IMPACT-ECHO RESPONSE OF ROCK-SOCKETED DRILLED SHAFTS

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ABSTRACT

Numerical and experimental model studies were conducted to get the transient responses of shafts subjected to elastic impact in the impact-echo testing technique. The impact responses corresponding to several toe boundary conditions such as free-, fixed-, soft bottom-, and rock-socketed-condition were investigated. In order to simulate the rock-socketed drilled shafts, polyurethane mock-up shafts were used and bonded firmly with plastic material that has much higher acoustic impedance than polyurethane. One-dimensional finite element studies using ABAQUS were performed for mock-up shafts under the various toe boundary conditions. The experimental model studies were also performed for the same cases to verify the finite element models. These studies were carried out to provide an improved understanding of the impact responses of rock-socketed drilled shafts that are mostly designed and built in Korea. Subsequently, the preliminary experimental field studies were also carried out on concrete shafts that were socketed into the weathered rock. The results of experimental laboratory tests were in good agreement with those of numerical simulation and field tests, showing the usefulness of FEM model in the simulation of impact-echo method. These results also showed the potential and limitations of applying economical impact-echo method to assess the integrity of the drilled shafts especially socketed into the rock.

1. Introduction

Drilled Shafts socketed into rock are now frequently used for deep foundations of long-span bridges in Korea. The shafts, however, may have flaws such as soft bottoms, voids, cracks, and necks due to improper quality control, and unexpected construction error, etc. These flaws will cause a decrease of load-bearing capacity of the shaft and/or an increase of settlement, and the subsequent damage of the superstructures. In consequence, the development of nondestructive testing method for the integrity evaluation of drilled shafts, particularly with soft bottom in the rock-socketed shaft, has become important.

So far there are several nondestructive testing methods to evaluate the flaws in drilled shafts: (a) cross-hole sonic logging, (b) nuclear density testing through the use of gamma-gamma testing, (c) sonic echo testing, and (d) impulse response testing [6]. These four methods are commonly in use for drilled shaft inspection, and since they have advantages, disadvantages and limits, therefore, it is important to choose the appropriate method for the integrity evaluation of drilled shafts. In practice, the cross-hole sonic logging test is being widely used in the field of quality control of drilled shafts in Korea, but the method requires the boreholes that should be installed in the drilled shafts during construction, which means that the cost of the test is expensive. Therefore the cost-effective non-destructive tests that do not use the borehole are needed.

In this paper, the sonic echo testing (impact-echo testing) is employed and the impact responses corresponding to several toe boundary conditions such as free-, fixed-, soft bottom-, and rock-socketed-condition were investigated respectively. In order to simulate the various end boundary conditions, polyurethane mock-up shafts were fabricated and a pedestal made of monocast that has much higher acoustic impedance than polyurethane was used to assume a rock. The rod wave speed of polyurethane is about 450 m/sec and the P-wave speed of monocast is about 1900 m/sec, and thus it was observed that the waveform of the mock-up shaft was similar to that of the drilled shaft in the field. The end boundary conditions used in this study are shown in Fig. 1.

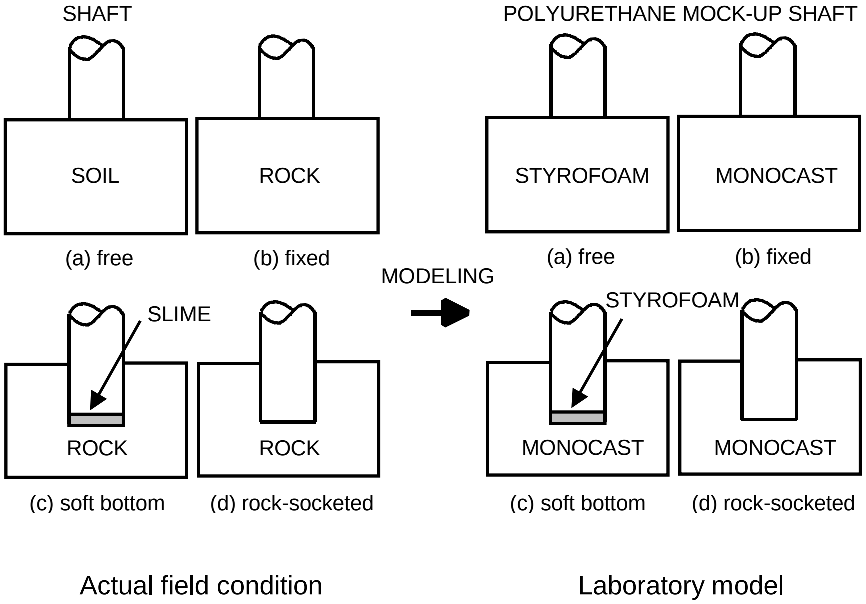


Fig. 1. Various end boundary conditions: left hand side is actual possible field conditions; right hand side is corresponding laboratory model.

The free condition was simulated only putting the mock-up shaft upon the soft Styrofoam, whereas in the fixed condition, the mock-up shaft was put upon the monocast pedestal. The free condition represents that the toe of drilled shaft is located in soil, and the fixed condition represents that the toe of shaft is extended to the rock. The rock-socketed condition was simulated using the mock-up shaft bonded firmly with monocast pedestal that has much higher acoustic impedance than the shaft. In practice, the soft bottom is usually occurred in the field when the drilled shaft is constructed, and it is filled with slurry like slime. So the boundary condition was modeled similarly as the rock-socketed condition except the existence of Styrofoam between shaft and bottom.

2. Numerical studies

One-dimensional finite element studies using ABAQUS were performed for mock-up shafts under the various toe boundary conditions. The mock-up shafts considered in this paper were discretized using truss elements in the one-dimensional analyses. The diameter and the length of the shaft is 0.06m and 0.6m respectively. The modulus of elasticity, Poisson's ratio, and the density were 0.25 GPa, 0.45, and 1133 kg/m^3, respectively, and these constants resulted in rod wave speed of 470 m/sec. In the finite element modeling of the shaft, the duration of the impact (t_c) is an important factor because it determines the frequency content of the stress wave that is generated [7]. In this finite element study, the duration of the impact was determined to be 1.5x10^{-3} sec, and the loading pressure was assumed to have a sinusoidal impact of half a cycle as shown in Fig. 2.

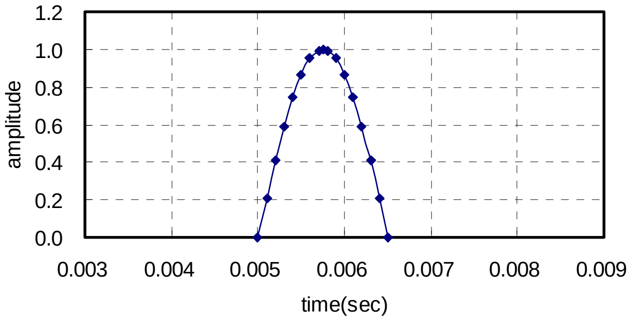


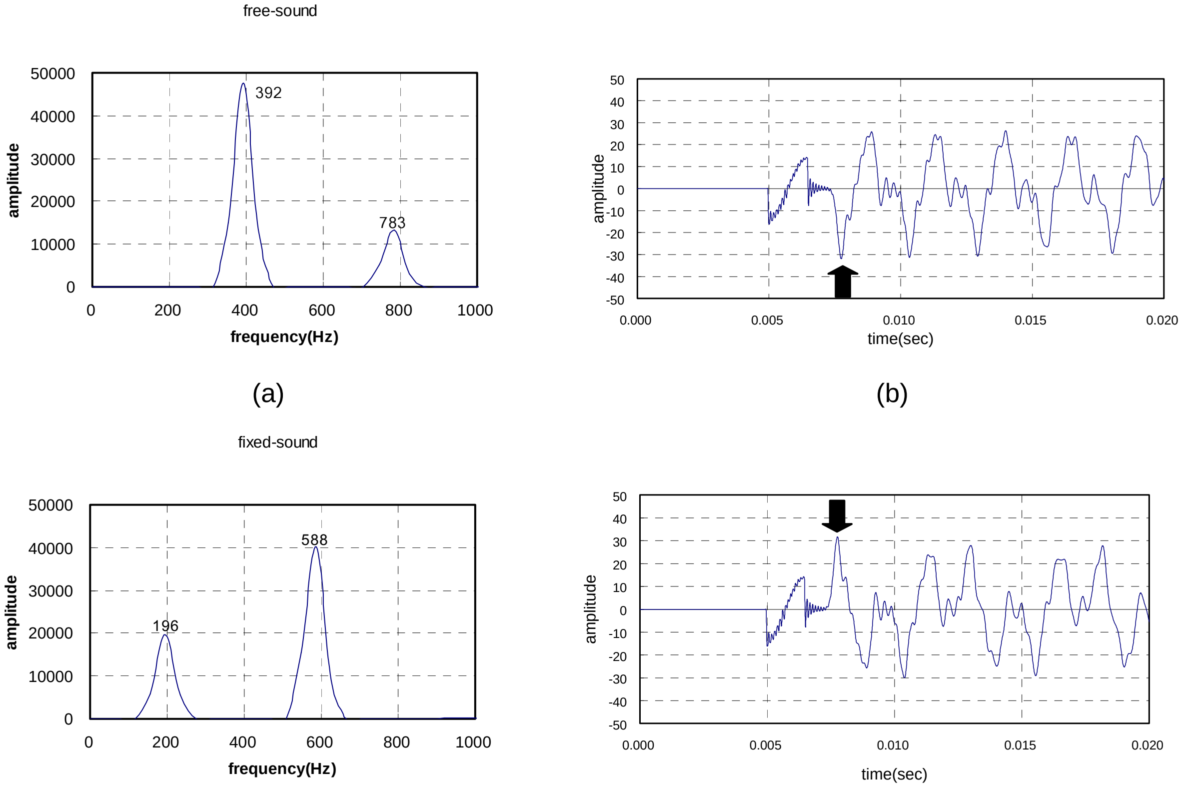
Fig. 2. Sinusoidal impact of half a cycle duration

Another important factor influencing the results of finite element analysis is the element size, and it is shown that in order to obtain a satisfactory result, the element size should be less than about one tenth the wavelength of the highest frequency waves propagating in the structures [4]. In this study the element size was determined to be 1cm.

2.1 Free and fixed end condition

To simulate the polyurethane mock-up shaft under free end condition, the surrounding air was modeled as a weak and light material with minimal acoustic impedance. Therefore, the shear wave velocity, Poisson’s ratio, and the density were assumed to be 0.05m/sec, 0.01, and 0.001kg/㎥ respectively. Figure 3 (a) shows the amplitude spectrums determined by one-dimensional finite element model. The resonance peaks occur at 392 Hz and 783 Hz which is identical with that determined by following equation (1).

$$f_n = \frac{nV_p}{2T} = n \cdot \frac{470m / \sec}{2 \times 0.6m} = 392{,}783Hz, \cdots (n = 1{,}2{,}3, \cdots) \qquad (1)$$



(a) (b)

(c) (d)

Fig. 3. Impact response of a solid shaft: (a) acceleration spectrum under free condition; (b) waveform under free condition; (c) acceleration spectrum under fixed condition; and (d) waveform under fixed condition

The spectrum and waveform of fixed end condition are different from those of free end condition as shown in Figs. 3(c) and (d). The resonance peaks occur at 196 Hz and 588 Hz which is identical with that determined by following equation (2).

$$f_n = \frac{nV_p}{4T} = n \cdot \frac{470m / \sec}{4 \times 0.6m} = 196{,}588Hz, \cdot \cdot \cdot (n = 1{,}3{,}5, \cdot \cdot \cdot) \qquad (2)$$

In the waveform of the fixed end condition, it is noted that the impact compressive stress wave is clearly reflected as a compressive wave at the interface boundary between mock-up shaft and rigid material and does not change sign, and therefore the waveform of acceleration at this time is upward (arrow point), which provides the key to distinguish free end condition from fixed end condition.

2.2 Rock-socketed condition

A two node, truss element is shown schematically in Fig. 4. To simulate the effect of the rock material on the side of the mock-up shaft, distributed springs with elastic stiffness k_v and dashpots with damping coefficient c_v are applied to each segment below the rock interface. The rock material effect at the base of the mock-up shaft is also taken into account with a spring with elastic constant K_v, and a dashpot with damping coefficient C_v.

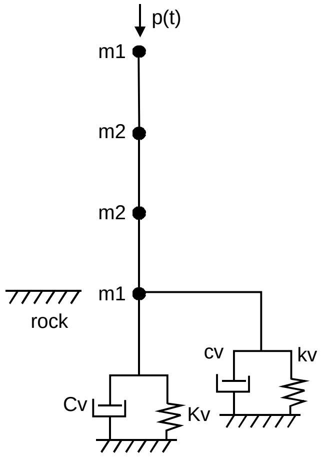


Fig. 4. One-dimensional finite element model for rock-socketed end condition

The following equations were adopted to determine the elastic constants of the spring and the dashpot constants [3].

$$k_v = 2.3G_s \quad (\mathrm{N/m^2}) \qquad (3)$$

$$c_v = 2\pi\rho_s V_s r_p \quad (\mathrm{Kg/m\text{-}s}) \qquad (4)$$

$$K_v = 4G_s r_p / (1 - \nu_s) \text{ (N/m)} \tag{5}$$

$$C_v = 0.85 K_v r_p / V_s \text{ (N-m/s)} \tag{6}$$

where G_s, ρ_s, ν_s are the shear modulus, mass density, and Poisson's ratio, respectively, and V_s is the shear wave velocity of the rock material, and r_p is the radius of the mock-up shaft.

The waveforms for the mock-up shaft under the rock-socketed and fixed condition are shown in Fig. 5. It is observed that the shape of each waveform is similar, but the waveform of the rock-socketed condition is shifted toward left in the time axis. This fact implies that the stress wave is reflected to the interface between the mock-up shaft and rock material, and therefore the reflection time of the rock-socketed condition is a little faster than that of the fixed condition. Consequently, this time lag may be used to calculate the socketed length into the rock material. In this case, the time difference between these conditions (note the arrow point) is obtained to be 2.2×10^{-4} sec, and this time lag gives the socketed length of 5.2 cm that is approximately near the exact value of 6 cm.

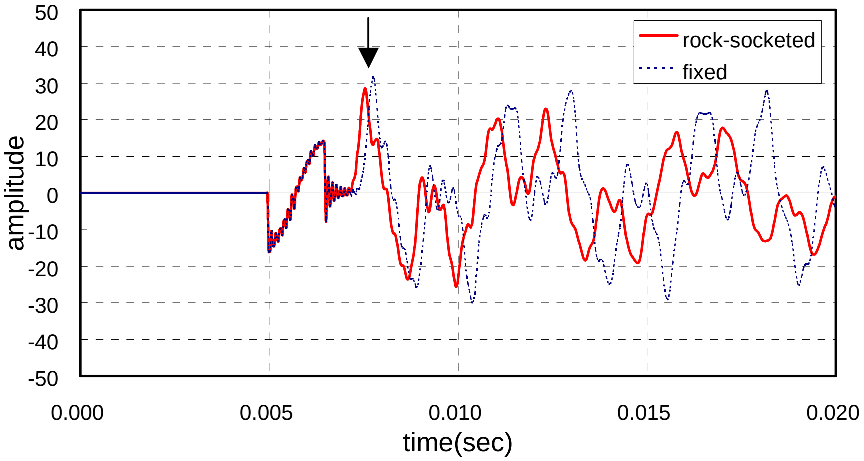


Fig. 5. Waveforms for the mock-up shafts under the rock-socketed and fixed end condition

3. Laboratory studies

Laboratory studies were also carried out to verify the results obtained from the finite element analyses. The impact-echo testing system consists of an impact source and a receiving transducer. In this study, several steel balls were used as impact sources, and accelerometer was used as a transducer. Waveforms were recorded and analyzed using a dynamic signal analyzer.

The polyurethane mock-up shafts, 60mm in diameter and 0.6 m long, were used, and the impact responses for mock-up shafts under various end conditions were obtained respectively.

To simulate the free end condition, the mock-up shaft was put upon the Styrofoam that is soft and light material with minimal acoustic impedance. The fixed end condition was simulated replacing the Styrofoam with the rigid plastic material, and the rock-socketed condition was simulated using the mock-up shaft bonded firmly with plastic material that has higher acoustic impedance than the shaft. The socketed length is designed to be 60 mm. And the soft bottom end condition is same as rock-socketed condition except the existence of air gap between the shaft toe and the rock material.

The waveforms of the mock-up shafts under four end conditions are shown in Fig. 6, Fig. 7, and Fig. 8. Fig. 6 shows the typical waveforms of free and fixed condition, and the upward signal (arrow point) in the fixed condition is caused by the reflection from the rigid end boundary

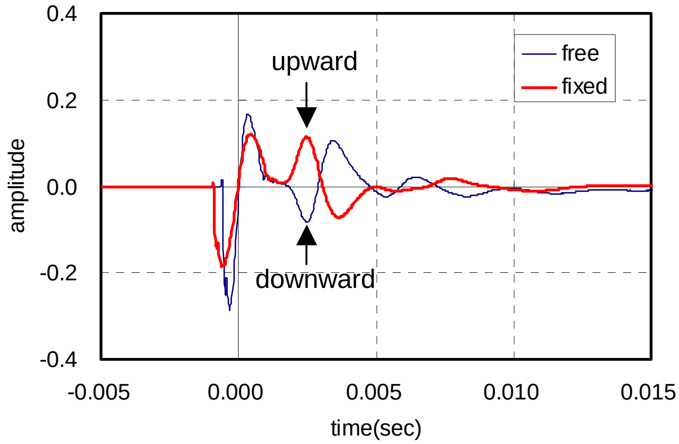


Fig. 6. Waveforms for the mock-up shafts under free and fixed end condition

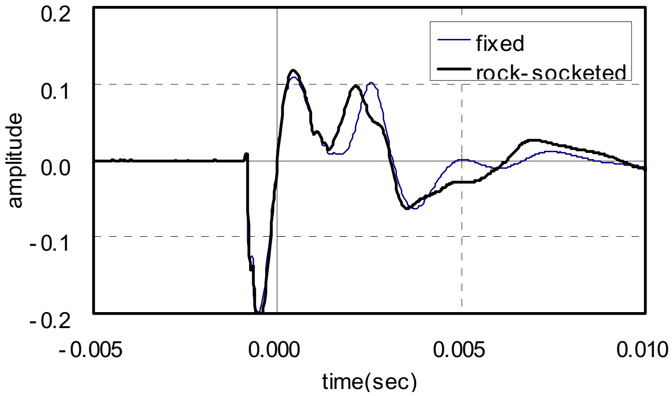


Fig. 7. Waveforms for the mock-up shafts under rock-socketed and fixed end condition

Fig. 7 shows the waveform of the rock-socketed condition, and it was founded that the results of laboratory test are in good agreement with those of finite element analyses. As has been shown previously, it is observed that the waveform of the rock-socketed condition is shifted toward left in the time axis. This fact implies that the stress wave is reflected at the interface between the mock-up shaft and rock material, and therefore the reflection time of the rock-socketed condition is a little faster than that of the fixed condition. From this time lag, the socketed length into the rock material is calculated to be about 10.8 cm that is over-estimated compared to the exact value of 6 cm. This discrepancy seems to be caused by the fact that the stiffness of polyurethane of the mock-up shaft is dependent upon the frequency, and therefore the rod wave speed varies at different frequencies.

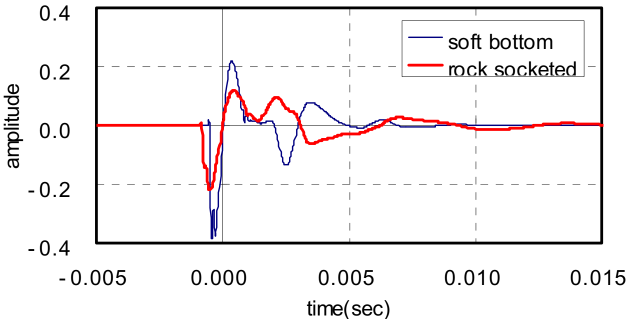


Fig. 8. Waveforms for the mock-up shafts under soft bottom and rock-socketed condition

It was obtained that the waveform of mock-up shaft under soft bottom condition was different from that of the fixed and rock-socketed condition, and rather similar to that of free condition as shown in Fig. 8. This fact provides one of the important information to inspect the slime in the drilled shaft. And two-dimensional axisymmetric finite element study is now underway to investigate the effects of soft bottom on the waveform in detail.

4. Field studies

To evaluate the potential of the impact-echo method for testing drilled shafts, field studies were performed. Eight shafts were constructed to have free, soft bottom, and rock-socketed end condition respectively. The diameter of the shafts is 0.4 m and the length of them varies, and therefore the socketed length into the rock is variable. The ground investigation shows that the depth to the weathered rock is estimated to be about 7.0 m below the ground surface, and the soil is classified to silty-sand and clay with P-wave velocity of 530 m/sec, and the P-wave velocity of the weathered rock is 1716 m/sec. In this paper, the shafts under free and rock-socketed condition were preliminarily examined. The shaft of free condition was constructed to the length of 7.6 m in soil, and Styrofoam was inserted to simulate the free condition. And the shaft of fixed condition was driven into the rock with the socketed length of 3 m, and the total length is 10 m. An illustration of the shafts under different end condition is shown in Fig. 9.

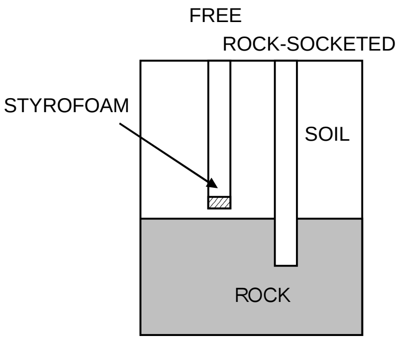
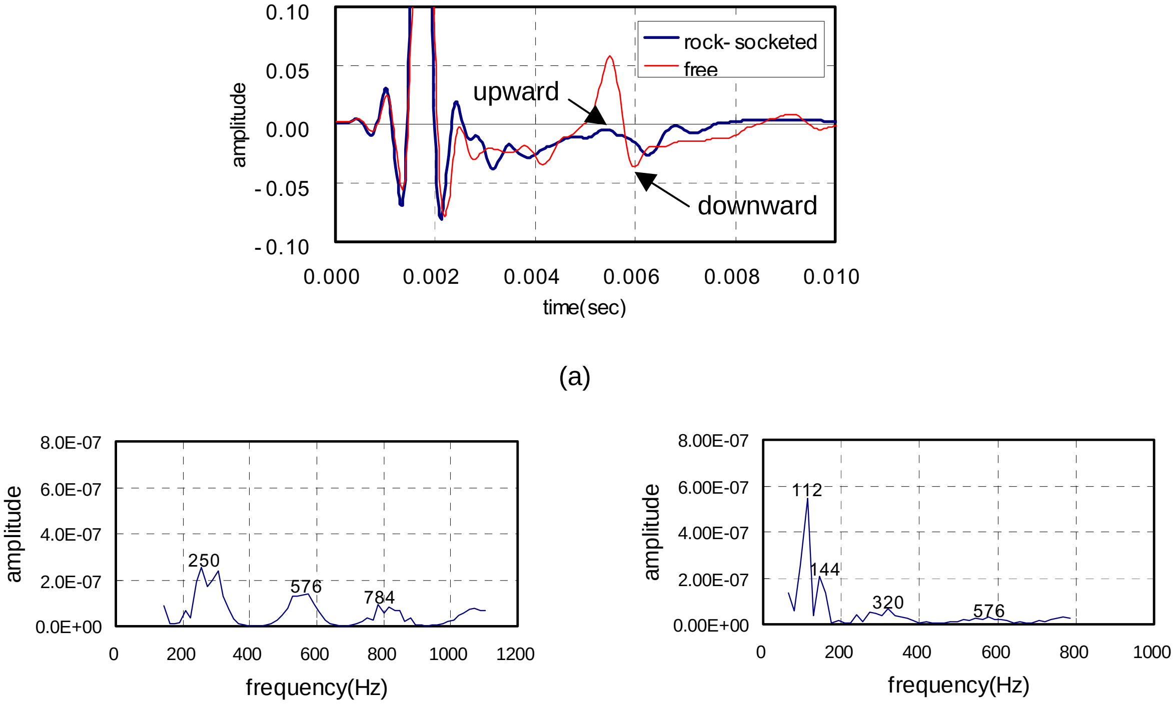


Fig. 9. An illustration of the shafts under different end condition



(a)

(b) (c)

Fig. 10. Waveform of the shaft under rock-socketed and free condition: (a) waveform; (b) spectrum for free condition; and (c) spectrum for rock-socketed condition.

The waveform and spectrum of the shaft under the two end conditions is shown in Fig. 10. In time domain in Fig. 10(a), the signal obtained for both cases is not satisfactory due to the unexpected noise, but the differences between the two cases are observed. In frequency domain in Fig. 10(b), the amplitude spectrum for free condition exhibits peaks at the depth frequency and its multiples (n=1, 2, 3, . . .). In Fig. 10(c), the amplitude spectrum for rock-socketed condition exhibits peaks at the depth frequency and its multiples (n=1, 3, 5, . . .) approximately.

Conclusions

This paper presented the results of numerical, laboratory, and field studies to provide an improved understanding of the impact-echo test for drilled shafts under various end conditions. The conclusions obtained are as follows:

(1) The upward signal of waveform is caused by the reflection from the rigid end boundary, and this can be a key to inspect the fixed end condition of drilled shafts.

(2) The waveform for the shaft under the rock-socketed condition is similar to that of fixed condition, but is shifted toward left in the time axis. This time lag may be used to calculate the socketed length into the rock, but further studies need to be performed.

(3) The waveform of shaft under soft bottom condition is different from that of the fixed and rock-socketed condition, and rather similar to that of free condition.

(4) The characteristic amplitude spectrum for free condition exhibits peaks at the depth frequency and its multiples (n=1, 2, 3, . . .), whereas for rock-socketed condition, the amplitude spectrum exhibits its multiples (n=1, 3, 5, . . .).

Acknowledgement

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