Reliability Evaluation of Cross-Hole Sonic Logging for Bored Pile Integrity

D. Q. Li¹; L. M. Zhang, M.ASCE²; and W. H. Tang, Hon.M.ASCE³

Abstract: Defects present in a pile may not be encountered during a cross-hole sonic logging (CSL) test. Even when defects are indeed encountered, they may not always be detected. This paper proposes a probabilistic analysis procedure for evaluating the reliability of CSL, thereby providing a theoretical supplement to existing experimental evaluations of CSL. The reliability of this integrity testing method is represented by the inspection probability, which is expressed as the product of the encountered probability and the detection probability. Mathematical models to calculate the encountered probability are formulated and a detection probability model is suggested based on existing CSL test data. Several examples are presented to illustrate the proposed procedure. The results indicate that there exists a minimum detectable defect size below which the defect cannot be inspected. For a given number of access tubes, the minimum detectable defect size, as a percentage of the pile cross-sectional area, decreases with the pile diameter. The encountered probability can be taken as an index to determine the required number of access tubes. When the target encountered probability is specified as 0.95, three and four access tubes will be sufficient to encounter defects larger than 15 and 5% of the pile cross-sectional area, respectively.

DOI: 10.1061/(ASCE)1090-0241(2005)131:9(1130)

CE Database subject headings: Bored piles; Defects; Probabilistic methods; Nondestructive tests; Reliability.

Introduction

Large-diameter bored piles are commonly used to support heavy structures such as high-rise buildings and bridges. From time to time, due to errors in handling slurry, casings, reinforcement cages, concrete, and other factors, minor or major anomalies in piles can be introduced both during and after construction. An anomaly is any irregular feature in the nondestructive testing results. If an anomaly, because of either size or location, can affect pile shaft performance, then the anomaly is considered as a defect (Amir 2002). Some examples of defects are voids, honeycomb-ing, cracks, necking, soil inclusions, and corroded rebars (Hassan and O’Neill 1998; O’Neill and Reese 1999). The presence of these defects, especially if they are sufficiently large and frequent, can lead to unsatisfactory performance of bored piles (Sarhan et al. 2002; O’Neill et al. 2003; Sarhan et al. 2004). Therefore, to ensure the safety of pile foundations and to avoid the use of excessively conservative designs, such defects should be identified as soon as possible prior to their incorporation into the final foundation works. For this reason, some nondestructive evaluation (NDE) tests are often conducted after pile construction, such as cross-hole sonic logging (CSL), sonic echo, impedance logging, and impulse response testing.

During a nondestructive integrity test, an accurate description of a defect (i.e., its type, size, and location) is of fundamental importance in assessing the structural soundness of a given pile. Defects that are present within a pile are not always detected during integrity testing, therefore some defects may actually remain within the pile foundation throughout its service life (Barker et al. 1993; Liao and Roesset 1997; Samman and O’Neill 1997; Finno and Gassman 1998; Chernauskas and Paikowsky 2000; Briaud et al. 2002; Sarhan et al. 2002; Iskander et al. 2003). Furthermore, many practitioners have difficulty interpreting NDE results when faced with an anomalous test response. Consequently, both owners and contractors are often skeptical about the results of pile integrity testing. As a result, the reliability of NDE methods to identify defects is an important issue. Since CSL is a common method for integrity testing of large-diameter bored piles (G-I Deep Foundations Committee Task Force 2000), this paper will focus on the reliability of CSL.

To ensure an adequate coverage of potential defects during a CSL test, several access tubes are usually installed within a pile cross section (Tijou 1984; Turner 1997; O’Neill and Reese 1999; Thasnanipan et al. 2000; Works Bureau 2000; MOC 2003). The recommended number of access tubes for different bored pile diameters is summarized in Table 1. It can be seen that there is a general trend in which the number of access tubes increases with pile diameter, except for Works Bureau (2000). O’Neill and Reese (1999) suggested that one more access tube should be used for each 0.3 m increment in the pile diameter. Yet, there exists an inconsistency in the number of access tubes for the same pile diameter adopted by the current practice. To date, no probabilistic analysis has been performed to suggest the number of access tubes in a rational manner. Deciding upon the number of access
tubes to be installed in each individual pile can be an important issue, especially when there is a large population of piles at a particular site. Existing practice may use more preformed access tubes or boreholes than are actually necessary to ensure the desired level of quality assurance. The cost impact in such cases can be significant. Therefore, to improve current practice, it would be beneficial to investigate the required number of access tubes in a more rational and quantitative manner.

The reliability of CSL is highly influenced by several practical factors, such as number of access tubes, distance between access tubes, distance of perimeter access tubes from shaft perimeter, quality of bonding between concrete and access tubes, and experience of the testing engineer in the interpretation of test data (Davis 1999). Several experimental studies (Barker et al. 1993; Hassan and O’Neill 1998; Chernauskas and Paikowsky 2000; Iskander 2001; Iskander et al. 2003) have addressed the ability of CSL to detect defects in piles. Based on these studies, and from expert opinion, there is a lower limit on the size of defect that can be detected by CSL. Baker et al. (1993) found that CSL could only detect defects that occupied about 15% of the cross-sectional areas of the drilled shafts. Amir (from Sarhan et al. 2002) indicated that CSL could reliably detect soft soil inclusions that comprised about 9% of the cross-sectional area of a 760 mm diameter drilled shaft. Hassan and O’Neill (1998) concluded that voids occupying cross-sectional areas up to 15% could remain undetected by CSL. Chernauskas and Paikowsky (1999, 2000) found that CSL was useful to detect defects comprising 20% or more of the cross-sectional areas of drilled shafts. Similarly, Iskander (2001) and Iskander et al. (2003) concluded that CSL was able to identify defects exceeding 10% of the pile cross-sectional area, and that defects smaller than 5% of the pile cross-sectional areas were typically undetectable. Based on the above five investigations, the minimum detectable defect size and the detectable defect size with certainty (i.e., the defect size beyond which a defect can be detected with certainty) are summarized in Table 2. The minimum detectable defect size varies from 5 to 10.7% of the pile cross-sectional area, while the detectable defect size with certainty ranges from 9 to 20% of the pile cross-sectional area.

All the above studies focused on evaluating the reliability of CSL using field tests. Such experimental evaluation should be supplemented with a systematic theoretical framework. This paper proposes a probabilistic analysis procedure to evaluate the reliability of CSL testing for bored piles. First, the concept of inspection probability is proposed as a quantitative measure of CSL reliability. Then, the encountered probability and the detection probability are formulated to facilitate the evaluation of the inspection probability. Finally, several numerical examples are presented to illustrate the proposed procedure.

### Inspection Probability

The reliability of CSL can be described by the inspection probability that an inspection finds a defect. The inspection probability is expressed as a product of the encountered probability and the detection probability

\[ P(x) = P(E|x)P(D|E,x) \]  

where \( P(x) \) = inspection probability for a given defect size \( x \); \( E \) = event that a defect with a given size \( x \) is encountered; \( D \) = event that a defect with a given size \( x \) is detected if it is indeed encountered; \( P(E|x) \) = encountered probability that a defect is encountered by an inspection of a given inspection plan if a defect indeed exists; and \( P(D|E,x) \) = detection probability that an inspection detects a defect if a defect is indeed encountered.

To conduct the reliability evaluation of CSL, it is necessary to determine

### Table 1. Summary of the Recommended Number of Access Tubes for Different Pile Diameters

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>600–750</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>3 to 4</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>750–1,000</td>
<td>2 to 3</td>
<td>3 to 4</td>
<td>2 to 3</td>
<td>3 to 4</td>
<td>3</td>
<td>2 to 3</td>
</tr>
<tr>
<td>1,000–1,500</td>
<td>4</td>
<td>4 to 5</td>
<td>4 to 5</td>
<td>3 to 4</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>1,500–2,000</td>
<td>4</td>
<td>4 to 5</td>
<td>5 to 7</td>
<td>3 to 4</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>2,000–2,500</td>
<td>4</td>
<td>4 to 5</td>
<td>7 to 8</td>
<td>3 to 4</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>2,500–3,000</td>
<td>4</td>
<td>4 to 5</td>
<td>8</td>
<td>3 to 4</td>
<td>8</td>
<td>4</td>
</tr>
</tbody>
</table>

### Table 2. Summary of the Minimum Detectable Defect Size and the Detectable Defect Size with Certainty

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pile diameter (mm)</td>
<td>882</td>
<td>760</td>
<td>762</td>
<td>914</td>
<td>900</td>
</tr>
<tr>
<td>Number of access tubes</td>
<td>4</td>
<td>—</td>
<td>3</td>
<td>4</td>
<td>3 to 4</td>
</tr>
<tr>
<td>Percentage of detectable defect area with certainty</td>
<td>15%</td>
<td>9%</td>
<td>16.6%</td>
<td>20%</td>
<td>10%</td>
</tr>
<tr>
<td>Percentage of minimum detectable defect area</td>
<td>—</td>
<td>—</td>
<td>10.7%</td>
<td>—</td>
<td>5%</td>
</tr>
<tr>
<td>Detectable defect diameter with certainty (mm)</td>
<td>342</td>
<td>228</td>
<td>310</td>
<td>409</td>
<td>285</td>
</tr>
<tr>
<td>Minimum detectable defect diameter (mm)</td>
<td>—</td>
<td>—</td>
<td>249</td>
<td>—</td>
<td>201</td>
</tr>
</tbody>
</table>
The two access tubes with a width of about 2 m can theoretically scan the path between a pile with two access tubes as shown in Fig. 1. The smallest defect size that can be reasonably detected by an inspection, the center of the defect must be located inside the shaded area. In other words, the distance between the center of the defect and the signal path must be larger than the radius of the defect. The probability of the event that a defect can be encountered by any of the signal paths can be simply taken as the ratio of the shaded area to the cross-sectional area of the reinforcement cage.

\[
P_E(E|x) = \frac{A_S}{A_0}
\]

where \(A_0\) and \(A_S\) = shaded area and the cross-sectional area of reinforcement cage, respectively; \(A_0\) can be calculated in terms of the diameter of the reinforcement cage \(D_0\), which is approximately equal to the pile diameter \(D\) for large-diameter bored piles.

In the subsequent analyses, \(D_0\) is replaced by \(D\) for simplicity. Referring to Fig. 1, the shaded area is

\[
A_S = \frac{\pi D^2 x}{2} - \frac{x^2}{2} + \lambda + 2 \left(\frac{x}{2} + \lambda\right) \sqrt{\left(\frac{D}{2}\right)^2 - \left(\frac{x}{2} + \lambda\right)^2}, \quad 0 \leq x \leq \frac{D}{2}
\]

Similarly, the shaded area for other numbers of access tubes can be obtained.

As an illustration, the wavelength of 0.08 m is adopted for the analysis of encountered probability in this study. Suppose the defect location is uniform over the cross section of the pile. Fig. 2 shows the encountered probability for different defect sizes with a given pile diameter and a given number of access tubes. Several conclusions can be drawn from Fig. 2:

1. As expected, the encountered probability increases with the defect size. In particular, the encountered probability is equal to one for very large defects because they will be encountered with certainty by all signal paths.
2. The encountered probability decreases with the increase of the pile diameter for the same number of access tubes and the same defect size. Therefore the required number of tubes should be increased with the pile diameter to maintain a specified target encountered probability for a particular defect size.
3. For a given pile diameter and a given defect size, the encountered probability increases significantly with the number of access tubes. However, the margin of increase in the encountered probability diminishes as the number of access tubes increases.

Since the detection probability is only dependent on inspection devices and operators’ skills if a given defect is indeed encountered by an inspection, the inspection probability largely depends on the encountered probability. Therefore, as the encountered probability directly depends on the number of access tubes for a given defect size, this paper suggests that the encountered probability be adopted as an index to determine the required number of access tubes. If a target encountered probability is further specified, the required number of access tubes can be determined for a given pile diameter and defect size. For instance, if a target encountered probability of 0.9 is specified and a given defect with a diameter of 500 mm is present in a 1,000 mm diameter pile, it can be seen from Fig. 2(a) that at least three access tubes should be used.
target encountered probabilities, \( P_E = 0.9 \) and 0.95, are specified. The number of access tubes required to achieve the desired encountered probability decreases with increasing defect size and increases with increasing pile diameter.

The defect size is sometimes expressed as a percentage of the pile cross-sectional area (Baker et al. 1993; Hassan and O’Neill 1998; Sarhan et al. 2002; Iskander et al. 2003). Fig. 3 shows the encountered probability for different pile diameters and for defects occupying 5, 10, and 15% of the pile cross-sectional area. The encountered probability for different pile diameters with four access tubes is approximately equal to one in Figs. 3(a–c), which indicates that a defect occupying larger than 5% of the cross-sectional area

<table>
<thead>
<tr>
<th>Pile diameter (mm)</th>
<th>( P_E = 0.9 )</th>
<th>( P_E = 0.95 )</th>
<th>( P_E = 0.9 )</th>
<th>( P_E = 0.95 )</th>
<th>( P_E = 0.9 )</th>
<th>( P_E = 0.95 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>600–750</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>750–1,000</td>
<td>3 to 4</td>
<td>3 to 4</td>
<td>2 to 3</td>
<td>2 to 3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1,000–1,500</td>
<td>4</td>
<td>4 to 5</td>
<td>3</td>
<td>3</td>
<td>2 to 3</td>
<td>2 to 3</td>
</tr>
<tr>
<td>1,500–2,000</td>
<td>4 to 5</td>
<td>5</td>
<td>3 to 4</td>
<td>3 to 4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>2,000–2,500</td>
<td>5</td>
<td>5 to 6</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>3 to 4</td>
</tr>
<tr>
<td>2,500–3,000</td>
<td>5 to 6</td>
<td>6</td>
<td>4 to 5</td>
<td>4 to 5</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>
Table 4. Recommended Number of Access Tubes for Given Defect Sizes as a Percentage of Pile Cross-Sectional Area at $P_E=0.9$ and 0.95

<table>
<thead>
<tr>
<th>Pile diameter (mm)</th>
<th>$P_E=0.9$</th>
<th>$P_E=0.95$</th>
<th>$P_E=0.9$</th>
<th>$P_E=0.95$</th>
<th>$P_E=0.9$</th>
<th>$P_E=0.95$</th>
</tr>
</thead>
<tbody>
<tr>
<td>600–750</td>
<td>3</td>
<td>3 to 4</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>750–1,000</td>
<td>3 to 4</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>1,000–1,500</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>3 to 4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>1,500–2,000</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>2,000–2,500</td>
<td>4</td>
<td>4</td>
<td>3 to 4</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>2,500–3,000</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

sectional area of the pile can be encountered with certainty if four access tubes are used. Given a defect size, the encountered probability decreases with the increase of pile diameter. However, the decrement of the encountered probability becomes smaller with the pile diameter. This is because a decrease of the encountered probability due to the increase of pile diameter can be partially compensated by an increase of the encountered probability due to the increase of defect size.

If the target encountered probability is specified, then the required number of access tubes can also be obtained based on Fig. 3. As an illustration, two target encountered probabilities, $P_E=0.9$ and 0.95, are specified again. The required number of access tubes is shown in Table 4. If the target encountered probability is specified as 0.9 or 0.95, three to four access tubes will be sufficient to encounter defects larger than 5% of the cross-sectional area of the pile with a diameter ranging from 600 to 3,000 mm. This is consistent with the practice reported by Turner (1997); Works Bureau (2000); and JGJ 106-2003 (MOC 2003) as shown in Table 1. According to Baker et al. (1993); Hassan and O’Neill (1998); and Sarhan et al. (2002), a defect occupying 15% of the pile cross-sectional area could be taken as a minor defect. It can be seen from Table 4 that, for a minor defect, three tubes will be sufficient to achieve a specified target encounter probability of 0.90.

Analysis of Detection Probability

In the previous analyses, the encounter probability with different numbers of access tubes has been evaluated for a given pile diameter and defect size. As discussed earlier, a defect may go undetected during inspection although it is indeed encountered during a CSL test. Therefore the detection probability should be evaluated.

Based on experimental results of crack inspection using an ultrasonic method, Yang and Trapp (1975) proposed the following detection probability function:

$$P_d(a) = \begin{cases} 
0, & 0 < a \leq a_1 \\
\left( 1 - \frac{a - a_1}{a_2 - a_1} \right)^m, & a_1 < a \leq a_2 \\
1, & a > a_2
\end{cases}$$

(4)

where $P_d(a)$ = detection probability for a given crack size $a$; $a_1$ = minimum detectable crack size below which a crack cannot be detected; $a_2$ = detectable crack size with certainty beyond which a crack can be detected with certainty; and $m$ = parameter. If $m$ is assumed to be one (e.g., Ang and Tang 1975), then the detection probability is a linear function of crack size. Similarly, Harris (1977) proposed a lognormal function for fitting the detection probability of ultrasonic inspection. In both detection prob-

![Fig. 4. Geometry of an assumed circular defect](image)
the signal path is related to the defect diameter $x$ as

$$l = 2\sqrt{\left(\frac{x}{2}\right)^2 - y^2}, \quad 0 \leq y \leq \frac{x}{2}$$  \hspace{1cm} (5)$$

where $y$=distance from the center of defect to the chord. Since the location of the signal path relative to the center of the intercepted defect can vary, this distance $y$ is a random variable with a probability distribution function $F(y)$. By replacing $a$ in Eq. (4) with $l$, the detection probability can be determined by virtue of the total probability theorem

$$P_d(x) = \int_0^{a/2} P_d \left[ 2\sqrt{\left(\frac{x}{2}\right)^2 - y^2} \right] f(y)dy$$  \hspace{1cm} (6)$$

where $f(y)$=probability density function of $y$.

The probability distribution function $F(y)$ and probability density function $f(y)$ can be derived as follows. The event $(Y \leq y)$ requires that a signal path be located within a radius $y$ from the center of the defect or, alternatively, the center of the defect lies within a radius $y$ from a given signal path. In the absence of any systematic trend, a reasonable assumption is that the defect location is uniformly distributed over the cross section of a pile. Thus, for an encountered defect, the probability distribution function of $y$ is

$$F(y) = P(Y \leq y) = \frac{4y^2}{x^2}, \quad 0 \leq y \leq \frac{x}{2}$$  \hspace{1cm} (7)$$

According to Eq. (7), the probability density function $f(y)$ can be given by

$$f(y) = \frac{dF(y)}{dy} = \frac{8y}{x^2}, \quad 0 \leq y \leq \frac{x}{2}$$  \hspace{1cm} (8)$$

Combining Eq. (6) with Eq. (8) gives

$$P_d(x) = \int_0^{a/2} \left[ 2\sqrt{\left(\frac{x}{2}\right)^2 - y^2} \right] f(y)dy$$  \hspace{1cm} (9)$$

As an illustration, the detection probability shown in Eq. (4) in which $m$ is assumed to be 1.0 is adopted for the analysis of the detection probability. Substituting Eq. (4) into Eq. (9), the detection probability can be obtained

$$P_d(x) = \begin{cases} 0, & 0 < x = \frac{3a_1}{2} \\ \frac{2x - 3a_1}{3a_2 - 3a_1}, & \frac{3a_1}{2} < x \leq \frac{3a_2}{2} \\ 1, & x > \frac{3a_2}{2} \end{cases}$$  \hspace{1cm} (10)$$

As can be seen from Eq. (10), only two parameters, $a_1$ and $a_2$, need to be determined. As mentioned earlier, a CSL test can identify concrete voids or soil inclusions that occupy a minimum percentage of the cross-sectional area of the pile (see Table 2). Based on these results, supplemented with some judgments, one can obtain the minimum detectable defect size and the detectable defect size with certainty. For example, if the defect with a diameter of $x$ can be assumed to be circular over the pile cross section, then the relationship between $x$ and the ratio of $A_D$ to $A_0$ is

$$x = D \sqrt{\frac{A_D}{A_0}}$$  \hspace{1cm} (11)$$

where $A_D$=defect area. For instance, given a defect occupying 5% of the cross-sectional area of the pile with a diameter of $D$=900 mm, the defect size $x$ will be 210 mm using Eq. (11). From the defect size as a percentage of the pile cross-sectional area shown in Table 2, the minimum detectable defect diameter and the detectable defect diameter with certainty can be obtained using Eq. (11) and are also summarized in Table 2. The minimum detectable defect diameter and the detectable defect diameter with certainty are taken to be 200 and 300 mm, respectively. These are the rounded mean values of the data in Table 2. Thus the values of $a_1$ and $a_2$ are 133.3 and 200 mm according to Eq. (10), respectively. Accordingly, the detection probability function for the special case shown in Eq. (4) can be written as

$$P_d(x) = \begin{cases} 0, & 0 < x = 133.3 \text{ mm} \\ \frac{x - 133.3}{66.7}, & 133.3 < x \leq 200 \text{ mm} \\ 1, & x > 200 \text{ mm} \end{cases}$$  \hspace{1cm} (12)$$

and the general detection probability shown in Eq. (10) can be written as

$$P_d(x) = \begin{cases} 0, & 0 < x = 200 \text{ mm} \\ \frac{x - 200}{100}, & 200 < x \leq \text{ mm} \\ 1, & x > 300 \text{ mm} \end{cases}$$  \hspace{1cm} (13)$$

The detection probabilities are plotted against the defect diameter in Fig. 5 using Eqs. (12) and (13). As expected, the detection probability for a general case in which a defect is uniformly distributed over the cross section of the pile is lower than that for a special case in which the signal path passes through the center of the defect. The detection probability will be overestimated if only the special case is taken into account.

### Analysis of Inspection Probability

The encountered probability and the detection probability are analyzed separately in the previous sections. In this section, the com-
combined effect of these two probability measures is considered to determine the inspection probability using Eq. (1). For illustrative purposes, two field cases are reconsidered in this study. One case was conducted by Hassan and O’Neill (1998). Six full-scale drilled shafts with a nominal diameter of 762 mm were constructed at the University of Houston National Geotechnical Experimentation Site. Five test shafts (shaft 1–shaft 5) contained artificial defects with different sizes at different locations, and shaft 6 without defect served as a reference. Three 50.8 mm PVC access tubes were attached to the drilled shaft cages of each test shaft. The other case was conducted by Iskander (2001). Six 900-mm diameter, 14.3-m long drilled shafts were constructed at the National Geotechnical Experimentation Site at the University of Massachusetts, Amherst. Four 50-mm i.d. black iron access tubes were installed in all test shafts except one in which only three access tubes were installed.

Based on the proposed procedure, the detection probabilities for the two cases are calculated using Eq. (13). The inspection probabilities for the above cases are plotted against the defect size as a percentage of the pile cross-sectional area in Fig. 6. For the Hassan and O’Neill case, random defects smaller than 7% of the pile cross-sectional area are likely undetectable. The minimum detectable defect size is slightly smaller than that found in the Hassan and O’Neill (1998) tests in which the built-in defects smaller than 10.7% of the pile cross-sectional area are undetectable. On the other hand, the random defects larger than 15.6% of the pile cross-sectional area are likely detectable, which is approximately the same as that concluded by Hassan and O’Neill (1998). In their tests, the built-in defects larger than 16.7% of the pile cross-sectional area were detectable.

For the Iskander case, the results of the present study in Fig. 6 show that the CSL can hardly detect random defects smaller than 5% of the pile cross-sectional area. This is the same as that concluded by Iskander (2001). In addition, the CSL is able to detect random defects larger than 11% of the pile cross-sectional area, which is similar to that concluded by Iskander (2001). In these tests, defects larger than 10% of the pile cross-sectional area were detectable. The results show a good agreement between the conclusions from Hassan and O’Neill (1998) and Iskander (2001) and these from this study.

As can be seen from the above results, due to the difference in the pile diameter, there is a difference between the minimum detectable defect size as a percentage of the pile cross-sectional area for the Hassan and O’Neill (1998) case and that for the Iskander (2001) case. To account for the effect of pile diameter, Fig. 7 shows the inspection probability for defect size as a percentage of the pile cross-sectional area with three access tubes. Note that, for a given number of access tubes, the minimum detectable defect size as a percentage of the pile cross-sectional area decreases with the increase of pile diameter. For instance, if three access tubes are installed in the 750-mm diameter pile, the 1,000-mm diameter pile, and the 1,500-mm diameter pile, the corresponding minimum detectable defect will occupy 7, 4, and 1.8% of the pile cross-sectional area, respectively. In addition, for the defect size in the same percentage of the pile cross-sectional area, the inspection probability decreases with the pile diameter. If a target reliability is specified as 0.9, three access tubes will be sufficient to detect defects larger than about 8% of the cross-sectional area of a 1,500-mm diameter pile.

Similarly, to consider the effect of defect diameter on the inspection probability, Fig. 8 shows the inspection probability for different defect diameters with three access tubes. When the defect diameter is smaller than 200 mm, the inspection probability in Fig. 8 is equal to zero. The reason is that, when the defect diameter is smaller than 200 mm, the CSL can hardly detect random defects smaller than 5% of the pile cross-sectional area. This is the same as that concluded by Iskander (2001). In addition, the CSL is able to detect random defects larger than 11% of the pile cross-sectional area, which is similar to that concluded by Iskander (2001). In these tests, defects larger than 10% of the pile cross-sectional area were detectable. The results show a good agreement between the conclusions from Hassan and O’Neill (1998) and Iskander (2001) and these from this study.
diameter is smaller than 200 mm, the detection probability is taken to be zero as shown in Eq. (13). The inspection probability in Fig. 8 has a turning point at the defect size of 300 mm. The reason is that, when the defect diameter is larger than 300 mm, the detection probability is taken to be 1.0 as shown in Eq. (13), so the inspection probability is only influenced by the encountered probability. It can be further seen that, for a given number of access tubes, the detectable defect diameter with certainty increases with the increase of pile diameter. For instance, if three access tubes are installed in the 750-mm diameter pile, the 1,000-mm diameter pile, and the 1,500-mm diameter pile, respectively, the corresponding detectable defect diameters with certainty are 300, 380, and 630 mm, respectively. For a given number of access tubes and a given defect diameter, the inspection probability decreases with the pile diameter. If a target reliability is specified as 0.9, three access tubes will be sufficient to detect defect diameter larger than 430 mm in a pile with a diameter of 1,500 mm.

Conclusions

This paper has proposed a probabilistic procedure for evaluating the reliability of cross-hole sonic logging (CSL) integrity testing for large-diameter bored piles. The encountered probability, detection probability, and inspection probability of CSL are formulated. Several examples are studied to illustrate the proposed procedure. Several conclusions can be drawn from this study:

1. Since not all defects in a pile may be encountered by CSL, and the defects that are indeed encountered may not be detected, there exists a minimum detectable defect size below which the defect cannot be inspected (i.e., become apparent to the engineer).
2. The inspection probability of CSL can be quantitatively evaluated using a probabilistic analysis procedure. The inspection probability depends on the encountered probability and the detection probability.
3. The encountered probability in a CSL test depends on the pile diameter, the defect size, and the number of access tubes. The encountered probability decreases with increasing pile diameter, but increases with defect size and number of access tubes.
4. The encountered probability can be taken as an index to determine the required number of access tubes to achieve a prescribed encountered probability. For instance, if the target encountered probability is specified as 0.95, then three access tubes will be sufficient to encounter defects larger than 15% of the pile cross-sectional area, and no more than four access tubes are needed to encounter defects larger than 5% of the pile cross-sectional area.
5. For a given number of access tubes, the minimum detectable defect size as a percentage of the pile cross-sectional area decreases with the pile diameter. For example, if three access tubes are installed in a 1,000-mm diameter bored pile, defects larger than 4% of the pile cross-sectional area can be detected by CSL.
6. For a given number of access tubes, the detectable defect size with certainty increases with the pile diameter. For example, if three access tubes are installed in a 1,000-mm diameter bored pile, defects larger than 380 mm in diameter can be detected by CSL with certainty.

Acknowledgment

This research was substantially supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region (Project No. HKUST6035/02E).

References


