Integrity evaluation of drilled shafts using borehole and non-borhole seismic methods

Evaluation d'intégrité des axes forés en utilisant des méthodes de forage et de non-forage sismiques

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ABSTRACT: The applicability of various integrity testing methods for drilled shafts was assessed using borehole and non-borehole seismic methods. The borehole seismic methods including the cross-hole sonic logging (CSL) test and the inhole test gave reliable results after being applied to the field drilled shafts. Non-borehole seismic methods consisting of impact-echo test and impulse response test were examined to provide the adequate responses of drilled shafts under various defects. In order to consider the effects to the response of drilled shaft, experimental model studies were carried out. The one-dimensional finite element studies of impact-echo test using ABAQUS were performed to review the applicability of this integrity test. Also, the effects of soil conditions on the transient response motion of drilled shaft were studied.

RÉSUMÉ: L'applicabilité des méthodes variées de test intégré pour les puits forés a étè estimée en utilisant les méthodes sismiques avec et sans un trou de sondage. Les méthodes sismiques avec un trou de sondage y compri le test du sondage sonore entre-trous et le test dans un trou donnent des résultats sûres après l'appliquation aux puits forés en site. Les méthodes sismiques sans un trou de sondage composées du test de l'écho d'impact et du test de la réponse d'impulsion ont étè examinées pour fournir une réponse appropriée des puits forés sous des défauts variés. Des études de modèle expéimental ont étè excutées pour considérer les effets à la réponse des puits forés. Des études des éléments finis en une dimension sur le test de l'écho d'impact en utilisant ABAQUS ont étè excutées pour réexaminer l'applicabilité de ce test integré. Les effets des conditions du sol sur le mouvement de la réponse transitoire des puits forés ont étè aussi etudiés.

1 INTRODUCTION

1.1 *Background*

Recently the drilled shafts are being frequently used for deep foundation of large-scale structures in Korea. During construction drilled shafts often contain the defects such as voids, cracks, necks, bulbs, soil intrusions, and soft bottom etc. Since the defects in the drilled shafts may cause a serious decrease of the support load and an increase of settlement, the development of integrity testing method that can detect the defects reliably is essential for safety and quality control of drilled shafts.

In practice, impact-echo testing, impulse response testing, cross-hole sonic logging (CSL) testing, and gamma-gamma testing methods are commonly in use to evaluate the integrity of the drilled shafts. Currently in Korea, CSL is being frequently used for the quality control of drilled shafts up to about 30% of total number of shafts, but this method is so expensive that it is not economical to examine all of the drilled shafts with CSL. Therefore, the non-borehole seismic methods such as impact-echo testing and impulse response testing are to be used as an assistant or alternative method, and thus, the reliable non-borehole seismic methods should also be developed.

In this study, the borehole seismic methods including the cross-hole sonic logging (CSL) test and the inhole test were applied to the field drilled shafts that have defects such as soil intrusion and soft bottom. The mock-up shafts that include various defects of which the size by area varies 30% to 80% were constructed and the experimental parametric studies were performed for impact-echo test. Also, one-dimensional finite element studies were performed using ABAQUS program, and the numerical parametric studies were carried out to simulate the effects of soil conditions on the vibration motion of drilled shafts.

2 BOREHOLE SEISMIC METHODS

2.1 *Crosshole test for a drilled shaft*

2.1.1 *Model of drilled shaft*

To investigate the propagation of stress-wave in a drilled shaft, a total of four models were built in a test site. Four models, which are designated as types A, B, C and D, have different anomalies embedded in the piles according to the type. Type A is an intact pile without any anomalies, which is used as a reference. Types B and D has void and soil intrusion in the middle of the shaft and slime underneath the base of the pile. Type C has slime only underneath the base of the pile. The void in the pile shaft was modeled by filling half of the section with Styrofoam. The soil intrusion was simulated by spreading a 5-cm thick soil layer at the middle section of the shaft. The slime underneath the base of the pile was simulated by a layer of plywood.

2.1.2 *Crosshole testing*

To perform crosshole testing, drilled shaft models A and B have four PVC casings installed in the pile. The diameter of PVC casings is 84 mm, and the distance between the PVC casings are kept to be 0.7 m. The crosshole testing was performed at depths from the top of the drilled shaft to the base of the drilled shaft at 0.25 m intervals. Both the shear and the compression wave velocities were determined from the crosshole testing by orienting the source and the receiver appropriately for the wave to measure. In case of shear wave measurement, the source was applied in two opposite directions to generate shear waves with different polarity, which is used for the clear identification of shear wave arrival.

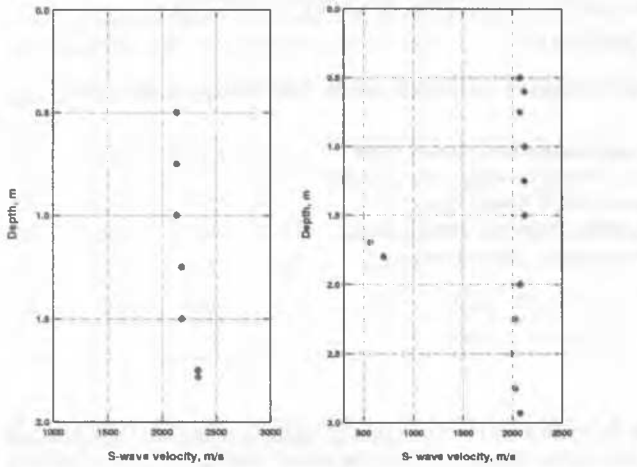


Figure 1. Shear wave velocity profiles for drilled shaft models A and B determined from crosshole testing

2.1.3 *Results of crosshole testing*

Wave velocities were determined at different depths with 0.25-m interval from the travel-time measurements for drilled shaft models A and B. The shear wave velocities of model A range from 2100 to 2300 m/sec. Model B of the drilled shaft model has also the same range of shear wave velocities besides the void and the soil intrusion sections. The section with Styrofoam shows a little drop in the velocity, which varies from 2000 to 2100 m/sec. The measured wave at the Styrofoam section appears to be the refracted wave traveling along the concrete-Styrofoam interface. The soil intrusion section showed the shear wave velocities of 570 to 700 m/sec. Profiles of shear wave velocity for types A and B are shown in Figure 1.

2.2 *Inhole testing for a drilled shaft*

2.2.1 *Inhole testing*

Inhole testing, of which the schematic diagram is shown in Figure 2, was performed for drilled shaft models C and D to investigate the slime, which may reside underneath the base of the drilled shaft. For the testing, a source and a receiver are linked in a vertical array with a distance of 0.7 m. The inhole testing was performed from the bottom of the drilled shaft to shallow depths with the interval of 0.1 m.

2.2.2 *Results of inhole testing*

The time history of acceleration measured by the receiver unit was transformed to the frequency domain, and the spectral amplitude was smoothened by moving average. The resulting spectra are shown in Figure 3. The drilled shaft without slime underneath the bottom has the trend of the plots, where the governing frequency of the amplitude spectrum appears around 1 kHz. On the other hand, the drilled shaft with slime has two distinct governing frequencies around 1 and 2 kHz as shown in Figure 3. Therefore, two distinct governing frequencies in the amplitude spectrum can be the indicator that there is slime residing between the drilled shaft and the bedrock.

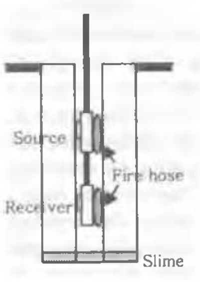


Figure 2. Schematic diagram of inhole testing for the drilled shaft

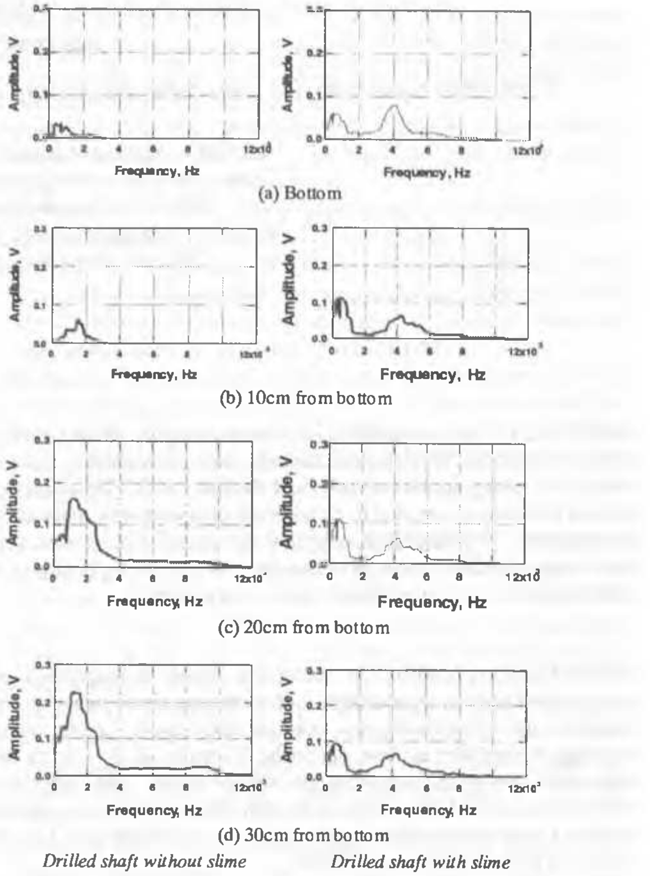


Figure 3. Amplitude spectrum determined for the drilled shafts with and without slime by inhole testing

2.2.3 *Summary*

The internal anomalies such as soil intrusion and void section, and the external defects including slime could be successfully detected by the analysis of stress-wave propagation. The crosshole testing using the PVC casings installed inside the drilled shafts was good to detect internal anomalies of drilled shafts, and the inhole testing was good for the detection of slime beneath the base of the drilled shafts.

3 NON-BOREHOLE SEISMIC METHODS

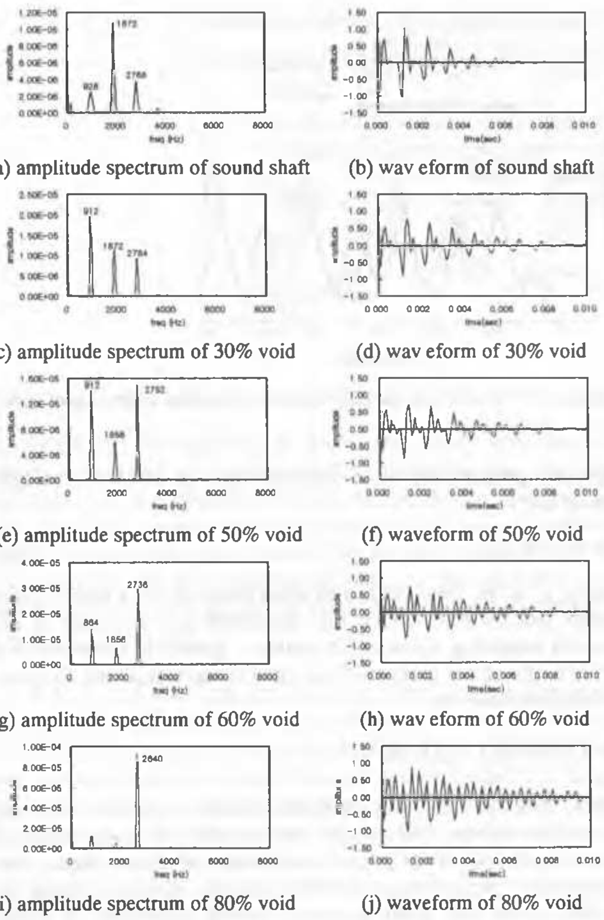
3.1 *Experimental parametric studies*

3.1.1 *Mock-up shafts*

To obtain the impact response of shaft with defect, the mock-up shaft was used. The monocast cylindrical mock-up shafts, 0.1 m in diameter and 1.0 m long, were used to study the impact-echo test. The rod wave speed in the solid shaft was determined to be 1880 m/sec by the FFRC (free-free resonance column) test [Kweon, 1998]. In contrast to concrete material, the monocast material has such advantages that it is homogeneous, and the intentional defects can be easily made at desired depths and sizes. The defect includes axisymmetric voids of which the size by area varies 30%, 40%, 50%, 60%, 70%, and 80%. The location of the defects was set to be at the depth of 0.4m and 0.6m to minimize the superposition effect of the frequencies corresponding to the defect and the whole length of the shaft.

3.1.2 *axisymmetric void*

Figure 4 shows the impact responses of mock-up shafts containing axisymmetric voids of which the size vary 30%, 50%, 60%, and 80% at 0.4m under the top of the surface of the mock-up shaft. It is noted that the waveform of the sound shaft is quite



(a) amplitude spectrum of sound shaft (b) wav eform of sound shaft
(c) amplitude spectrum of 30% void (d) wav eform of 30% void
(e) amplitude spectrum of 50% void (f) waveform of 50% void
(g) amplitude spectrum of 60% void (h) wav eform of 60% void
(i) amplitude spectrum of 80% void (j) waveform of 80% void

Figure 4. Impact responses of shafts containing ax isymmetric voids (depth=0.4m) in soil by experiment

different from that of the shaft containing axisymmetric voids, and the defects such as axisymmetric voids can be identified clearly in the time domain, even when the size of voids is 30%, whereas it is difficult to detect the voids of same size confidently in amplitude spectrum. Also, as the voids become greater, the higher amplitude spectrums are obtained, and this is because the waveform of the solid shaft is mixed with the reflected waves on the interface of voids, and consequently is apt to be consisted of a single sinusoidal wave.

It is shown that the presence of the flaw can be identified by amplitude spectrum if the size of void is greater than 50%, and the location of the voids is estimated to be 0.34m.

3.1.3 *Correlation between size and location of defects*

From the waveforms of impact responses of shafts containing axisymmetric voids, the normalized amplitudes (amplitude corresponding to the defect divided by first peak amplitude) were obtained, and plotted in Figure 5. In this figure, it is noted that the normalized amplitude increases as the void ratio increases.

It is obtained from the previous experimental studies that the estimated location of the defects by the impact-echo method is

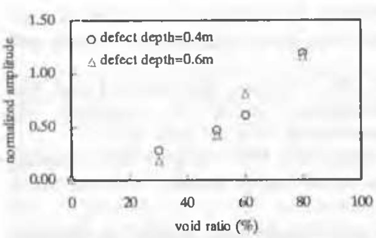


Figure 5. Normalized amplitude corresponding to defect by experimental analysis

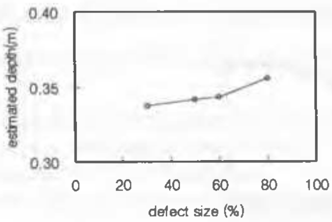


Figure 6. Correlation between the size and estimated location of defects

closer to the exact value, according as the defect size becomes greater as shown in Figure 6. On the other hand, this figure shows the limitations that the exact location of defect cannot be predicted by the impact-echo method, even when the defect size exceeds more than 80% of the cross-sectional area of the shaft. This is because the resonance frequency corresponding to the defect is superimposed by the second and / or third resonance frequency corresponding to the whole length of the shaft. However, the actual drilled shafts constructed in the field are long enough that these limitations may be recovered with minimal difficulties.

3.2 *Analytical Studies*

A variety of parametric studies were conducted to investigate capabilities of non-borehole seismic techniques to identify defects in drilled shafts. The 1-dimensional finite element analysis using ABAQUS was applied to obtain vibratory motions of a drilled shaft for the transient, uniformly distributed disk load excited at the shaft head. The signal of dynamic responses was interpreted by means of both the impact-echo and the impulse response techniques. Among the studies, results for typical defects, neck and bulb, are mainly dealt with in this paper.

3.2.1 *A Soil-Shaft System*

The location, type, and size of defect need to be generally estimated when involving defects of neck and bulb. To investigate capabilities of non-borehole seismic techniques estimating these variables, a typical soil-shaft system is chosen. The length (L) and the diameter (D) of the shaft are assumed to be 20 m and 1 m, respectively. The shaft is constructed in a soil deposit except the length of 1 m near the top of shaft.

For convenience, a neck or bulb defect is assumed to locate at the middle of shaft. Though the location of defect has been clearly known to affect on test results, cases where defects exist other than the middle are not dealt with in this study. Defects are considered in analyses by decreasing or increasing the radius of shaft to r_p, from the intact radius, r_o, of 0.5 m. The vertical length of defect is assumed as 0.5 m.

The soil deposit is assumed to be homogeneous. Detailed material properties for soil and shaft are not described here. However, it should be noted that the ratios of L/D and V_s/V_c, where V_s is the shear wave velocity of soil and V_c is the compression wave velocity of shaft material, are selected to admit the condition that the length and the size of intact shaft can be well estimated using non-borehole seismic techniques (Liao, 1997; Finno, 1998).

3.2.2 *Defects of Neck and Bulb*

Time histories of vibratory motion for the soil-shaft system are summarized according to the size of defects in Figures 7 and 8 for neck and bulb cases, respectively. It can be seen that defects are apparently reflected on the displacement pattern, even for the cases where the defect size is relatively small.

Based on the first arrival time, t_c, of reflected waves at a defect, the location of defect can be determined by the equation

$$L = V_c t_c / 2 \quad (1)$$

For cases of various sizes of neck and bulb, locations of defects are averagely determined as about 11 m far from the top of shaft. The error of estimation is shown to be less than 4 %.

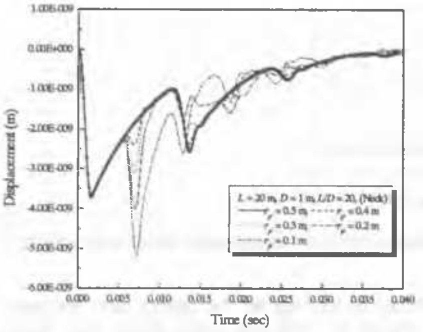


Figure 7. Variations of vertical displacement r esponse according to the size of neck

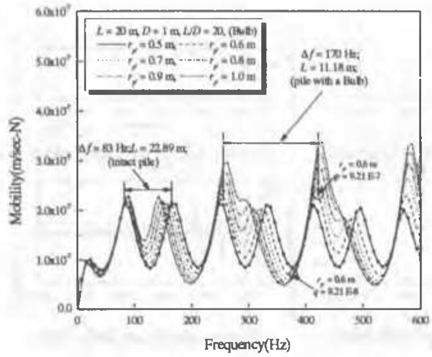


Figure 10. Variations of mobility response according to the size of bulb

In addition, the above time histories are processed according to the impulse response technique. Variations of mobility in frequency domain for neck and bulb cases are shown in Figures 9 and 10, respectively. Based on the frequency interval (Δf) determined from the results, the location of defect can be estimated by

$$L = V_c / 2\Delta f \tag{2}$$

Locations of defects are, then, determined as around 11 m far from the top, which is almost equivalent to the actual location. Accordingly, it can be mentioned that the location of defect can be identified reasonably by non-borehole seismic techniques.

The type of defect can possibly be estimated by interpreting the pattern of response. Comparing the responses shown in Figures 7 and 8, it can be seen that directions of displacement for reflected waves at defects can be apparently separated according to the type of defect.

The size of defects can be estimated based on mobility plots shown in Figures 9 and 10. Using the geometric mean of the

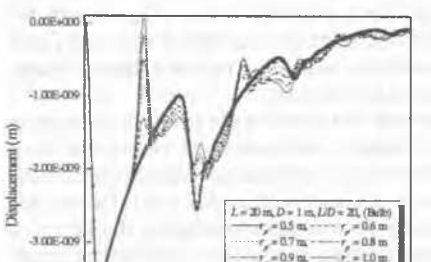


Figure 8. Variations of vertical displacement response a ccordi7ng to the size of bulb

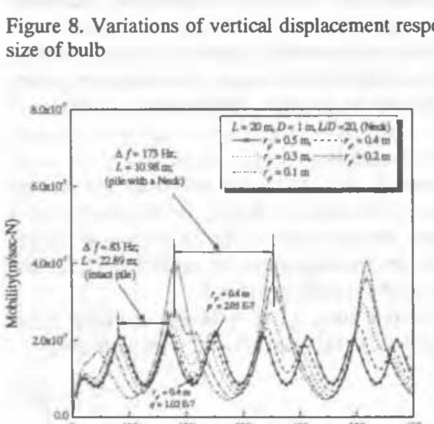


Figure 9. Variations of mobility response according to the size of neck

mobility peak R, the cross-sectional area of shaft can be estimated as:

$$A_c = 1 / R\rho_c V_c, \tag{3}$$

where ρ_c is the mass density of shaft material. As a result, a tendency can be seen, which the calculated area increases or decreases according to the defect pattern. However, the estimating error to the actual cross-sectional area is too significant for practical application yet.

4 CONCLUSIONS

Both borehole and non-borehole seismic methods including crosshole, inhole, impact-echo, and impulse response methods were employed for the integrity evaluation of drilled shafts. The crosshole testing using the PVC casings installed inside the drilled shafts was good to detect internal anomalies of drilled shafts, and the inhole testing showed the potential for the detection of slime beneath the base of the drilled shafts.

In the experimental parametric studies on impact-echo test, the defect such as axisymmetric void can be located in amplitude spectrum, if the area reduction is more than 50%, whereas the defects can be identified in the time domain, if the area reduction is more than 30%. The results of both the experimental and numerical studies provided the feasibility and limitation of impact-echo and impulse response methods.

5 ACKNOLEDGEMENT

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