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REVIEW ARTICLE

A Review of Cross-Hole Ultrasonic Logging for Foundation Integrity Testing and its Evaluation Criteria

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ABSTRACT - Since the concrete quality of cast in-situ foundation is crucial, the cross-hole ultrasonic logging (CSL) method has become an effective method to assess the homogeneity and integrity of concrete without being limited by the pile length or soil type. Although the testing procedure for CSL is well defined by test standards including ASTM, the interpretation and evaluation criteria of CSL testing results, in contrast, are not well defined and controlled by uniform standards. The current state of practice recorded the application of different rating criteria with different parameters applied for foundations acceptance evaluation. A task force formed by Deep Foundations Institute (DFI) in 2019 has proposed improved rating criteria for CSL results evaluation with the vision of standardized and uniform evaluation criteria in the future. This paper summarizes the current practice of the CSL method and compares the commonly used rating criteria with the currently proposed improved criteria.

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1.0 INTRODUCTION

Cast in-situ concrete foundations such as drilled shafts or bored piles refer to foundation elements that are cast in place by inserting reinforcement cages followed by fluid concrete into a drilled hole [1]. Bored piles are often designed as deep foundations with large diameters and high working loads, thus reducing the total number of piles required as compared to driven piles [2]. Construction of these deep foundations can cause various uncertainty and a higher tendency of anomalies despite quality control measures taken during the construction process hence, it is deemed to be impossible to confirm the structural integrity of the foundation.

Although unable to provide information about load-carrying capacity, non-destructive tests (NDT) have been practiced over the years and proven to be effective and reliable methods to assess the homogeneity and integrity of cast in-situ concrete foundations as well as other concrete structures such as diaphragm wall. NDTs that are dominating in present days are acoustic methods such as low strain pile integrity test (PIT) and cross-hole ultrasonic logging (CSL) [3-5]. CSL methods are used to identify and locate structural flaw or defect such as soft bottom or soft toe, voids, honey-combing, soil inclusions, and poor concrete quality which might affect the structural performance of the foundation during its service. Further testing will be conducted to verify and evaluate the defects before the decision is made on whether the foundation will be used as-is with a compromised capacity, repaired, or replaced. This paper will review and discuss relevant literature related to the utilization of the CSL method for foundation integrity testing and the rating criteria available for CSL results evaluation.

2.0 CROSS-HOLE ULTRASONIC LOGGING (CSL) METHOD

This part provides an overview of the CSL method and its current practice in the industry. CSL is a downhole integrity testing via access tubes that utilizes ultrasonic compression wave propagation with a frequency between 30 kHz to 60 kHz, following the standard test method ASTM D6760-16 [6]. Apart from ASTM, other available standards for CSL are the Chinese and French standards [7]. However, only the ASTM standard will be referred to further in this paper since it is practiced widely, including in Malaysia. CSL requires preformed access tubes, mainly steel or PVC access tubes, installed within the reinforcement cage along the foundation element. The total number of access tubes was routinely determined such that one tube is required for every 0.3 m of pile diameter, following the suggestion by [1]. [6] on the other hand, suggested the range of 0.25 m to 0.30 m diameter of the pile for each tube, with three and eight as minimum and maximum total numbers respectively.

2.1 Parameters in CSL method

The CSL method primarily works based on the concept of velocity of sonic wave propagation. Shear (S) waves are disregarded in the CSL method because of their lower velocity compared to longitudinal (P) waves [6]. Thus, any parameters derived in CSL are based on P wave propagation only. For a constant distance of wave path, the main factors affecting the velocity and travel time of sonic wave propagation are the concrete material density and stiffness. Hence,

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variation in the concrete quality will significantly increase the travel time and lower the velocity compared to sound concrete. Typical sonic wave velocity in good-quality concrete is between 3600 m/s to 4400 m/s [6].

The most common parameters used for CSL interpretation and assessment were first arrival time (FAT) and relative energy (RE) which were obtained independently from the processing of the signals. Consistent indications in both FAT and RE test results will lower the uncertainty and strengthen the assurance of the interpretation made [8]. CSL also allows tomography analysis which combines results from all CSL profiles to produce a 3D wave speed profile as a function of shaft length for better interpretation. However, tomography will not be discussed extensively in this paper since the application of tomography was seen to be applied extensively for research purposes only, with very little application in the industry.

FAT refers to the time taken for each of the pulses to travel from the transmitter to the receiver, which is the direct and shortest path available. In CSL software, FAT picking was done automatically with the application of advanced image processing tools. Although apparent concrete wave velocity can be derived by dividing the tube spacing with the FAT, the wave velocity cannot be used as an absolute indicator for concrete quality assessment as the tube spacing may not be parallel throughout the pile length [2]. Besides, the selected FAT also includes the travel time of the waves through the transmitter, water, and access tube wall, thus might be misleading if used to represent the wave velocity, especially for smaller diameter shafts or shorter tube spacing profiles [9]. Therefore, FAT is more accurate than wave velocity to be used to assess concrete quality.

Another important parameter used in CSL results evaluation is the RE of the signal. Since the energy of transmitted ultrasonic waves is constant, the energy of the received pulse is expected to be almost constant for a high-integrity and homogenous concrete. Therefore, any defect or inhomogeneity in concrete will cause energy loss, hence lowering the energy recorded by the receiver. The energy or the strength of the ultrasonic pulse recorded by the receiver, E is the summation of absolute voltage, V values along the received pulse. Unlike the E, RE is the relative signal strength which is calculated by comparison with a reference signal strength, E_{max} where E_{max} is the maximal possible value of strength [10]. RE is presented in the power ratio unit, dB. Unlike FAT which only depends on the direct path between the access tube, RE may provide some information about defects located outside the shortest direct path which will not show any delay in FAT [8].

2.2 Flaws and defect detection using CSL method

Various studies conducted by numerous researchers over the years have proven the ability of CSL in detecting different types of structural defects in drilled shafts and bored piles [2, 3, 10-15]. In a study, the authors summarized the results of CSL of more than 400 shafts constructed in South Carolina where only 24 % were anomalies free while the majority of the anomalies were detected within the upper or lower two diameters of the shaft [16]. Besides field experience, studies were also conducted on test piles with built-in defects from time to time to evaluate the accuracy of current technology in the CSL method [2, 10, 17]. Different materials were used to fabricate common defects to test the ability of the CSL method in detecting inhomogeneity with various densities and properties within the concrete. This includes Styrofoam, plywood box, bandage, steel, sand, soil, as well as intentional voids placed at different depths along the pile.

In terms of the defect size detectable by CSL, [18] summarized from the literature that the minimum detectable defect size ranges from 5 to 10.7 % of pile-cross section area while the detectable defect size with certainty varies from 9 % to 20 % of pile cross-section area. However, based on the probabilistic analysis conducted by the authors, the detectable defects were highly dependent on the pile diameter, defect size, and number of access tubes. For instance, the accuracy of defect detection will increase with an increasing number of access tubes and larger defect size with respect to the pile cross-section area. In a different study, [17] reported that the detectability of flaws is dependent on both defect size and location with respect to the access tube. The authors reported that defects with the size of at least 10 % of the pile cross-section area or exceeding one-third of the access tube spacing can be detected by modern CSL equipment, provided that the defect is located about halfway between the two access tubes.

The limitation of the vertical extent of defect detectable by CSL was not discussed extensively in previous literature since the studies were focused on the defect size in terms of the cross-sectional area. [11] in their study highlighted that "Consequently, a defect with a significant vertical 'foot-print' can normally be intercepted/detected, whereas a thin horizontal-running crack may not be detected because the signal can go around this defect through neighboring sound concrete or water without any significant change of FAT and/or received signal strength". Studies using test piles with built-in defects fabricated the defect with size varying from 0.15 m to 0.4 m in height (vertical extent), and recorded the ability of CSL to detect the defects accurately. In a field case study at an airport bridge project, [5] reported that CSL was able to detect the anomaly caused by a soft zone of 0.1 m to 0.2 m thickness, and soft toe caused by approximately 1ft thick soil at the bottom of the shaft. Hence, it can be concluded that CSL can detect defects with vertical extent or thickness as small as 0.1 m.

Intensive research and development to improve the CSL method resulted in the availability of sophisticated CSL software and tools, including the development of tomography analysis. Consequently, CSL was used as acceptance criteria for drilled shafts in many countries including the United States [2], and even set as a mandatory test such as by the Hong Kong Housing Authority (HKHA) for every project with bored piles foundation [10]. CSL is also very common in Malaysia, even for large-diameter bored piles such as the 2.5 m diameter bored piles constructed for the Penang Second marine bridge project [19].

To summarize, numerous studies as discussed earlier had proven the capability of CSL to detect defects throughout the whole shaft length regardless of the shaft diameter, provided that the defects were located within the reinforcement cage and the access tubes were installed close enough to the bottom of the shaft. In terms of size, defects located about halfway between access tubes with a size of at least 10 % of the pile cross-section area or exceeding one-third of the access tube spacing can be detected by modern CSL equipment. As for vertical extent, the CSL method can detect defects with vertical extent or thickness as small as 0.1 m.

3.0 EVALUATION CRITERIA FOR CSL RESULTS

3.1 General overview

[13] in their study highlighted the lack of common agreement on the limiting value of FAT delay or amplitude reduction to define a defect, causing the interpretation to be subjective to engineering judgment and site-dependent. Since there were no well-defined CSL acceptance criteria, different rating criteria were developed and adapted over the years. While most of the evaluation criteria were developed based on FAT and RE, some criteria were also developed based on the percentage of velocity or wave speed reduction rather than FAT, for instance, the current criteria for the Federal Highway Administration of United States, the Chinese Standards, and French Standards. [20] in their studies also applied the rating criteria based on ultrasonic pulse velocity to determine the concrete quality of the pile. However, it is important to note that the percentage of FAT delays is not equivalent to the percentage of velocity reduction. As discussed in the previous part, wave speed reduction is therefore not recommended to be used for evaluation because the velocity calculated will be inaccurate if the access tube is unparallel, since the wave speed is calculated using access tube top spacing.

[21] mentioned that further investigations are required for CSL results with a 15 % to 20 % delay of FAT based on the study of factors affecting CSL results by England in 1991. Since then, different criteria were developed from numerous studies over the years.

3.2 Commonly used evaluation criteria

One of the commonly used criteria, as applied by [5] and [4] in their studies, were proposed by [2] based on the author’s experience, is summarized in Table 1. The criteria were developed based on FAT increase and RE reduction.

Table 1. Commonly used CSL evaluation criteria proposed by [2]

Category	Comment	FAT Increase	AND/OR	Energy Reduction
G	Good	0 % to 10 %	AND	< 6 dB
Q	Questionable	10 % to 20 %	AND	< 9 dB
P/F	Poor/Flaw	21 % to 30 %	OR	9 dB to 12 dB
P/D	Poor/Defect	≥ 31 %	OR	> 12 dB

After identification of FAT increase or energy reduction, further assessment will be required to estimate the extent of the anomaly by comparing the results of all available profiles. For instance, FAT increase or energy reduction recorded in only one of the diagonal profiles of a four tubes shaft will require no further investigation as it only covers a small percentage of the cross-section [4]. Other criteria suggested by [2] are as follow:

a) Flaws (P/F) should be addressed if recorded in more than 50 % of the profiles.
b) Defects (P/D) should be addressed if recorded in more than one profile.
c) Localized flaws or defects should be evaluated by tomography and/or additional procedure like excavation, coring, or pressure grouting.

However, some studies only applied a single criterion to delineate good and defective concrete, instead of classifying the CSL results based on both parameters. For instance, the study by [15] defined concrete with at least 20 % of FAT delay as a defect, while a different study by [22] defined concrete with less than 6 dB RE as good quality concrete. On the contrary, some studies applied more than one criterion, such as the study by [23] where the authors applied the criteria based on FAT increase, RE reduction, and velocity.

3.3 Proposed terminology and criteria for CSL results by Deep Foundations Institute (DFI)

Over the years, the dependency on CSL results for evaluation of shaft acceptance was high as mentioned by [24] “CSL rating criteria based on first arrival time (or wave speed) and relative energy have often incorrectly evolved to be the sole means of determining the acceptability of a shaft”. Therefore in 2019, a task force formed by an international association of field professionals in deep foundation works, Deep Foundations Institute (DFI) published a white paper proposing an improved CSL rating criteria based on over 20 years of field experience.

Besides proposing new rating criteria, the task force formed by DFI also exclude the terms “flaw” and “defect” from the new criteria to avoid ambiguity since the terms were often used interchangeably even though some opinions have exclusively defined the terms. Hence, new terms with clear delineations in between were introduced to refer to the CSL test result, acceptable and abnormal. The newly proposed rating criteria based on FAT increase and RE reduction are shown in Figure 1. Compared to the criteria by [2], this improved criteria only categorized the results into 3 classes; Class A, B, and C, with slightly different limiting values of FAT and RE.

For comparison, the criteria by [2] were plotted using a similar graphical format in Figure 2 which revealed the grey area of the criteria for CSL results with FAT increase between 0 % to 10 % and RE reduction of 6 dB to 9 dB. It is observed that a higher FAT increase (15 % compared to 10 %) and higher RE reduction (9 dB compared to 6 dB) limit were used for acceptable or good piles in the new criteria. This showed that cumulative field experience of more than 20 years had recorded that FAT increase of less than 15 % and RE reduction of less than 9 dB did not represent significant flaws in piles and the previous criteria were more conservative.

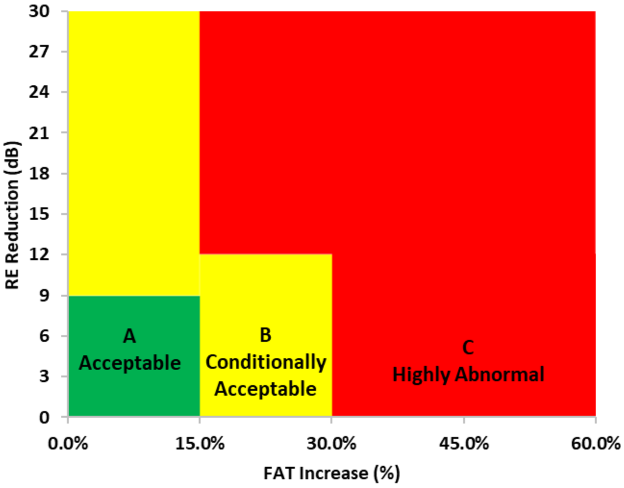

Figure 1. Improved CSL rating criteria proposed by DFI [24]

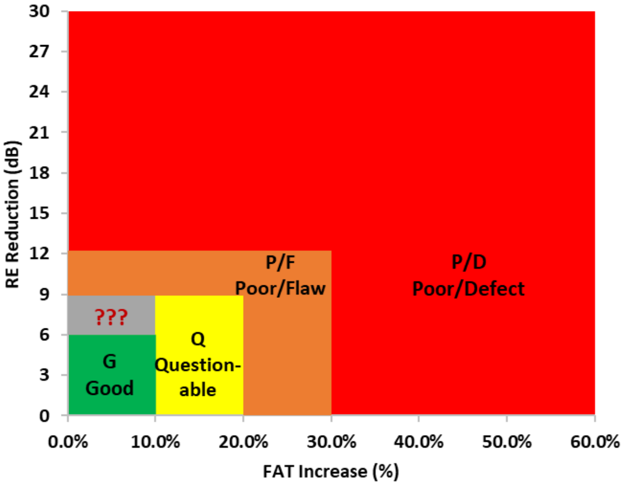

Figure 2. The simplified plot of CSL rating criteria by [2]

The set of improved rating criteria was proposed based on the collective experience of the authors with the goal of a more uniform standard for the evaluation of CSL results in the future. More research and studies were encouraged by the authors to further improve the proposed criteria to produce comprehensive rating criteria. However, the authors strongly emphasized that CSL results should not be used as the only component for shaft acceptability evaluation, instead should be evaluated together with the construction records. However, until recently, the application of this improved rating criteria on CSL results interpretation, especially on field data, is very limited. For instance, [10] applied the rating criteria to the CSL results of a test pile with built-in defects before carrying out tomography analysis. Since the criteria were intended to be a living document, more research and studies were encouraged by the authors to further improve the proposed criteria.

4.0 CONCLUSION

Since the concrete quality of the cast in-situ foundation is crucial, the CSL method has become an effective and competent method to assess the homogeneity and integrity of the concrete. Although the testing procedure for CSL is well defined by test standards, the lack of uniform standards in the evaluation criteria is agreed upon by researchers. The current state of practice recorded that different rating criteria were applied for CSL results evaluation. Improved rating criteria were then proposed by DFI in 2019 as a living document with the purpose to be used as the uniform standard in the future. Since the criteria were proposed quite recently, studies of CSL results using these criteria are very limited. Hence, more field case studies by researchers worldwide are needed to contribute to the evaluation of the new criteria so that further improvements can be made before being incorporated as the standardized evaluation criteria of CSL in the future.

5.0 AUTHOR CONTRIBUTIONS

Nur Hidayah Che Rosli: Writing- Original draft preparation

Dayang Zulaika Abang Hasbollah: Writing- Reviewing and Editing

6.0 DATA AVAILABILITY STATEMENT

The data used to support the findings of this study are included in the article.

7.0 ACKNOWLEDGEMENT

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8.0 CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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