The objective of this study is to compare the capability of several stress wave nondestructive testing (NDT) techniques such as sonic echo (SE), impulse response (IR), and ultra seismic (US) methods, in detecting various types of defects in piles. Four model piles with planned defects were constructed and tested using three different sizes of hammers with various tip materials to investigate the effects of impact duration on the response of the three NDT techniques. Results of this study indicate that the SE method can detect all three types of defects in the model piles. However, when short impact duration was used, the reflected wave from the circumference of the pile may offset the reflected wave from the defects thus making it very difficult to identify the defects. On the other hand, the mobility spectrum from IR method is less influenced by the impact duration, but it can not detect the thin weak layer in the model pile. Although the US method has more restriction on the accessibility of the pile, this method still has the advantage of that it does not need the propagation speed of stress wave to determine the location of defects.

**Keywords:** pile, integrity, nondestructive testing

1. **INTRODUCTION**

During the last decade, advances in construction technologies and environmental requirement made drilled shafts a preferable choice over driven piles (O’Neill and Reese 1999). Since drilled shafts are constructed on site, it does not easily allow for inspection of the shaft prior to and during placement of concrete. Therefore, engineers have concerned about the possibility of undetected construction defects in the shafts. As a result, several nondestructive testing (NDT) techniques, such as cross-hole sonic logging (Rix et al. 1993); seismic-echo method (Steinbach and Vey 1975); and impulse-response method (Davis and Dunn 1974), were developed to access the integrity of drilled shafts after construction. Although these NDT methods already became a standard procedure (ASTM 1995), many practitioners still have difficulties in interpreting test results when encountering a defect. Consequently it became necessary to investigate what kinds of defects are detectable, how do the signal look like, and how they vary.

The objective of this study is to compare the capability of several surface reflection NDT techniques such as sonic echo (SE), impulse response (IR), and ultra seismic (SE) methods, in detecting various types of defects in piles. Four 3-meter-long model piles were constructed. Out of the four piles, one is intact, while the other three contain planned defects at known locations. These piles were tested using three different sizes of hammers and with various tip materials to investigate the effects of impact duration on the response from the three NDT techniques.

2. **TESTING PROGRAM**

As shown in Fig. 1, four 3m long, 0.3-m in diameter concrete model piles were constructed for this study. Model pile P1 is an intact pile. Pile P2 contains a 1-mm-thick styrofoam (polystyrene) 1.2 meters below
the pile head to simulate a cold working crack. Pile P3 contains a 10cm-long, 25% cross-sectional area reduction necking defect. Pile P4 contains a 10-mm-thick styrofoam to simulate a complete broken pile.

Three different size of sledge hammers with various tip material were used to investigate the effects of impact duration on the response of different NDT methods. The properties of these hammers are shown in Table 1.

### Table 1 Properties of hammers used in this study

<table>
<thead>
<tr>
<th>Hammer</th>
<th>Mass (Kg)</th>
<th>Tip material</th>
<th>Impact duration (μs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>1.640</td>
<td>steel</td>
<td>390</td>
</tr>
<tr>
<td>S2</td>
<td>0.167</td>
<td>bronze</td>
<td>300</td>
</tr>
<tr>
<td>S3</td>
<td>0.167</td>
<td>steel</td>
<td>270</td>
</tr>
<tr>
<td>S4</td>
<td>0.167</td>
<td>polyethylene</td>
<td>520</td>
</tr>
<tr>
<td>S5</td>
<td>0.006</td>
<td>steel</td>
<td>160</td>
</tr>
</tbody>
</table>

3. RESULTS

**Sonic Echo method**

The velocity waveforms recorded at pile head of the intact model pile P1 are shown in Fig.2. It is obvious that except for sledge hammer S5 (curve “e” of Fig.2), the stress wave reflected from the pile tip can be identified easily. The numerical study performed by Lin et al. (1991) indicated that when the contact time $t_c$ of an impulse is less than $1.5D/C_R$ ($D$ is the diameter of the pile, and $C_R$ is the R-wave propagation velocity), the time domain response is dominated by the R-wave reflected from the shaft perimeter. The diameter of the model piles used in this study is 0.3 meter. The R-wave velocity of concrete is about 2200 m/s. Therefore, according to Lin et al., an impulse contact time $t_c$ greater than 200 μs should be good enough to prevent the influence of R-wave reflection. However, the high frequency oscillations from R-wave in curve “b” of Fig.2 ($t_c = 200$ μs for hammer S2) suggest that an impact duration longer than the one recommended by Lin et al. is needed to minimize the effects of R-wave reflection from the shaft perimeter.
For the pile containing minor defects (model pile P2), the stress wave reflected from pile tip (boxed in Fig.3) can be identified by using all hammers except for S5. However, signal reflected from defect (circled in Fig.3) can be identified only if hammers S1 and S4 were used. On the other hand, for piles containing major defects (model piles P3 and P4), the signal of defects can be identified with all hammers except for S5 (Fig.4 and Fig.5). Therefore, from the results of this study, it is recommended that an impact duration of greater than 3D/C\text{R} should be used in order to detect different types of defects in the piles.

**Impulse Response method**

The mobility spectra of the four model piles from the IR tests are shown in Fig. 6 to Fig.9, respectively. The pile length or the distance between pile head and defect can be calculated from the frequencies of the periodical events in the mobility spectrums using the following equation:

\[
L = \frac{C_p}{2f}
\]

where: \(C_p\) is the P-wave velocity, and

\(f\) is the frequency of the periodical event.
As can be seen from these mobility spectra, for the same model pile, changing the sledge hammer has little influence on the mobility spectra. However, the pile with minor defect (pile P2) only shows the periodical event with respect to pile length, while the pile with necking (P3) shows periodical events associated with both pile length and defect. On the other hand, only the periodical event corresponding to defect is presented in the mobility spectra of the completely broken pile P4. Thus, it is clear that using the IR method can only provide information related to major defects.

**Ultra Seismic method**

In contrast to the SE method and IR method where the receivers are placed on the top surface of the pile head, in the US method the receivers are placed on the side of the piles. In this study, the accelerometers are placed 20, 40, and 60 cm below the pile head. The waveforms of pile with necking (pile P3) using hammer S1 are shown in Fig. 10. The location of necking and pile length can be determined by connecting the incident and reflective waves from necking and pile tips. The major advantage of the US method is, in contrast to the SE and IR methods, the distance between pile head and defect or the pile length can be determined without knowing the wave propagation velocity in advance.

4. **CONCLUSIONS**

From the results of this study, the following conclusions can be made:

1. For nonuniform materials such as concrete, an impact duration greater than 3D/C_r is required in order to prevent reflection of R-wave from the shaft perimeter to interfere with signal reflected from defects along the pile length.

2. Unlike the Sonic Echo method, the Impulse Response method is less influenced by the impact duration. However, this technique can only detect major defects in the shafts.

3. Although the Ultra Seismic method has more restriction on the accessibility of the pile, this method still has the advantage of that it does not need the stress wave propagation speed to determine the location of defects.
ACKNOWLEDGEMENTS

The work presented in this paper is sponsored by the National Science Council of Taiwan under Grant No. NSC-91-2211-E324-010.

REFERENCES


