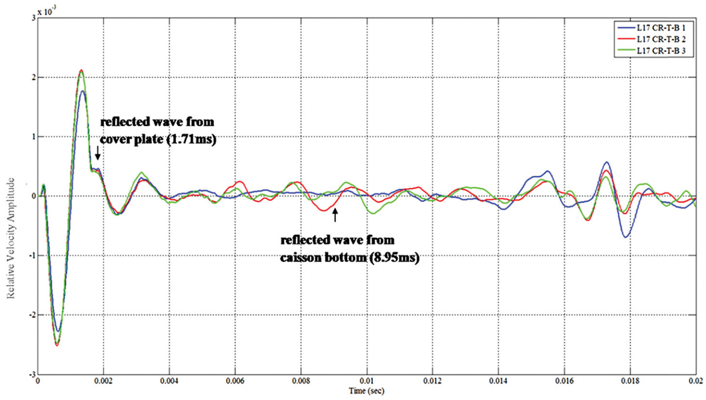



Fig. 15 Numerical velocity responses of SE test performed at locations 1, 2 and 3 on compound caissons with bottom and top plates

other sources come earlier than that associated with caisson bottom. The reason for this phenomenon can be found as the plan view shown in Fig. 10 for these three testing locations is examined. Doing SE test at location 1 may have a reflection coming from the transition interface in geometry before that coming from caisson bottom. If SE test is carried out at location 2, stress wave going a round trip on the top of the chamber plate may arrive earlier than that from caisson bottom. In other word, location 3 is the better place to perform the SE test than the other two sites.

This conclusion is still valid for caissons at the second construction stage. Shown in Fig. 14 are the results of SE test performed at locations 1, 2 and 3, on the compound caisson at the second construction stage, i.e., when the bottom plate is poured. It is still at location 3 that the reflection signal associated with the caisson bottom stands clearly as the first surge in the response curve. This is not true for the other two curves because the reflections associated with other sources come earlier than that associated with caisson bottom.

At the third construction stage when the top plate of the caisson is poured, the results of SE test performed at locations 1, 2 and 3 are presented in Fig. 15. From this figure it can be seen that top plate is the dominant factor on the success of the SE test. When SE test must be performed atop the top plate of the caisson, it is much harder to identify reflection signals from caisson bottom because they will submerge in many reflection surges generated in the top plate. This conclusion exhibits the limitation of applying SE tests on caissons for their depths.

## 6. Results of in-situ tests

The capability of SE test for evaluating the depth of caisson foundations is now examined with in-situ experiments. An in-construction site, Sofong Brook Bridge, was selected for the study. Two types of caissons, cylindrical and compound caissons were used as the foundations for this bridge system. As shown in Fig. 16, the SE test was first performed on the cylindrical caisson shown in Fig. 5. The result is presented in Fig. 17. The test was performed on the top of the water wall (5 m high) and thus the reflection from the interface of the water wall and caisson can be clearly observed. Another clear reflection may be identified at about 15 ms which corresponds to a depth of 26.55 m. This should be the total depth of water wall and the caisson, which is 25 m in design.

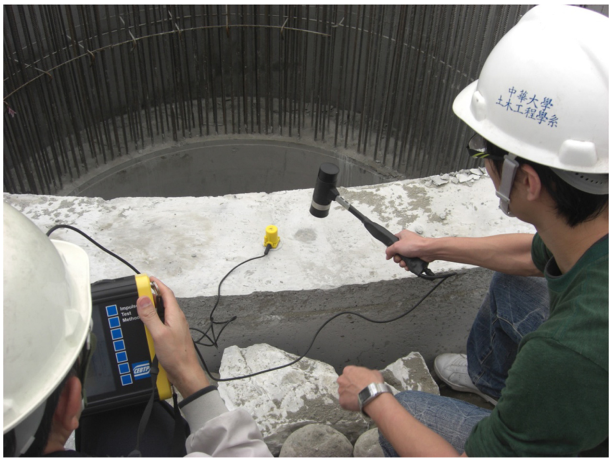


Fig. 16 In-site photo of the SE test on cylindrical caisson

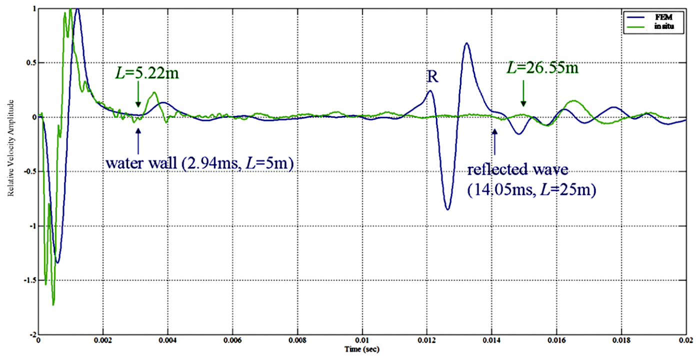



Fig. 17 Velocity response of in-situ SE test on cylindrical caisson

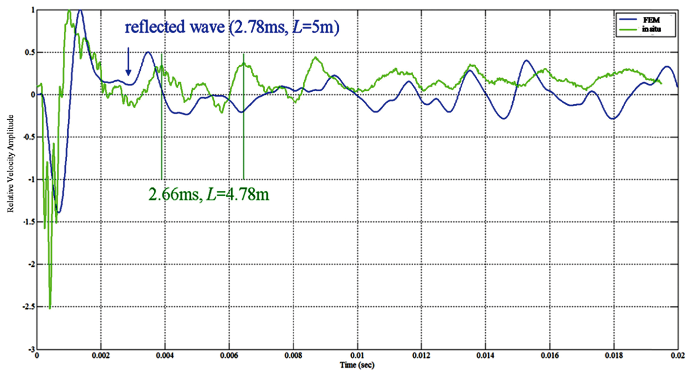



Fig. 18 Velocity response of in-situ SE test on compound caisson without bottom and top plates

For comparison purpose, the result of finite element simulation is also presented in the figure. It is found that the propagation of Rayleigh wave on the circular top surface of the water wall can clearly be observed only in the numerical simulation. Later exploration by the authors revealed that the surface wave propagation attenuates out in the in-situ soil conditions surrounding the caisson.

Next consider the compound caisson as shown in Fig. 6. At the time of performing SE test, the caisson was constructed only to a depth of 5 m, as depicted in Fig. 7. The result of SE test performed at location 3 is presented in Fig. 18. The periodic reflections from caisson bottom can be clearly observed for now the depth is very shallow.

## 7. Conclusions

In this paper the feasibility of applying Sonic Echo tests to caisson foundations for evaluating their depths is preliminarily studied. Two types of caissons were considered for the study. They are cylindrical caisson and compound caisson with chambers. From the study, some conclusions may be drawn as follows:

1. In absence of the top plate, evaluating the depth of simple caissons of cylindrical type with Sonic Echo test is feasible, no matter when there is a bottom plate. Once the caisson is covered with a top plate, it is no longer easy to obtain a good evaluation.
2. Unlike for pile foundations, Rayleigh wave propagation plays an important role in the SE test for caisson foundations. Special care must be taken to distinguish the arrivals of reflections from caisson bottom and the propagation of Rayleigh wave on the top surface of the foundation.
3. It is harder to obtain successful results of SE tests on compound caissons with chambers than on simple cylindrical caissons. Chamber plates may provide shortcuts for stress waves, especially Rayleigh wave, to travel along and thus may interfere in identifying the arrivals of the bottom reflections.
4. Successful SE tests on compound caissons also depend on the locations where the tests are performed. A good testing location should be selected to avoid the interference due to the reflections from the sources other than the caisson bottom. From this study, location 3 which is at the mid-length of the straight strip that connects two chambers is a good choice for performing SE test.

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