FINDING COMMON GROUND®

Terminology and Evaluation Criteria of Crosshole Sonic Logging (CSL) as applied to Deep Foundations*

Task Force
E. Anna Sellountou, Ph.D., P.E., M.ASCE, Chair
Joram Amir, Ph.D., C.E., D.GE, F.ASCE
Greg Canivan, P.E., M.ASCE
Les Chernauskas, P.E., M.ASCE
Bernie Hertlein, FACI, M.ASCE
Peter Kandaris, P.E., M.ASCE
Tim Kovacs, P.E., M.ASCE
Garland Likins, P.E., M.ASCE

October 2019

INTRODUCTION

Nondestructive testing of drilled shaft foundations via Crosshole Sonic Logging (CSL) is often performed as part of the quality assurance process to assess the soundness of concrete. The intent of CSL testing is to identify irregularities such as soil intrusion, necking, soft bottom, segregation, voids and other defects that could result in poor structural performance of the foundation. Over time, CSL rating criteria based on first arrival time and relative energy have incorrectly evolved to often be the sole means of determining the acceptability of a shaft. Some of these criteria have found their way into regulatory agency specifications, with acceptance values often differing from agency to agency.

---

* ***Disclaimer and Limitation of Liability****-*

This white paper has been prepared in accordance with recognized engineering principles and should not be used without the user's competent knowledge for a given application. The publication of this white paper by Deep Foundations Institute (DFI) is not intended to warrant that the information contained herein is suitable for any general or specific use.

Neither DFI nor any of its members, directors, employees or other representatives shall be liable for damages arising out of or in connection with the use of information, processes, or products contained herein even if advised of the possibility thereof. This limitation of liability shall apply to all damages of any kind, including, without limitation, indirect, special, incidental and consequential damages, punitive damages, loss of data, income, profit or goodwill, attorneys' fees, litigation costs, loss of or damage to property and claims of third parties, even if DFI is advised of the possibility of such damages. This limitation of liability applies to claims based on breach of contract, breach of warranty, tort (including negligence), product liability or otherwise.

The contents of this white paper reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of DFI. This white paper does not constitute standard specifications or regulations.

The purpose of this document is to review the state of the practice (including experience gained over the past 20 years), propose improved CSL rating criteria and make recommendations for additional assessment, as well as educate the industry on the proper interpretation of CSL test. **CSL test results alone should not be the sole means of rejecting or accepting a shaft.**

A task force of industry exerts was formed to review the existing CSL rating criteria and propose improvements where appropriate. The recommendations presented herein are the consensus of the task force, which believes that they should be incorporated into future criteria, codes and specifications.

This paper was produced as a joint effort between the Codes and Standards Committee, the Drilled Shafts Committee and Testing and Evaluation Committee. A task force was authorized under Testing and Evaluation Committee. The task force contributed their expertise in web-based discussions often every two weeks over a period of three years. Interested participants were invited to participate at any time. The document had two rounds of broad industry review, two rounds of DFI Technical Advisory Committee reviews, and a Public Comments process. All comments were considered in producing the final document.

LITERATURE REVIEW

The construction of cast-in-situ deep foundation elements can introduce unintended structural flaws that, depending on size and location, can compromise the foundation performance. The causes of such flaws have been discussed by several researchers including Baker and Khan (1971), Reese and Wright (1977) and O'Neill (1991). **Authors of the various references cited here often use the terms "flaw" and "defect" indiscriminately or interchangeably.** The terminology used throughout this section is the terminology used in the original references; recommended terminology is provided subsequently in this document.

O'Neill (1991) categorized the causes of structural defects into five (5) categories, namely defects arising from

- general construction problems,
- drilling problems,
- casing management problems,
- slurry management problems, and
- design deficiencies.

O’Neill does not separately categorize defects arising from concrete placement, as they are included in all of the above categories.

The most commonly used testing methods for evaluation of the structural integrity of drilled deep foundations are:

- Low Strain Integrity Testing (ASTM D5882),
- Crosshole Sonic Logging (ASTM D6760),
- Gamma-Gamma Density Logging, and
- Thermal Integrity Profiling (ASTM D7949).

State-of-practice Non-Destructive Test (NDT) methods can detect some of these larger flaws, whereas smaller flaws can remain undetected. O’Neill and Sarhan (2004) state that large voids and soil inclusions, occupying more than 15% of the cross-sectional area of the shaft, can usually be detected with state-of-practice nondestructive evaluation methods. In their paper, the authors consider all flaws that can be identifiable by NDT methods as “not minor”, by definition. Sarhan and O’Neill (2002a) mention that “*flaws large enough to be detected by non-destructive evaluation methods (NDE) are almost always repaired or the drilled shaft is replaced*”, whereas the effect of minor undetectable flaws should be accounted for in the design.

Several researchers and industry practitioners have investigated the ability of NDT methods to detect flaws introduced during the construction process. Sarhan et al. (2002b) summarize some of these studies in their paper “Flexural Behavior of Drilled Shafts with Minor Flaws”. As presented in their summary:

- Baker et al. (1993) conclude “down-tube” techniques could detect flaws that occupied only 15% of the cross-sectional area of drilled shafts;
- Amir (personal communication) indicates cross-tube ultrasonic tests could reliably detect soft defects that comprise about 9% of the cross-sectional area of a 0.76m (30-in) diameter drilled shaft;
- Chernauskas and Paikowsky (1999 and 2000), through several case histories and using various NDT methods, conclude that these methods are useful in detecting flaws comprising 20% or more of the cross sections of drilled shafts;
- Iskander et al. (2001) conclude down-tube methods are generally able to identify flaws exceeding 10% of the cross-sectional area; and
- Sarhan et al. (2000) conclude that, after a field study on six full-scale drilled shafts installed in stiff clay and employing pre-installed void flaws of areas ranging from 10.7% to 16.7% of the cross-sectional area, void-type flaws occupying areas up to 15% of the cross-sectional area could

remain undetected. The study employed NDT tests ranging from surface techniques to down-tube methods.

Amir and Amir (2009) found, in both controlled site testing and finite element modeling, that modern CSL equipment can detect flaws occupying 10% of the pile's cross-section, provided the flaw is within the reinforcing cage.

The previously referenced cross-sectional area percentages refer to defects located inside the reinforcing cage and confirm O'Neill's findings that flaws occupying as little as 15% of the cross-sectional area can be detected. CSL methods can only detect defects when such defects are in the path between access tubes; and since the tubes are generally attached to the inside of the cage, defects outside the cage in the cover zone cannot be detected. If the entire cover is missing, the cross-section percentage can be significantly greater than 10% and be undetected.

Baker and Khan (1971) suggest the use of multiple NDT methods wherever feasible, as this approach will produce more definitive answers than the use of a single NDT method.

Several studies investigate the percentage of drilled shafts with detectable defects. O'Neill and Sarhan (2004) report rejection of 20% of drilled shafts in the Caltrans database constructed during the period of 1996-2000 under drilling slurry due to flaws identified by NDT methods. By their definition, flaws identifiable by NDT are "not minor". Their paper reports other case study findings with similar percentages of shafts with identifiable flaws (18%, 20%, etc.). Faiella and Superbo (1998) present a study where CSL testing detected flaws in 25% of drilled shafts from 37 sites in Italy. The database included 6800 shafts.

Jones and Wu (2005) report in their paper that 56% of 299 drilled shafts tested with CSL in Mid-Western US presented some type of anomaly (defined as at least a 25% wave speed reduction). Most of the shaft anomalies (81%) were located within the top or bottom one meter of the shafts. Jones and Wu (2005) also comment that coring is problematic, is difficult to perform correctly, and may not necessarily confirm a CSL anomaly.

Camp et al. (2007) compiled a database of 400 CSL-tested shafts installed by ten different contractors in South Carolina. The authors found 33% of the tested shafts contained an anomaly (defined as at least a 20% wave speed reduction) and that 90% of anomalies were within the top or bottom two shaft diameters. Camp et al. (2007) also make a distinction between anomalies and actual defects that compromise the performance.

The real question to be answered is whether these flaws or defects affect the intended performance of the shafts. Proper defect characterization and assessment of their effect in the load-bearing capacity of the shaft should include analyzing the defects' shape, size and location, and other factors like the geotechnical capacity of the shaft, whether the defect is on the compression side in the flexural zone, etc. Defects occurring in zones of high load transfer and high internal stresses are critical. Therefore, defects occurring at the top of the shaft will likely affect foundation performance and are of greater concern. When combined with the O'Neill and Sarhan (2004) survey conclusion (the most probable location of a flaw to be within the upper five diameters of the shaft), the critical aspect of the proper evaluation of defects becomes obvious. Defects at the bottom of the shaft are important when end bearing is part of the design.

Sarhan et al. (2002b) investigated the effect of the shape of structural defects on the flexural capacity of the shaft in an experimental study including small scale and large-scale laboratory tests. The authors analyzed two types of flaws commonly observed in drilled shafts resulting from soil cuttings floating on the rising column of fluid concrete in a slurry pour:

- Type A flaw has most of its area lying outside of the reinforcement cage (only a small area is penetrating inside the cage), whereas
- Type B flaw penetrates inside the cage into the core of the shaft.

Both flaw types occupy 15% of the gross cross-sectional area (the limit of identifiable versus unidentifiable flaw size through NDT methods according to O'Neill). It was shown that the Type B void flaw associates with the greatest reduction in flexural resistance under flexural loading conditions. More specifically, the Type B flaw results in a reduction in flexural resistance of 32%, whereas the Type A flaw has a reduction of only 17%. The results of the full-scale laboratory tests show reduction in flexural resistance for the Type B flaw of 27%. The research demonstrates that the shaft acceptance process must consider both flaw location and mode of foundation resistance, not just flaw size.

O'Neill (1991) in the context of his paper defines defects "*as structural flaws that may or may not affect the serviceability of the foundation. Only a careful evaluation of the location and extent of defects relative to zones of high load transfer and high internal stresses can determine whether the defect requires repair*". Many parameters (i.e. shape, size, and location of the defect, maximum stresses expected on the shaft, redundancy of the shaft, design parameters such as friction shaft or end-bearing shaft, seismic and uplift concerns) must be evaluated upon detection of flaws/defects via NDT testing in order to understand their effect on the performance of the shaft and whether the shaft should be accepted as is, repaired or rejected.

Webster et al. (2011) indicate that structural problems detected by NDT methods are significant and their effect on structural capacity has to be evaluated and, if deemed necessary, mitigated. They suggest a classification system for both CSL testing and low strain integrity testing. Many state departments of transportation currently use their CSL classification system and includes the separate terms of "flaw" and "defect". The authors also discuss NDT result evaluation techniques and mitigation solutions - e.g. flaws have to be addressed if they are indicated in more than 50% of the profiles, whereas defects must be addressed if they are indicated to affect more than one profile and involve at least three tubes.

Rohrbach et al. (2012) list various factors unrelated to concrete quality that can cause anomalies in CSL test results and adversely affect their interpretation. The authors propose that improvements are needed in the terminology that CSL testing providers use in order to avoid terms that may be ambiguous or controversial. They also call for increased communication between CSL testing providers and Engineers of Record to provide the information necessary for the proper use of engineering judgment in drilled shaft acceptance.

The question of which CSL results may indicate an anomaly is addressed by the Chinese and French CSL standards (Amir & Amir, 2008), where both refer to First Arrival Time (FAT) and Relative Energy (a measure of the signal intensity at the receiver probe). Alternately (and as a matter of policy), ASTM D6760 avoids interpretation of test results and leaves shaft acceptance to engineering judgment. Likins et al. (2004) state that, although CSL testing is straightforward, "*there is no general common consensus (in most parts of the world) concerning what reduction in amplitude or delay in first arrival time defines a defect*". The authors state that a 20% FAT delay is a commonly suggested limit for a defect (e.g. French code AFNOR NF P94-160-1) and suggest that either the signal amplitude or relative energy should be included in CSL rating criteria. They also recommend shafts with "local partial defects" (shafts not designated as "good" or clearly "defective") be analyzed by 3D tomography in order to gain a clearer visual-spatial illustration of defects, allowing more effective remediation or evaluation by the structural engineer.

The current CSL rating criteria guideline developed for the Federal Highway Administration called the Concrete Condition Rating Criteria (CCRC) is based on the percentage of velocity (or wave speed) reduction from the nominal, rather than FAT delays. The CCRC has been modified by several state departments of transportation (DOTs) with respect to the range for

“Questionable” concrete. Some state DOTs use velocity reductions of 10% to 20%, while others use 10% to 25% to indicate questionable concrete. Some authorities define “Poor” concrete as velocity reductions or FAT delays greater than 30%. Note that a 30% reduction in velocity is not equivalent to a 30% increase in FAT (see Table 1). Still, others utilize a combination of FAT delays (or velocity decreases) with energy reductions.

Table 1: Relation between FAT increase and Velocity Decrease

% FAT increase	% velocity decrease
10	9
11	10
15	13
18	15
20	17
25	20
30	23
33	25
35	26
40	29
43	30
45	31

DISCUSSIONS AND RECOMMENDATIONS

Over time, 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. Some of these measures have found their way into regulatory agency specifications, with acceptance values often differing from agency to agency. The literature review notes a lack of quantitative assessment for these measurements, suggesting that “hard” boundary values presently used by many for shaft acceptance overstep our industry’s current state of knowledge. Recommendations contained herein are based on the collective experience of the authors over the past 20 years. They are intended to replace current CSL rating criteria and place CSL testing in proper perspective, as part of the evaluation for shaft acceptance.

TERMINOLOGY

This document updates shaft evaluation using CSL rating criteria to incorporate industry experience collected since their inception, with the purpose of improving the current state-of-practice. The following sections present new recommended CSL rating criteria and exclude the use of words

such as “flaw” and “defect”. There are opinions in the industry that the term “defect” should not be used until an irregularity has been proven likely to significantly reduce the shaft’s capacity or durability.
Researchers and engineers often use the terms “flaw” and “defect” indiscriminately or interchangeably. Moreover, some practitioners assume an “anomaly” to be a “defect”. The following definitions are proposed in an effort to eliminate misuse or confusion in the industry among these terms (Figure 1):

Anomaly: Abnormal data that deviates from expectations, and may indicate a flaw or defect.

Flaw: Any imperfection in the planned shape or material of the foundation that may not necessarily affect its performance.

Defect: Any flaw that, because of size, location and inferred concrete properties, will have a significant adverse effect on the performance of the foundation.

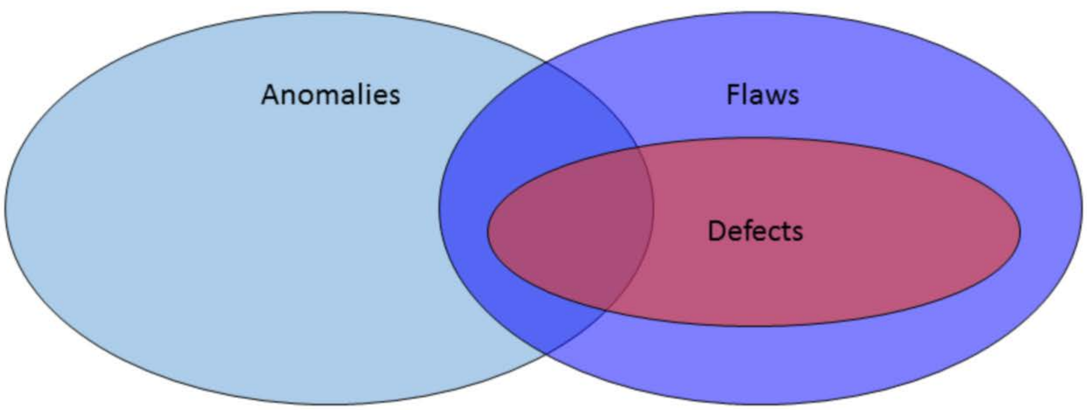

Figure 1: Anomalies, flaws and defects

This paper defines other important terms discussed as follows:
Profile: The graphical representation versus depth of the CSL data between two tubes.

First Arrival Time (FAT): The time required for the leading edge of the ultrasonic pulse to travel from the transmitter to the receiver.

Relative Energy (RE): The relative signal strength of the pulse arriving at the receiver compared with a reference signal strength.

Tomography or tomographic analysis: A mathematical procedure applied to CSL data in order to provide a 2D or 3D map of the wave speed data (and therefore a visual identification of potential flaws or defects within a shaft).

Engineer of Record: A professional who is responsible for acceptance of the foundation. Foundation acceptance requires the evaluation of a wide array of information and should not be based on the CSL data alone.

ASSESSING CSL DATA ANOMALIES

From the reviewed published literature, the authors of this document suggest that the use of the word “anomaly” be restricted to describing only the test data, i.e. the CSL test data are either acceptable or abnormal. Where abnormal test data are observed, the first steps taken by the tester and/or the analyst must be to verify proper function and operation of the test equipment, according to the appropriate standards (such as ASTM D6760) and manufacturer’s recommendations.
Possible causes of abnormal CSL results (not necessarily related to flaws and defects in the shaft) include but are not limited to

- insufficient wait time between concrete placement and testing;
- tube disturbance while the concrete is setting;
- non-parallel tube alignments or over-sized tube diameters;
- the differential rate of hydration curing (e.g. concrete mix variability, shaft stick-up in water or air, moving water etc.);
- bleed water channels along the interface between the tubes and the concrete, especially in cased shafts;
- structural attachments within the shaft and other interferences within the rebar cage (e.g. multiple concentric cages, cage stiffeners, embedded bi-directional load cells, etc.);
- tubes placed outside the reinforcing cage;
- tube connectors, tapes and foreign substances on the tubes;
- concrete mix quality (e.g. shrinkage cracks);
- debonding; and
- lack of water or insufficient water in one or more access tubes at the time of testing.

If any of the aforementioned reasons are applicable, they should be discussed in the report. This information is vital so that the Engineer of Record can assess the validity of the CSL data results relative to other installation records and testing performed on the shaft.

PROPOSED CSL RATING CRITERIA

CSL data should be used as a part of the shaft acceptance process, and thus needs some form of classification to delineate acceptable versus abnormal results. Once the possibility of equipment malfunction or improper testing procedures has been eliminated, CSL test results for each profile should be classified into one of the following categories:

Class A: Acceptable CSL test results.
Class B: Conditionally acceptable CSL test results.
Class C: Highly abnormal CSL test results.

The definition of each Class is as follows (see Figure 2):

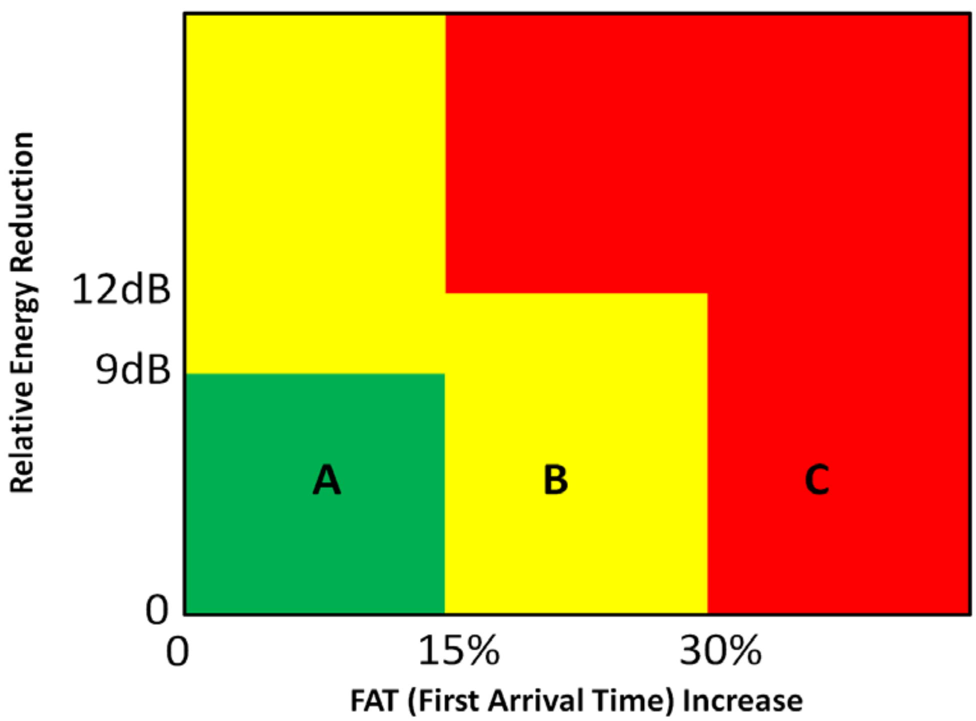

Figure 2: Graphical representation of the proposed CSL rating criteria

Class A: Acceptable CSL test results

For any section of the profile

> First Arrival Time (FAT) increases are less than 15% of the local average FAT value, AND reductions in relative energy are less than 9 dB of the local average value of relative energy.

Recommendations
Data within normal ranges. No additional assessment needed.

Class B: Conditionally acceptable CSL test results
For any section of the profile

First Arrival Time (FAT) increases are between 15 and 30% of the local average FAT value, AND reductions in relative energy are less than 12 dB of the local average value of relative energy.
OR
First Arrival Time (FAT) increases are less than 15% of the local average FAT value, AND reductions in relative energy are greater than 9 dB of the local average value of relative energy.

Once abnormal CSL data are observed within the shaft, an assessment is needed to determine the significance of the results relative to shaft performance.
The number of affected CSL profiles at any given depth should be considered when evaluating Class B results. The tester should report the number of Class B occurrences and their respective locations. **These observations are not to be interpreted as a single overall evaluation of the shaft as being Class B.**

Recommendations (the following are recommended in no particular order and as appropriate):

- If the abnormal CSL data are observed near the top of the shaft (possible tube debonding), consider flooding the top of the shaft with water to restore the bond. Retesting after at least 30 minutes allows the water to seep down the interface between the tubes and the concrete and may improve the CSL results.
- For shafts with six or more access tubes and where not all tube combinations were tested during the original investigation, additional testing including the remaining tube combinations can improve delineation of any potential flaws.
- Class B results suggest that a detailed desktop evaluation may find the shaft as acceptable for the intended function. The desktop evaluation should consider:
    - the number of affected profiles, depth and vertical extent of affected zones, and severity (proximity to the upper or lower limits of Class B);
    - low or high concrete strength (a low overall estimated wave speed, even if consistent with depth, may indicate low strength concrete. Similarly, a high overall estimated wave speed may indicate higher strength concrete and should be considered when

evaluating local FAT delays in relation to the application of the CSL results. Wave speed should be evaluated preferably from the major diagonal profiles. Perimeter profiles with shorter tube spacings are more sensitive to errors related to tube alignment and the path length through water within the tubes.); and
    - construction records.
- Tomography should be considered where it may help to define the extent of the affected zone as accurately as possible.
- If the concrete is too young or retarders were used in the mix, retesting after a sufficient waiting period could improve test results. If the data improve significantly, then the Class B result can perhaps be accepted, particularly if the result is now near the lower Class B limit.
- The Engineer of Record may recommend retesting using another independent tester.
- Consider performing other tests having complementary capabilities. Depending on the horizontal extent and vertical location of the affected zone, use of alternative testing methods or investigations such as low strain impact integrity testing (ASTM D5882) may provide additional information for the foundation assessment.
- Near-surface excavation could be done to facilitate visual inspection for necking. Additionally, sampling through the side of the shaft (i.e. by chipping) for contaminated concrete may help to further define the extent and nature of the flaw.
- If after retesting, the Class B CSL result is still near the upper rating criteria limit given in Figure 2 and occurs in many profiles, consideration for additional recommended measures as presented in the following discussion of Class C would be prudent.

Class C: Highly abnormal CSL test results

For any section of the profile

First Arrival Time (FAT) increases are greater than 30% of the local average FAT value.

OR

First Arrival Time (FAT) increases are greater than 15% of the local average FAT value, AND reductions in relative energy are greater than 12 dB of the local average value of relative energy.

Once anomalous data are observed within the shaft, an assessment is needed to determine the significance of the results relative to shaft performance.

The number of affected CSL profiles at any given depth should be considered when evaluating Class C results. The tester should report the number of Class C occurrences and their respective locations. **These observations are not**

to be interpreted as a single overall evaluation of the shaft as being Class C.

Class C results typically need more evaluation, often requiring an assessment by the Engineer of Record and have a greater likelihood of requiring more invasive field testing and potentially shaft remediation.

<u>Recommendations</u>

- Follow all relevant Class B recommendations listed previously, plus consider performing a direct assessment of concrete quality and strength:
    - Core sampling may help to further define the extent and nature of the affected zone. If coring is performed, the selection of the core diameter should consider aggregate size, testing purpose and potential remediation options.
    - Perform compressive strength testing of core sample(s) from the affected zone. Compare test results with the specified minimum design strength, as well as with the strength of samples from a “normal” zone.

SHAFT ACCEPTANCE

The CSL testing specialist has been contracted to perform a specific test using well-established CSL procedures (ASTM D6760) and report findings in the form of arrival times, relative energy and a “waterfall diagram” for each tube combination profile. The client or specifying agency should understand that the CSL testing specialist is rarely provided with installation records or foundation design parameters. Therefore, the CSL testing specialist is usually not in a position to decide shaft acceptability. The Engineer of Record and the Design Team, with possible feedback from the CSL testing specialist, should review all the CSL data and construction records to determine the likely effect on foundation performance and decide shaft acceptability.

SUGGESTIONS FOR FUTURE RESEARCH

The literature review highlights the lack of quantitative assessment relating CSL test results (FAT increase and relative energy) to deficiencies in reinforced concrete drilled shaft foundations. The problem is compounded by the proliferation and variety of standards for evaluation of CSL results. Moreover, FAT increase and energy reduction limits noted herein are the collective experience of the authors and reflect the general bounds of current guidelines and long-time industry experience. The goal of this document is to propose improved CSL rating criteria and help in adopting more uniform standards. However, this is intended to be a living document and the following suggestions are provided to focus future research studies to further improve the proposed CSL rating criteria:

- Perform analyses (statistical or other quantitative approaches) to evaluate FAT increase and/or energy decrease limits in relation to foundation deficiencies (flaws/defects). A quantitative assessment of existing empirical guidelines is recommended, encompassing both existing and new data via field case studies.
- Quantitatively assess the relative importance of FAT increase versus energy decrease to determine if one or both should be used as CSL rating criteria.
- Perform analysis to determine a quantitative relation between energy reductions and concrete strength and condition.
- Perform assessment in large diameter shafts to quantify the advantage of testing all profiles.

CONCLUSIONS

There are no universal or standard criteria to evaluate CSL test results. The current CSL rating criteria developed for the Federal Highway Administration called the Concrete Condition Rating Criteria (CCRC) is based on the percentage of velocity (or wave speed) reduction from the nominal, rather than the proposed FAT delays. The CCRC is outdated and does not reflect the collective industry experience and research over the last 20 years since CCRC was originally developed. FAT delays are recommended instead of velocity reductions because the tubes are often not parallel, and therefore the velocities calculated from top spacings may not be accurate.
Based on this task force’s collective experience the CSL rating criteria proposed herein present an improvement over commonly used criteria. More specifically:

- Terminology is improved to avoid ambiguous or misused terms like “anomaly”, “defect”, “questionable” etc. that often lead to improper interpretation or application of CSL test results.
- CSL rating criteria are simplified to three categories and thresholds are updated to reflect accumulated industry experience since the inception of the original rating criteria.
- Differentiation is made between abnormal CSL test results and shaft acceptability. The tester should report the number of Class B and C occurrences and their respective locations. **These observations are not to be interpreted as a single overall evaluation of the shaft as being Class B or C**. The Engineer of Record and the Design Team, with possible feedback from the CSL testing specialist, should review all

the CSL data and construction records to determine the likely effect on foundation performance and decide shaft acceptability.

- CSL test results alone should not be the sole means of rejecting or accepting a shaft.
- Recommendations are given in a step-by-step fashion to assist the engineer in resolving any potential issues arising from the CSL test results.

The recommendations presented herein are the consensus of the task force, which believes that they should be incorporated into future criteria, codes and specifications. These guidelines are intended as a living document. As more research and experience are accumulated, the criteria recommended herein can be further improved.

ACKNOWLEDGMENTS

The assistance, comments, encouragement and interest in this project from DFI and their technical committees (Augered-Cast-In-Place Piles, Codes and Standards, Drilled Shafts, and Testing & Evaluation) are gratefully appreciated. The editorial expertise of Mary Kandaris improved the final document.

REFERENCES

1. Amir, J.M and Amir, E.I. (2008). “Critical Comparison of Ultrasonic Pile Testing Standards,” *Proc. 8th Intl. Conf. on Application of Stress Wave Theory to Piling*, Lisbon, pp. 453-457.
2. Amir, J.M. and Amir, E.I. (2009). ”Capabilities and Limitations of Cross Hole Ultrasonic Testing of Piles,” *Proc. IFCEE*, Orlando, FL.
3. ASTM D5882-16, “Standard Test Method for Low Strain Impact Integrity Testing of Deep Foundations”, ASTM International, West Conshohocken, PA, 2016, www.astm.org
4. ASTM D6760-16, “Standard Test Method for Integrity Testing of Concrete Deep Foundations by Ultrasonic Crosshole Testing”, ASTM International, West Conshohocken, PA, 2016, www.astm.org
5. ASTM D7949-14, “Standard Test Methods for Thermal Integrity Profiling of Concrete Deep Foundations”, ASTM International, West Conshohocken, PA, 2014, www.astm.org
6. Baker, C. N., and Khan, F. (1971). “Caisson Construction Problems and Correction in Chicago,” *Journal of the Soil Mechanics and Foundation Division,* ASCE, Vol. 97, No. 2, pp. 417-440.
7. Baker, C. N., Drumright, E. E., Briaud, J-L., Mensah, F. D., and Parikh, G. (1993). “Drilled Shafts for Bridge Foundations,” *Publications No. FHWA-RD-92-004*, Federal Highway Administration, Washington DC, 336 pages.

8. Camp III, W. M., Holley, D. W., and Canivan, G. J. (2007). "Crosshole Sonic Logging of South Carolina Drilled Shafts: A Five Year Summary," *ASCE Geo Denver*, Denver CO.
9. Chernauskas, L. R., and Paikowsky, S. G. (1999). "Deep Foundation Integrity Testing: Techniques and Case Histories," *Civil Engineering Practice*, Vol. 14, No.1, Boston Soc. of Civil Eng Sec/ASCE, pp. 39-56.
10. Chernauskas, L. R., and Paikowsky, S. G. (2000). "Defect Detection and Examination of Large Drilled Shafts using a New Cross-Hole Sonic Logging System," *ASCE Specialty Conference, Performance Verification of Constructed Geotechnical Facilities*, University of Massachusetts, Amherst, April 9-12.
11. Faiella, D., and Superbo, S. (1998). "Integrity Non-Destructive Tests of Deep Foundations by Means of Sonic Methods - Analysis of the Results Collected on 137 Sites in Italy," *Proceedings of 3rd International Geotechnical Seminar on Deep Foundations on Bored and Auger Piles*, Ghent, Belgium, 19-21 Oct., Balkema, Rotterdam, pp. 209-213.
12. Iskander, M., Roy, D., Ealy, C., and Kelly, S. (2001). "Class-A Prediction of Construction Defects in Drilled Shafts," *Transportation Research Record 1772,* Paper No. 01-0308, Washington DC.
13. Jones, W. C., and Wu, Y. (2005). "Experiences with Cross-Hole Sonic Logging and Concrete Coring for Verification of Drilled Shaft Integrity," *Proc. GEO Construction Quality Assurance/Quality Control Tech. Conf*., Dallas-Ft. Worth TX, pp. 376-387.
14. Likins, G., Webster, S., and Saavedra M. (2004). "Evaluation of Defects and Tomography for CSL," *Proceedings of the Seventh International Conference on the Application of Stresswave Theory to Piles,* Petaling Jaya, Selangor, Malaysia, pp. 381-386.
15. O'Neill, M.W. (1991). "Construction Practices and Defects in Drilled Shafts," *Transportation Research Record 1331*, Washington DC, pp. 6-14.
16. O'Neill, M. W., and Sarhan H. A. (2004). "Structural Resistance Factors for Drilled Shafts Considering Construction Flaws," *Current Practices and Future Trends in Deep Foundations*, GSP 125 ASCE, pp. 166-185.
17. Reese, L.C., and Wright, S.J. (1977). "Drilled shaft Manual: Vol 1: Construction Procedures and Design for Axial Loading," *Report IP77-21, FHWA*, US Department of Transportation.
18. Rohrbach, M. A., Kovacs, T. R., and Saidin, F. (2012). "Uncertainties in CSL Test Interpretations and Recommendations towards a More Efficient Process," Proceedings of the DFI 37th Annual Conference, Houston TX.
19. Sarhan, H. A., O'Neill, M. W., and Tabsh, S. W. (2000). "Structural Resistance Factors for Drilled Shafts with Minor Anomalies-Deterministic Study," *Department of Civil and Environmental Engineering*, University of Houston, Houston, Texas.

20. Sarhan, H. A., and O'Neill, M. W. (2002a). “Aspects of Structural Design of Drilled shafts for Flexure,” *ASCE Intl. Deep Foundation Cong.*, GSP 116, Orlando FL, pp. 1151-1165.
21. Sarhan, H. A., Tabsh, S. W., O'Neill, M. W., Ata, A., and Ealy, C. (2002b). “Flexural Behavior of Drilled Shafts with Minor Flaws,” *Proc. Intl. Deep Foundation Congress*, GSP No.116, Reston, VA, pp. 1136-1150.
22. Webster, K., Rausche, F., and Webster, S. (2011). “Pile and Shaft Integrity Test Results, Classification, Acceptance and/or Rejection,” *Compendium of Papers of the Transportation Research Board (TRB) 90th Annual Meeting*, Washington, DC.