Discussion of "Reliability Evaluation of Cross-Hole Sonic Logging for Bored Pile Integrity" by D. Q. Li, L. M. Zhang, and W. H. Tang

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During the last decade cross-hole sonic logging, alternatively referred to as ultrasonic cross-hole testing of piles (ASTM 2002), has established itself as the preferred method for quality control of bored piles (alias caissons and drilled shafts). While the principles lying behind the test are now well understood, there is still disagreement as to the number of access tubes that are necessary to perform the test. This subject has a clear economic consequence: While increasing the number of access tubes in a pile may improve the test's flaw detection capability, these tubes carry a price tag in material, workmanship, and increased testing costs. The effort made by the authors to determine the optimal number of access tubes for each situation should therefore be commended.

For the paper presented to qualify as a practical guide, it has to fulfill certain conditions:

1. The work has to address the technical features specific to the test.
2. It should be based on reasonable assumptions, commensurate with observed facts and common knowledge.
3. The mathematical treatment must be rigorous.

Being guided by these criteria, the discusser would like to raise certain reservations related to the methodology followed by the authors. These are presented in the following paragraphs.

Technical Features

Typically, two distinct parameters are measured in the ultrasonic cross-hole test: first arrival time (FAT) and relative energy (ASTM 2002). Each of these has its special significance in the interpretation of the test results. Certain flaws are better expressed in FAT terms, while others have more influence on the relative energy. It is regrettable, therefore, that in discussing inspection probability the authors do not mention which of these two they refer to.

Furthermore, the heterogeneity of concrete may cause test results to exhibit large scatter (Amir et al. 2004). Under these conditions, a defect of a given size may escape detection when its effect on the test results is of the same order as the scatter. In such a noisy environment, the definition of what constitutes an anomaly is rather arbitrary, with different codes providing different prescriptions. The Chinese code (MOC 2003), for instance, defines as anomalous any result in which the apparent wave velocity deviates from the mean by $\lambda\sigma$, or a prescribed number of standard deviations. The authors tacitly circumvent this crucial problem by assuming those detection thresholds are independent of the signal-to-noise ratio.

Validity of Assumptions

The authors make several assumptions, among which the most important are

1. On the basis of Fleming et al. (1992), the authors assume that a defect may occupy, with equal likelihood, any position within the pile cross section. However, a careful study of the numerous photographs provided by Fleming et al. (1992) clearly shows that most of them depict defects in the periphery. O'Neil (1991) explains this phenomenon, to which many practitioners can testify from personal experience (Fig. 1), by the interaction of the rising concrete column and the slurry with the surrounding soil, groundwater, temporary casing, and reinforcement cage—all located at the pile's periphery. The widespread usage of the terms "necking" or "waisting" in describing pile integrity attests to this phenomenon.
2. The authors claim that what they define as the "encountered probability" of a defect depends only on its size. Evidently, this is necessarily incorrect: While an air void of a few millimeters caused by tube debonding is clearly detected, a defect two orders of magnitude larger may escape detection if it is located farther away from a tube. Thus, defect position is not less and maybe more important than its size.

To illustrate this point, a finite element simulation of the

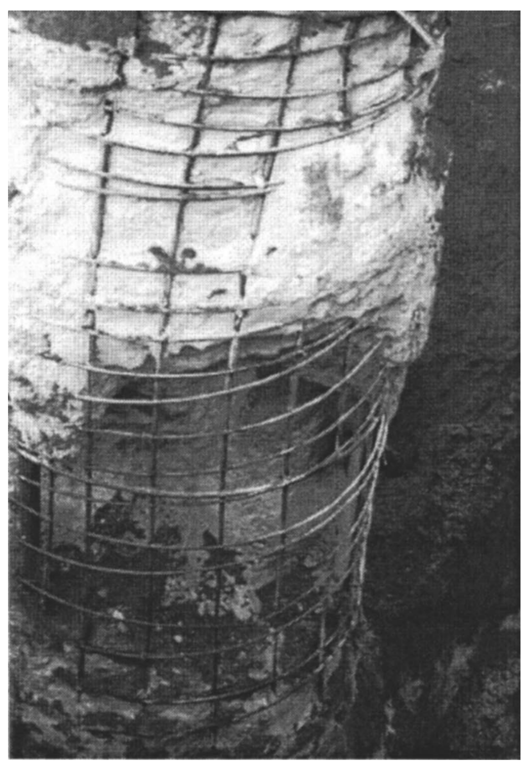

Fig. 1. Typical defect in bored pile constructed with polymer slurry

J. Geotech. Geoenviron. Eng., 2007, 133(3): 342-343

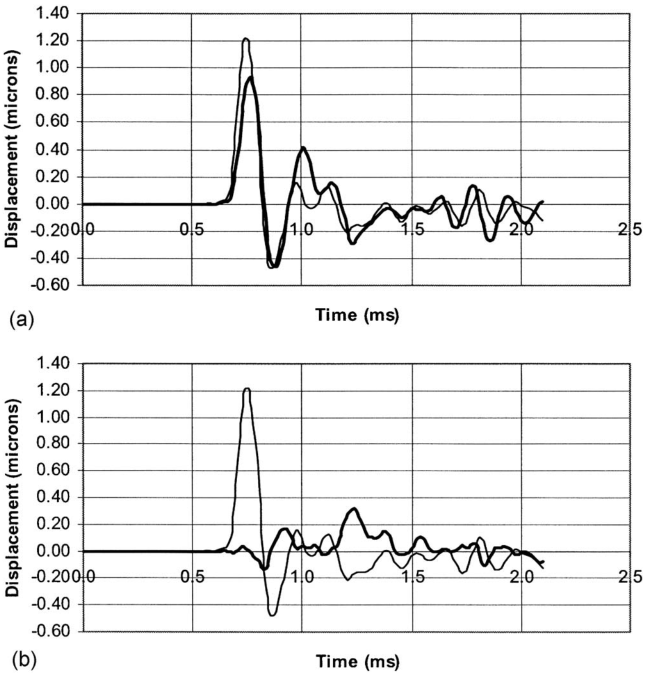

Fig. 2. Pile with no defect (thin line), with defect halfway between tubes (a), and with defect close to transmitter (b)

cross-hole test was run, using the Plaxis program, for three cases: no defect; circular defect, 5 wavelengths in diameter halfway between the transmitter and receiver; and circular defect, 5 wavelengths in diameter, close to the transmitter.

The results of the simulation, presented as horizontal displacement versus time, are reasonably similar to those obtained in a real test. The results (Fig. 2) show that a defect halfway between the tubes is hardly discernible, while an identical one located close to the emitter (or in fact to the receiver) is easily detected: the FAT is at least 20% larger, and the maximum amplitude 75% (or 12 dB) smaller.

3. In defining the detection probability for a defect in a pile (Eq. 4), the authors adopt results developed for cracks in metal. The validity of this analogy is, however, not self-evident. Concrete in piles, unlike metal, is far from homogeneous, and typical defects in piles are not well-defined features but of rather fuzzy character. Thus, the detection threshold of defects in piles must be much higher.

d. The authors assume that waves propagate in straight lines. While this may be true for homogeneous media, it is not necessarily so in heterogeneous materials like concrete (Santamarina et al. 2001). Even in a homogeneous medium with inclusions of foreign materials, waves will travel in curved paths to go around those inclusions and minimize arrival time (Fermat's postulate).

Analysis

In Eq. 1 the authors express inspection probability $P(x)$ as a product of encountered probability $P(E|x)$ and the detection probability $P(D|E,x)$, both dependent on defect size x. Since the law of multiplication is only applicable to statistically independent probabilities (Bulmer 1967), the use of Eq. 1 is not justified.

Summary

The treatise presented by the authors appears to be based on simplifying assumptions that seem to contradict both empirical evidence and accepted principles. Moreover, the statistical treatment of the problem is flawed, and above all, the authors do not address the specific parameters that characterize real-life cross-hole tests. As a result, the validity of their results is questionable, and extra caution is deemed necessary in the application of their conclusions to practical situations.

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Technical Features

The authors did not consider the detection capability of cross-hole sonic logging (CSL) directly from the technical features of CSL such as first arrival time and relative energy. Instead, the detection probability for bored piles considered in this paper is based on past CSL performance. A detection probability function by Yang and Trapp (1975) is used, and the minimum detectable void size and the detectable void size with certainty are selected based on

J. Geotech. Geoenviron. Eng., 2007, 133(3): 342-343

past CSL detection performance for bored piles (Table 2 in the paper).

The discusser proposes to explore the detection probability of CSL based on technical features of CSL. This can certainly add physical understanding to the issue. This approach may at the same time, as pointed out by the discusser, be rendered ineffective by the heterogeneity of concrete and locations of anomalies (see Fig. 2 of the Discussion).

Validity of Assumptions

As mentioned by O'Neill (1991), defects such as necking and soil inclusions may be located at a pile's periphery, while defects such as voids and cracks can be located at any position within the pile shaft. For simplicity, it is assumed that the defect location is uniformly distributed over the cross section of the pile in the paper. This assumption may somewhat overpredict the encountered probability of CSL.

The concepts of encountered probability and inspection probability cannot be confused. The chance that a defect may be found by an integrity test is quantified through the inspection probability rather than the encountered probability alone. This is an important point that this paper attempts to clarify. Encountered probability depends only on the defect size and the arrangement of access tubes. The *encountered probability* referred to by the discusser is actually the inspection probability as defined by the authors.

The effect of defect location on the inspection probability has been taken into consideration through the detection probability defined in this study, which is illustrated in Fig. 4 in the paper. In Fig. 4, y is the distance from the center of the defect to the chord and is used to account for the effect of defect location. The effect is quantified in the subsequent analysis through Fig. 5 and Eqs. (12) and (13) in the paper. For instance, for a defect with a diameter of 200 mm, the detection probability is 1.0 for the case when the defect is located at the center of the signal path and 0 for the case when the defect is randomly located within the pile cross section. Obviously, the detection probability can differ considerably based on the difference in the defect location, though the defect size remains the same. Consequently, the probability that an inspection will find a defect can differ considerably.

The detection probability function shown in Eq. (4) in the paper is obtained based on data from ultrasonic inspection of fatigue cracks in metal structures (Yang and Trapp 1975). With regard to integrity testing for large-diameter bored piles, no detection probability functions have ever been reported in the literature. In this paper, Eq. (4) is assumed to apply equally well to CSL for large-diameter bored piles. It should be noted that the detection thresholds for defects have been determined based on experimental results of CSL for large-diameter bored piles rather than results of cracks in metals. The detection thresholds of defects are 133.3 and 200 mm in Eqs. (12) and (13) for the two cases considered in the paper. Both of them are considerably higher than 10 mm for cracks in metal structures (Ichikawa 1985) or 1.0 mm for magnetic inspection (Guedes Soares and Garbatov 1996).

Following Hassan and O'Neill (1998), the authors assumed that a cross-hole sonic logging test can scan the path between the two access tubes with a width of about 2λ, where λ is the wave length. The discusser is correct when he says that waves may travel in curved paths to go around inclusions. This will affect both the encountered probability and the detection probability and is certainly worthy of further study.

Analysis

A defect inspection requires the intersection of two events, namely (1) the defect must be encountered, and (2) the defect must be detected. Eq. (1) describes that the intersection probability can be expressed as the product of the encountered probability and the conditional probability that the defect will be detected if it has been encountered (that is, the detection probability). Clearly, both the encountered probability and detection probability are related to the defect size. The inspection probability will be zero if the defect is not encountered or if the defect is encountered but not detected by the CSL.

Summary

The major points in the discussion seem to have arisen from confusion between the encountered probability and the inspection probability. A thrust of this paper is to clarify the concepts of encountered probability, detection probability, and inspection probability. The paper provides a quantitative guidance for the number of access tubes for CSL based on past CSL performance. Indeed some assumptions are made for the analysis of the encountered probability and detection probability. The results presented in this paper are accordingly valid to the degree these assumptions are met.

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Discussion of "Comparison of Interface Shear Strength of Soil Nails Measured by Both Direct Shear Box Tests and Pullout Tests" by Lok-Man Chu and Jian-Hua Yin

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Although several tens of thousands of soil nails are installed annually to stabilize slopes in Hong Kong, there have been very few, if any, local detailed laboratory studies, on the pullout resis-

J. Geotech. Geoenviron. Eng., 2007, 133(3): 342-343

tance soil nails under Hong Kong conditions. The authors' study is a significant step toward a better understanding of the factors controlling pullout resistance of soil nails.

In Hong Kong, soil nails are commonly installed in existing slopes to stabilize soil and sometimes they are installed in newly formed cut slopes for temporary excavations. The construction method involves forming a drillhole, inserting a deformed bar, and grouting gravity.

When some preliminary findings of this paper were presented earlier by Chu and Yin (2004) in a seminar in Hong Kong, Li made the following remarks, which are believed to be applicable to the present paper.

Geotechnical structure behaviors are highly dependent on the method of construction. In the study of a soil nail's behavior, it is of paramount importance to mimic its method of construction.

When a stable drillhole is formed, the radial stress in the vicinity of the soil face will be close to zero, which is completely different from the test conditions devised by the authors in which the applied stress was exerted only after installation of the model soil nail. Consequently, the results presented by the authors may not necessarily be representative of the actual behavior in the field.

In this discussion, the writers would like to elaborate the above points further and share some thoughts on possible mechanisms by which soil nails develop their pullout resistance. In this discussion the term "soil nail" includes the annulus of grout around the deformed bar. The stress state around a drillhole is illustrated in Fig. 1. Before a drillhole is formed, the soil at the drillhole location is subjected to the overburden pressure σ_v' [Fig. 1(a)]. After a drillhole has been formed, stability of the hole is maintained by the arching effect, and hence the radial stress at the soil face must be close to zero [see Fig. 1(b)]. After installation, a small effective radial stress will be reintroduced with gravity grouting. In other words, both the stress path and the stress state in the vicinity of the nails in the field are significantly different from that in the laboratory study presented by the authors.

If the initial stress acting normal to the soil nail is small, it is interesting to speculate the possible mechanisms for the development of pullout resistance.

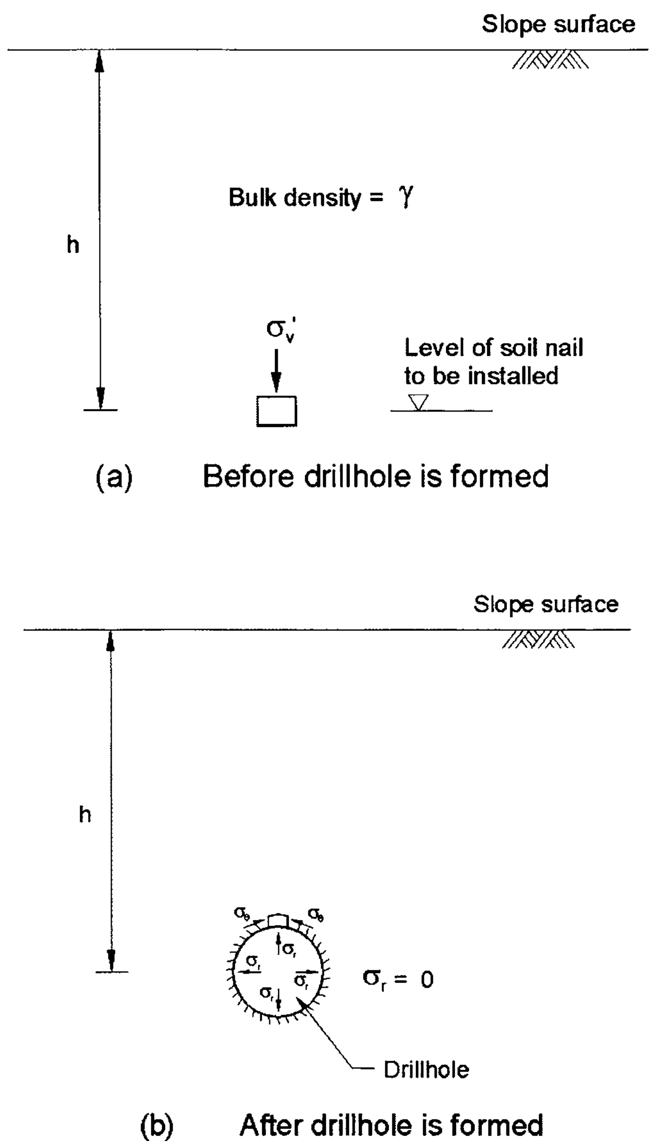

Fig. 1. Stress state around drillhole

Soil Dilatancy

During a pull-out test, soils in the vicinity of a nail will be subject to significant shearing. The additional normal stress induced by the mechanism of constrained dilatancy (Lo 2003) will cause friction, and hence pullout resistance will develop along the soil nail. Preliminary numerical studies using Mohr-Coulomb elastic-plastic model with a nonassociative flow rule presented by Lo (2002) clearly showed the significance of dilatancy. Loose soils have a small potential for soil dilation, and one may expect soil nails installed in such soils to have low pull-out resistance. However, field data indicate that soil nails installed in loose fill, for instance, can sometimes develop a significant pullout resistance. Other factors must contribute to this outcome.

Interface Dilation

Drillholes installed using techniques in Hong Kong have overbreak. Such drillholes will generate interface dilatancy during shearing in a manner similar to the development of side resistance in a rock socketed pile in weak rock.

Physical Bonding

When the drillhole is grouted, cement grout will permeate into the soils. The soil nail and the soils around it are mechanically bonded by the cement grout. Pullout resistance may then develop as a result of adhesion between the soil/soil-nail interface. Alternatively, the shear plane may move into the virgin soil, leading to a significant, larger "equivalent nail diameter" and thus a significantly larger pullout resistance.

To obtain meaningful results that can lead to the improved soil nail design and construction practices in Hong Kong, it is important that laboratory tests be devised to model the actual field conditions and to ascertain which one or combination of the above mechanisms are dominant. For instance, if bonding is important, one may perhaps recommend a higher water-cement ratio and the use of retarder for the cement grout, and a longer grouting period to encourage better permeation of the material into the soils. Pressure grouting may also be used to either improve grout

J. Geotech. Geoenviron. Eng., 2007, 133(3): 342-343

permeation or to introduce higher normal stress at the soil-nail interface.

According to data presented by the authors, the pullout resistance of soil nails increases approximately linearly with applied stress. Additional studies, both laboratory and numerical, are needed before making recommendations for the current design practice for the following reasons:

1. The issues of soil arching and constrained dilatancy should be addressed as discussed above. In this respect, it is interesting to note the design practice of tunnel lining. Tunnel engineers do not increase the thickness of tunnel lining for a deep tunnel in proportion with the thickness of overburden above a tunnel. Soil relaxation that occurs after the formation of a drillhole and before the grouting of the soil nail will also affect the normal stress acting on installed soil nails. The influence of the arching effect on pullout resistance can be studied by exerting the applied stress first before installing the model soil nail and varying the thickness of soil cover above the test nail.
2. Because the nails are significantly stiffer than the surrounding soil, the vertical stress in the vicinity of the nail may be significantly higher than the applied stress.
3. The authors installed the test soil nails using coring methods. In Hong Kong, soil nails are installed by percussive method, and soil cuttings are flushed out of the drillholes with compressed air. This is expected to create a rougher drillhole with higher overbreak and hence more significant interface dilation than would be created using coring method.
4. In the field, soil nails are installed in an inclined position to enable cement grout to stay in the drillhole and produce a small hydraulic head to facilitate permeation of cement grout into the soil. In the authors' study, the test nails are installed horizontally and permeation of cement grout into the soil may not be as effective as in the prototype soil nails.
5. The use of soil nails in Hong Kong is not restricted to steep slope. For gentler slopes, the determination of σ_v' becomes problematic. The current Hong Kong practice assumes $\sigma_v' \approx \gamma h$ for soil nails installed in a uniform soil above the ground water table [see Fig. 1(a)]. This assumption is true only for horizontal ground. It will be useful if researchers can perform numerical analyses to calibrate current Hong Kong practice and, if necessary, develop an alternative simple calculation model (maybe with the aid of design charts) for the design of soil nails.

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The authors would like to express sincere thanks to the two discussers for their insightful discussion on our paper and valuable suggestions for further studies.

The discussers make two remarks on our research project: (1) the construction process of a soil nail should have been simulated in the laboratory soil pullout tests and (2) a vertical pressure was applied first before the installation of the soil nail in the test so that the stress release in drilling of the hole was not considered and the behavior measured in the lab might not be representative of the actual behavior in the field.

The authors agree with the discussers that the simulation of the soil nail installation process is very important. The authors would like to mention that the study presented in the paper was not intended to simulate the installation process but rather to measure the fundamental shear strength of the interface between the cement grout (soil nail surface) and the surrounding soil. The performance of a soil nail in a slope, including the elements of the construction process, such as drilling a hole and grouting, is considered to be a boundary value problem. A numerical method based on the continuous mechanics shall be used to solve this boundary value problem. This method shall take into account of stress equilibrium, strain-displacement compatibility, proper constitutive equations for the soil and the soil-nail interface, and proper boundary conditions. Here, the constitutive equations for the soil and the soil-nail interface are for the fundamental behavior, also called elementary behavior. The behavior measured in our laboratory soil nail pullout tests is, in fact, the elementary behavior of the soil-nail interface. The soil nail pullout tests in the paper were very much like direct shear box tests. The results from such pullout tests can be used to obtain the fundamental (or elementary) soil-nail interface shear strength parameters.

The authors are happy to report that a new study has been carried out, using a new soil nail pullout box with comprehensive instrumentation, to simulate the soil nail installation process and to investigate the influence of overburden pressure, the degree of water saturation, and cement slurry pressure grouting. Based on the new test results, a new paper titled "Laboratory Testing Study on the Influence of Overburden Pressure on Soil Nail Pullout Resistance in Compacted Completely Decomposed Granite Fill" by Li-Jun Su, Terence C. F. Chan, Herman Y. K. Shiu, S. L. Chiu, and Jian-Hua Yin has been submitted to this journal for review and possible publication. This new study simulated the performance of a segment of a soil nail in the actual field condition. In

J. Geotech. Geoenviron. Eng., 2007, 133(3): 342-343

this new paper, the whole construction process and soil nail pullout, including the soil pressure caused by hole drilling (stress release) and changes caused by grouting and soil nail pull out, was closely monitored. The results from this new study indicate that the soil nail pullout resistance is not influenced by the overburden pressure. This new paper will address some of the discussers' concerns in greater detail.

The discussers present the mechanisms that affect the pullout resistance of a soil nail in the field—that is, dilatancy of soil, dilatancy of the nail-soil interface, and physical bonding. The authors appreciate the insightful analysis of the mechanisms. These mechanisms have been mostly investigated in our new studies using a new soil nail pullout box.

The discussers observe that the soil nail pullout resistance from tests presented in the paper increased with the applied vertical stress. This is true for elementary tests because the old pullout box tests were similar to direct shear box tests. The discussers make suggestions for further studies on a few important issues: (1) the issues of soil arching and constrained dilatancy, (2) the stress concentration on the soil nail as it is stiffer, (3) different coring methods such as the percussive method, (4) inclination of a soil nail hole with a small gravity head for grouting pressure, and (5) the determination of the vertical effective stress on the soil nail surface installed in a slope. The authors appreciate the valuable suggestions. The authors would like to report that we conducted a preliminary study of issues (2) and (3). Issues (1) and (4) have been investigated in our new study using a new soil nail pullout box. Issue (5) has not been addressed by us but has been pointed out by other researchers as well.

J. Geotech. Geoenviron. Eng., 2007, 133(3): 342-343