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DETERMINING THE QUANTITY OF ACCESS TUBES FOR QUALITY CONTROL OF BORED PILE CONCRETE BASED ON PROBABILITY APPROACH

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Abstract

Unexpected defects of concrete in a completed bored pile can arise during the construction stage. Therefore, post-construction testing of bored pile concrete is an important part of the design and construction process. The Cross-hole Sonic Logging (CSL) method has been the most widely used to examine the concrete quality. This method requires some access tubes pre-installed inside bored piles prior to concreting; the required quantity of access tubes has been pointed out in few literatures and also ruled in the national standard of Vietnam (TCVN 9395:2012). However, theoretical bases aiming to decide the required quantity of access tubes have not been given yet. A probability approach is proposed in this paper aiming to determine the essential quantity of access tubes, which depend not only on pile diameters, magnitude of defects, but also on the technical characteristics of CSL equipment.

Keywords: access tubes; bored piles; CSL method; defects; inspection probability.

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1. Introduction

Most bored piles are constructed routinely and are sound structural elements. However, unexpected defects in a completed bored pile can arise during the construction process through errors in handling of stabilizing fluids, reinforcing steel cages, concrete, casings, and other factors. Therefore, tests to evaluate the structural soundness, or "integrity", of completed bored piles are an important part of bored pile quality control. This is especially important where non-redundant piles are installed or where construction procedures are employed in which visual inspection of the concreting process is impossible, such as underwater or under slurry concrete placement [1].

From a management perspective, post-construction tests on completed bored piles can be placed into two categories [2]:

- Planned tests that are included as a part of the quality control procedure.

- Unplanned tests that are performed as part of a forensic investigation in response to observations made by an inspector or constructor that indicates a defect might exist within a pile.

Planned tests for quality control typically are Non-Destructive Tests (NDT) and are relatively inexpensive; such tests are performed routinely on bored piles. Meanwhile, unplanned tests will nor-

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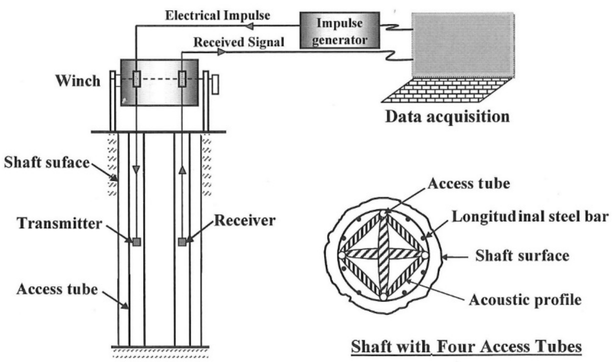
mally be more time-consuming and expensive, and the results can be more ambiguous than those of planned tests.

The most common NDT methods are the Cross-hole Sonic Logging (CSL), the Gamma-Gamma Logging (GGL), and the Sonic Echo (SE). Of these methods, the CSL method is currently the most widely used test for quality assurance of bored pile concrete. For this method, vertical access tubes are cast into the pile prior to concrete placement. The tubes are normally placed inside the reinforcing steel cage and must be filled with water to facilitate the transmission of high frequency compressive sonic waves between a transmitter probe and a receiver one, which are lowered the same time into each access tube. Acoustic signals are measured providing evaluation of concrete quality between the tubes (Fig. 1). This method has advantages that are relatively accurate and relatively low cost; by using a suitable number of access tubes, the major portion of pile shaft may be inspected. In addition, the testing performance for each acoustic profile is also relatively rapid. The limitation of this method is that it is difficult to locate defects outside the line of sight between tubes.



(a) Scheme of cross-hole sonic logging method

(b) Access tubes placed inside the reinforcing steel cage

Figure 1. Scheme of cross-hole sonic logging method

To detect potential defects by the CSL method, a required number of access tubes has to be pre-installed. The number of access tubes for different bored pile diameters has been recommended by different authors and technical codes [3–9]. The number of access tubes recommended in these studies mainly obtained from experimental data and expert experiences, without any theoretical base.

Li et al. [10] proposed a probability approach to determine the number of access tubes. The remarkable advantage of this approach is that the authors formulated a relatively rational manner, considering both the defect sizes and the target encountered probability. However, the shape of the defect is assumed to be spherical and the defect is equally likely located within the pile cross section. This may lead to an over-prediction of the encountered probability and, therefore, the number of access tubes trends to be small.

In this paper, another probability approach is presented, to which the inspection probability plays a key role. The essential quantity of access tubes is determined in accordance with a target inspection probability for different pile diameters and magnitudes of defect, considering the technical characteristics of CSL equipment. Some findings are also drawn in this paper.

2. Number of access tubes in literatures

Table 1 shows the recommended number of access tubes for different bored pile diameters according to different authors and technical codes.

Table 1. Recommended number of access tubes for different bored pile diameters

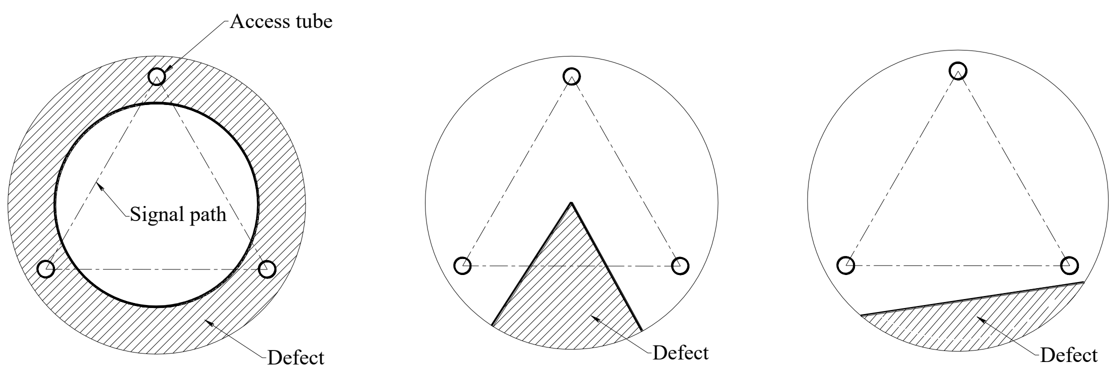
Pile diameter (mm)	Tijou [3]	Turner [4]	O'Neil and Reese [5]	Thasnanipan [6]	Work Bureau [7]	MOC [8]	TCVN 9395:2012 [9]
600÷750	2	3	2	2	3÷4	2	2
750÷1,000	2÷3	3÷4	2÷3	3	3÷4	2÷3	3
1,000÷1,500	4	4÷5	4÷5	4	3÷4	3	4
1,500÷2,000	4	4÷5	5÷7	6	3÷4	3	4
2,000÷2,500	4	4÷5	7÷8	6	3÷4	4	4
2,500÷3,000	4	4÷5	8	8	3÷4	4	4

It can be seen that there is a general trend in which the number of access tubes increases with the pile diameter, except for Work Bureau [7]. O'Neill and Reese [5] presented, as a rule of thumb employed by several agencies to determine the number of access tubes, is based on one access tube for each 0.3 m of pile diameter. Clearly, there exists an inconsistency in the number of access tubes for the same pile diameter adopted by the current practice and no probabilistic analysis has been performed to suggest the number of access tubes in a rational manner.

Theoretically, the more the number of access tubes, the more precise the CSL measurement. However, the overly increasing number of access tubes leads to a higher cost and may impede the flow of concrete during pile construction. Therefore, a pertinent number of access tubes to ensure the reliability of CSL measurements corresponding to a target probability is very important.

3. Shapes of defect

Assume that defects are randomly located at the periphery of piles. The defect shape is normally observed with some types, which are the annulus, sector, or circular segment, as depicted in Fig. 2. The possibility of occurrence of these types is equally likely. However, it can be seen that the encountered



(a) Annulus (b) Sector (c) Cicular segment

Figure 2. Shapes of defect located at the periphery of bored pile

probability of the first two types is certainly greater than that of the last type, the circular segment, because the first two types of defect readily intersect with the signal path as demonstrated in Fig. 2(a) and 2(b). For a more conservative purpose, the defect with the shape of circular segment is chosen as the examined object in this paper (Fig. 2(c)).

4. Inspection probability

The reliability of the CSL method can be described by the inspection probability, which is expressed as a product of the encountered probability and the detection probability:

$$P_I(a) = P_E(E_e|a)\, P_D(E_d|E_e, a) \tag{1}$$

where $P_I(a)$ is the inspection probability for a given defect size a; E_e is the event that a defect with a given size a is encountered; E_d is the event that a defect with a given size a is detected if it is indeed encountered; $P_E(E_e|a)$ is the encountered probability that a defect is encountered by an inspection of a given inspection plan if a defect indeed exists; and $P_D(E_d|E_e, a)$ is the detection probability that an inspection detects a defect if a defect is indeed encountered.

4.1. Encountered probability

Consider a general case, where a pile has n_t access tubes installed inside the reinforcing steel cage as shown in Fig. 3. A defect, which is indicated by the shaded area, has a shape of the circular segment at the periphery of pile. The defect is located by the chord, EF, and its magnitude is represented by the height of circular segment a. Consider two adjacent access tubes, i and $i+1$, being in the vicinity with the defect. AB is the chord going through the centers of the access tubes i and $i+1$. M is the middle point of the chord AB. The radius, ON, goes through the middle point, M, and is therefore perpendicular to the chord AB.

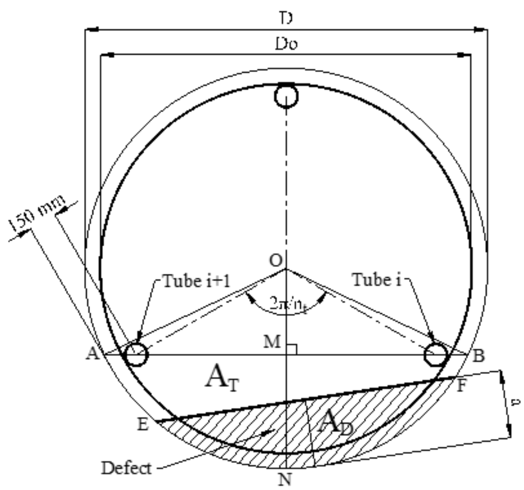


Figure 3. Geometrical diagram determining encountered probability

The probability of an event that the defect can be encountered by the signal path between the access tubes, i and $i+1$, can be determined as a ratio:

$$P_E(E_e|a) = \frac{A_D}{A_T} \tag{2}$$

where A_D is the cross-sectional area of the defect indicated by the shaded area in Fig. 3; A_T is the area of the circular segment located by the chord AB, i.e., the chord goes through the centers of two adjacent access tubes.

$$A_D = \frac{D^2}{8}\left\{2\arccos\left(\frac{0.5D-a}{0.5D}\right) - \sin\left[2\arccos\left(\frac{0.5D-a}{0.5D}\right)\right]\right\},\quad 150\text{ mm} \le a \le MN \tag{3}$$

$$A_T = \frac{D^2}{8}\left\{2\arcsin\left(\frac{AM}{0.5D}\right) - \sin\left[2\arcsin\left(\frac{AM}{0.5D}\right)\right]\right\} \tag{4}$$

$$AM = \sqrt{MN\,(D - MN)} \tag{5}$$

$$MN = 0.5D - (0.5D - 150)\cos\frac{\pi}{n_t} \tag{6}$$

in which, D is the pile diameter; the number of 150 in Eq. (6) is the shortest distance in millimeters from the center of access tube to the pile shaft perimeter.

Fig. 4 shows the encountered probability for different magnitudes of the defects with a given number of access tubes for a D = 1,000 mm bored pile. Fig. 5 indicates the relationship between the encounterable magnitude of the defects and the number of access tubes for different pile diameters with the target encountered probability, $P_E = 0.9$. Some findings can be given below:

- The encountered probability increases with the magnitude of the defect. The bored pile D = 1,000 mm is taken in Fig. 4 as an example. If the number of access tubes is three, the encountered probability increases from 0.34 to 1.0, as the magnitude of defect increases from 150 to 325 mm.

- For a given magnitude of the defect and a given encountered probability, a pile with a greater diameter requires a larger number of access tubes to be able to encounter the same magnitude of the defect. From Fig. 5, for a defect with a magnitude of 300 mm and a target encountered probability of 0.9, a bored pile D = 1,000 mm needs 3 access tubes, meanwhile a bored pile D = 2,500 mm needs up to 6 access tubes.

- For a given pile diameter and a given encountered probability, the magnitude of the defect that can be encountered decreases as the number of access tubes increases. However, the magnitude of the defect tends to be tangent with a certain value. This hints that, for a given pile diameter and a given encountered probability, the required number of access tubes should be limited at a certain value, over which it would be less efficient.

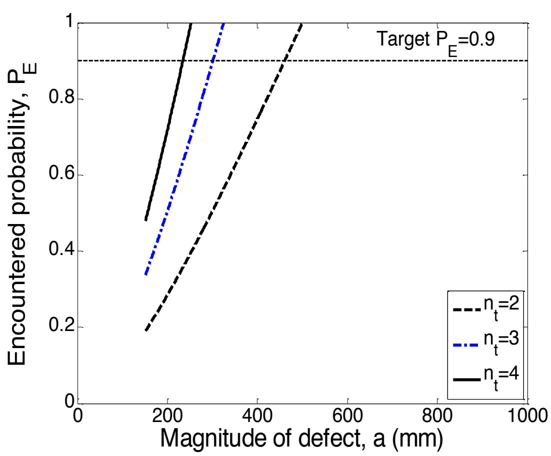


Figure 4. Encountered probability for bored pile D = 1,000 mm

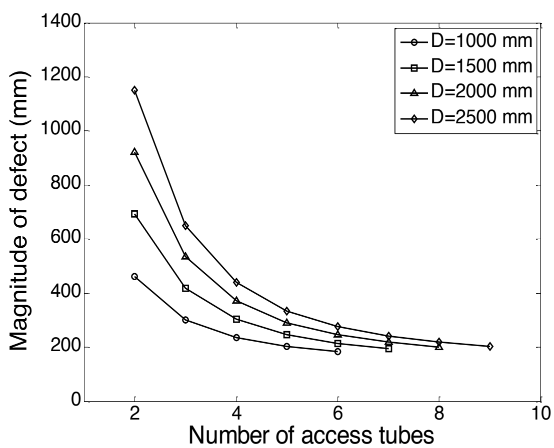


Figure 5. Encounterable magnitudes of the defect versus the number of access tubes

4.2. Detection probability

Once again, we consider a general case where a pile has n_t access tubes installed and a defect indicated by a shaded area has a position as shown in Fig. 6. Let point H be the middle point of the chord EF. The segment, OL, going through the middle point H is perpendicular to the chord EF and divides the defect into two equal parts. Therefore, the segment OL can be used as a location segment of the defect position, it represents the relative position of the defect compared to the two adjacent access tubes i and $i + 1$. Let point S be the intersection of the chord EF and the chord AB, and point T be the center of access tube i. It can be seen that the segment ST represents the length of the secant between the defect and the sonic signal path, which is formed from the center to center of two access tubes i and $i + 1$. Obviously, when the magnitude or the position of the defect changes, the secant ST changes correspondingly. This hints that the length of the secant ST can be used as a parameter representing the detection capability of defect with respect to the CSL method. Thus, the term of detection length is used instead of the length of the secant.

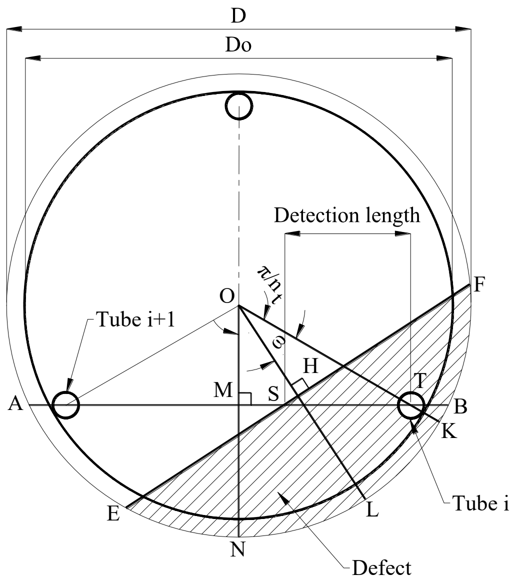


Figure 6. Geometrical diagram determining detection probability

Let point K be the intersection of the segment OT and the perimeter of the pile. The angle ω, determined by the segment OL and the segment OK, is used as the location angle of the defect. Since the symmetric performance of the circular cross section of pile and the access tubes are equally arranged along the reinforcing cage, the variation of the location angle, ω, from zero to an angle of π/n_t radians is sufficient to describe all positions of the defect compared to that of the access tubes i and $i + 1$.

The detection length ST can be determined as follows:

$$\text{Detection length} = \frac{(0.5D - 150)\left[\cos\dfrac{\pi}{n_t} + \sin\omega \sin\left(\dfrac{\pi}{n_t} - \omega\right)\right] - (0.5D - a)\cos\left(\dfrac{\pi}{n_t} - \omega\right)}{\sin\left(\dfrac{\pi}{n_t} - \omega\right)\cos\left(\dfrac{\pi}{n_t} - \omega\right)} \tag{7}$$

here, all parameters are the same as those in Eqs. (3) to (6). Note that, a is the magnitude of defect, $a = HL$.

Fig. 7 shows the variation of the detection length with the location angle of the defect for a given bored pile. Here, the pile has a diameter of 1,200 mm, the number of access tubes is assumed as 3, and the magnitude of defect is supposed to be 370 mm. As a result, when the location angle, ω, varies from zero to $\pi/3$ radians, the detection length gradually increases from a value of 254 mm and reaches a maximum value of 342 mm, and then decreases down to -∞, as the location angle approaches the value of $\pi/3$ radians.

For a more practical side, we assume that there exists a detection threshold, under which a CSL test may not detect a defect. In this case, a detection threshold is assigned, for instance, as 300 mm. In Fig. 7, we see that when the location angle lies in the range from 0.350 to 0.985 radians, the detection length is greater than or equal to the detection threshold.

When the location angle lies outside this range, a CSL test may not detect the defect. This issue hints at a way to determine the detection probability for a given magnitude of defect as:

$$P_D\left(E_d | E_e, a\right) \approx \frac{n_D}{n_\omega} \tag{8}$$

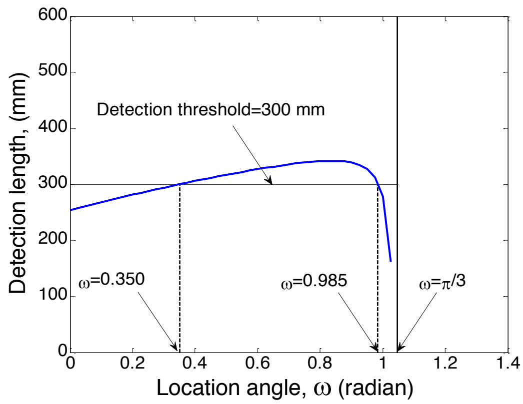


Figure 7. Geometrical diagram determining detection probability

where $P_D\left(E_d | E_e, a\right)$ is the detection probability; n_D is the number of values of ω, for which the detection length is greater than or equal to the detection threshold; n_ω is the total number of values of ω, being taken from the range of zero to π/n_t.

A question arising herein is, how much is the detection threshold, so that a CSL test really detects defects. In some literatures, the minimum detectable defect diameter is 249 mm (e.g., [11]) and 201 mm (e.g., [12]). Amir and Amir [13] presented detection thresholds with respect to different emitter frequencies and wavelengths of the ultrasonic signal as shown in Table 2.

Table 2. Detection threshold of CSL test

Technical characteristics	Unit	Values			
Frequency	kHz	20	30	50	100
Wavelength	mm	210	140	84	42
Detection threshold	mm	420	280	168	84

In Table 2, the frequency of 50 kHz and wavelength of 84 mm are adopted, since these values commonly selected in practice, the detection threshold is obtained as 168 mm. This detection threshold is clearly smaller than that presented above by [11, 12]. For conservative purposes, a detection threshold of 200 mm is adopted for this study.

Fig. 8 shows the detection probability for different magnitudes of defect with a given number of access tubes for a D = 1,500 mm bored pile. Some comments can be drawn:

- The detection probability increases with the magnitude of defect. If the number of access tubes is 3, the detection probability increases from zero to 1.0, as the magnitude of defect increases from 311 to 443 mm.

- For a given target detection probability, the magnitude of defect that can be detected decreases as the number of access tubes increases. For a target detection probability of 0.9, the magnitude of defect that can be detected decreases from 690 down to 260 mm as the number of access tubes increases from 2 to 5 tubes.

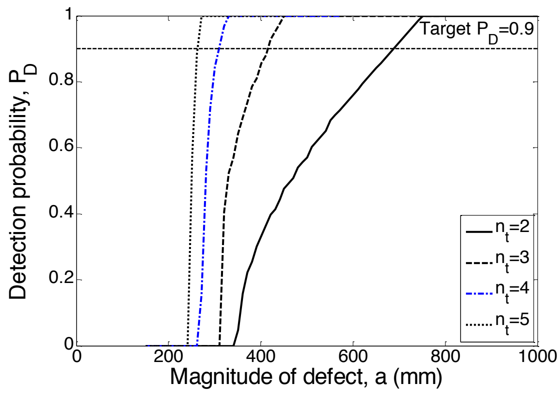


Figure 8. Detection probability for bored pile D = 1,500 mm

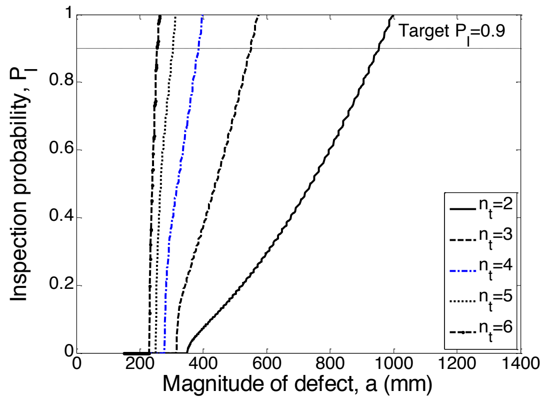


Figure 9. Inspection probability for bored pile D = 2,000 mm

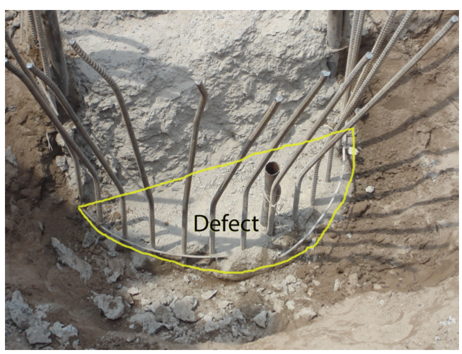
4.3. Inspection probability

The encountered probability and the detection probability are analyzed separately in the subsections 4.1 and 4.2. In this subsection, a combination of two probability measures is considered, aiming to determine the inspection probability using Eq. (1).

Fig. 9 shows the inspection probability for different magnitudes of defect with a given number of access tubes for a D = 2,000 mm bored pile. Basically, comments with respect to the inspection probability are the same as those for the encountered probability and the detection probability as discussed in the previous subsections.

For illustrative purposes, a case study is considered. A testing bored pile was conducted by [14], a D = 1,400 mm bored pile with 4 arranged access tubes was tested at a foundation of a collective building in Hanoi, Vietnam. A fatal defect was detected by the CSL method at a depth of about 3.0 m, and then the constructor excavated the soil surrounding the pile to the depth of the suspected defect aiming to perform a visually-checked work. As a result, a defect in a typical shape of circular segment with a magnitude of about 400 mm was exposed (see Fig. 10). Fig. 11 shows the inspection probability proposed by this paper for a bored pile D = 1,400 mm, which has the same diameter as

(a) Soil occupied the pile shaft



(b) Defect exposed after excavating

Figure 10. Defect in shape of circular segment [14]

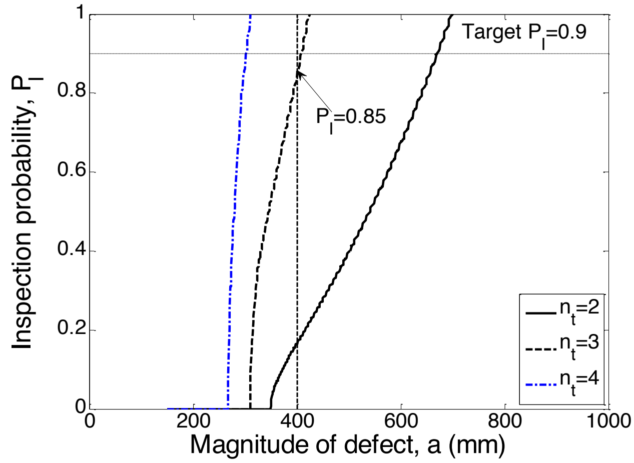


Figure 11. Inspection probability for bored pile D = 1,400 mm

that of the pile tested in the field. It can be seen that, for a magnitude of defect of 400 mm, if 3 access tubes are used, the inspection probability reaches 0.85. Meanwhile, if 4 access tubes are used, the inspection probability is obtained as 1.0, i.e., the defect is detected with certainty. This is true for the case considered.

5. Essential quantity of access tubes in this paper

Based on the analyses above, it can be seen that the number of access tubes is an important factor and strongly affects, not only on the measurement results of the CSL method, but also the construction costs of bored pile foundations. Particularly, in cases where there is a very large number of bored piles to be used in foundations. Thus, the number of access tubes needs to be addressed pertinently, so that they assure technico-economical requirements in the stage of design.

This section is used to synthesize the essential quantity of access tubes for different diameters of bored piles and different magnitudes of defect. The target inspection probability is assigned as 0.99. The recommended number of access tubes is indicated in Table 3. Through this table, several comments can be drawn:

- For the target inspection probability of 0.99, the detectable minimum magnitude of defect decreases with the increase of the number of access tubes to be used. However, the magnitude of defect tends to be tangent with a value of approximately 200 mm, regardless of the pile diameters. This value can be considered as a minimum magnitude of defect, under which the CSL test cannot detect the defect (see more in Fig. 5).

- With respect to the pile diameter in the range from 600 to 3,000 mm and the target inspection probability of 0.99, eight (8) access tubes can be considered as the maximum number of access tubes that can be used when the CSL method is required.

- Through Table 3, for a given pile diameter, a suitable number of access tubes can be selected based on the detectable minimum magnitude of defect, if a designer supposes that this magnitude of defect may adversely affect the safety degree of bored pile foundations.

Table 3. Detectable minimum magnitudes of defect (in mm) according to pile diameters and number of access tubes with target inspection probability of 0.99

Pile diameter (mm)	$n_t = 2$	$n_t = 3$	$n_t = 4$	$n_t = 5$	$n_t = 6$	$n_t = 7$	$n_t = 8$
600	349	293	257	237	225	215	209
750	375	305	265	242	228	216	209
1,000	497	324	279	251	234	221	213
1,200	596	372	288	257	239	225	214
1,500	744	447	324	268	245	229	218
2,000	992	571	397	312	262	237	223
2,500	1,241	695	469	359	296	257	232
3,000	1,489	819	541	406	329	282	251

6. Conclusions

This paper has proposed a probability approach for determining the essential quantity of access tubes in quality control of bored pile concrete when using the CSL method. The encountered probability, detection probability, and inspection probability for the CSL method are formulated. Based on the inspection probability, the quantity of access tubes is recommended to designers of bored pile foundations. Some findings can be given from the paper:

- The quantity of access tubes depends on pile diameters, magnitude of defects needed to detect, and the technical characteristics of CSL equipment.
- The value of 200 mm can be considered as a minimum magnitude of defect in shape of circular segment, under which the CSL test cannot detect.
- Eight access tubes can be considered as the maximum number of access tubes that can be used when the CSL method is required.

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