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Cross hole sonic test results for analysis of pile load test

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Abstract

Quality of concrete for pile can be checked using Cross-hole Sonic Logging (CSL) Test. A processing method wide-band CSL data is presented herein. First Time Arrival (FTA) is an important consideration. In pile capacity analysis or CSL analysis, it is assumed that pile cross section is uniform with uniform value of elastic modulus of concrete but in real practice both are non-uniform. The procedure identifies the location accuracy and further characterizes the features of the defect. FTA is used to find out the location of the distress in the pile. This method identifies the exact location of any void or defect inside the rebar cage of a drilled shaft. This method provides a significant improvement to current techniques used in quality control during construction of bridges. In this present paper, the analysis has been carried out based on uniform and non-uniform values of pile cross section and E value of concrete. Cross hole sonic and pile load test using O-Cell were carried out on same pile at 7 and 28 days of concreting. Same pipes were used for base grout after cross hole sonic test. These results were used to analyze O-cell test results based on a case study and presented in this paper. The distribution of skin frication and skin friction force has also been presented herein with both uniform and non-uniform cross section and E values of concrete. Based on the field test results and analysis a simplified methodology, has been proposed in this paper, for development of Equivalent Top Down Loading with consideration of elastic shortening of pile and surrounding soil for both cases i.e., uniform and non-uniform E values and pile cross sections.

Keywords: Osterberg cell, Bidirectional load test, Cross-hole sonic logging, First time arrival, Pile integrity test

1 Introduction

Generally the rivers widen near sea area than that at the origin of the river at hill. Navigation vehicles use the river and therefore wide spans of bridges are required at these locations. Soils near sea area generally have poor bearing capacity. Due to heavy load transfer, open foundation is not a feasible solution and hence deep pile foundations are required. Several methods of construction exist today for the construction of drilled shafts (Reese and O'Neill 1999). The most widely used method today is the wet method, i.e., shafts are cast under wet conditions using bentonite slurry in order to keep the borehole open vertical during drilling to avoid collapsing of soil and preventing proper casting of the concrete. Several defects in form of necking /bulging may be occurred. These defects occur due to failure of soft vertical strata after excavation of soil /during lowering of cage (Sarhan et al. 2003) and these defects occupying up to 15% of the cast in situ pile section could remain undetected. Camp et al. (2007) recorded that, out of 441 piles tested on different projects in South Carolina, around more than 70% of the projects had at least one pile containing a defect. Such defects in the integrity of the cast in situ pile can affect their pile capacity and ability to transmit the design loads and hence quality control of pile construction is a major important critical factor. Several methods are currently used to perform Non Destructive Testing (NDT) of deep foundations. CSL is a common and most reliable technique among the most common methods of NDT testing. Complete guideline is available in ASTM D 6760 (2008) It is observed that defects near the top of a drilled shaft will significantly affect its structural capacity due to unsound concrete. CSL is one of the most reliable techniques for determining the integrity of cast in-situ pile.

It is a NDT method which consists of ultrasonic signal transmission through the pile between two similar water filled tubes. The tubes are kept to the cage of reinforcement and cast forever into the pile. The total number of tube varies from two to four or more.

A transmitter and a receiver are dropped to the lowest point of the pile in separate tubes. Quantities of the signal transmission are captured @ 5 cm interval during rising of transmitter and receiver. Shapes are collected from all permutations of pipes. Flaws should be addressed if these are indicated in more than 50% of the profiles (Likins et al. 2007). Defects must be addressed if these are indicated in more than one profile.

1.1 Literature review

Li et al. 2005 stated that defects present in a pile may not be encountered during a Cross-Hole Sonic Logging (CSL) Test. Even when defects are indeed encountered, they may not always be detected. This paper proposes a probabilistic analysis procedure for evaluating the reliability of CSL, thereby providing a theoretical supplement to existing experimental evaluations of CSL. The reliability of this integrity testing method is represented by the inspection probability, which is expressed as the product of the encountered probability and the detection probability. Mathematical models to calculate the encountered probability are formulated and a detection probability model is suggested based on existing CSL test data. Several examples are presented to illustrate the proposed procedure. The results indicate that there exists a minimum detectable defect size below which the defect cannot be inspected. For a given number of access tubes, the minimum detectable defect size, as a percentage of the pile cross-sectional area, decreases with the pile diameter. The encountered probability can be taken as an index to determine the required number of access tubes. When the target encountered probability is specified as 0.95, three and four access tubes will be sufficient to encounter defects larger than 15 and 5% of the pile cross-sectional area, respectively.

Iskander et al. 2003 presented the results of nondestructive integrity tests (NDTs) and axial static load tests on drilled shafts constructed in varved clay at the National Geotechnical Experimentation Site in Amherst, Mass. The shafts were constructed with built-in defects to study: (1) the effectiveness of conventional NDT methods in detecting construction defects and (2) the effect of defects on the capacity of drilled shafts. Defects included voids and soil inclusions occupying 5–45% of the cross section as well as a soft bottom. Nine organizations participated in a blind defect prediction symposium, using a variety of

NDT techniques. Most participants located defects that were larger than 10% of the cross sectional area. However, false positives and inability to locate smaller defects and multiple defects in the same shaft were encountered. Static load tests indicated that (1) minor defects had little or no effect on skin friction; (2) a soft bottom resulted in a 33% reduction in end bearing relative to a sound bottom; and (3) reloading resulted in a 20–30% reduction in the geotechnical capacity.

1.2 Summary of literature review

From past study, it is observed that very limited studies were carried out on cross hole sonic test and its further uses to determine pile capacity. Therefore, there is a need of this study and it is also necessary to compare the test results obtained from conventional pile load test.

1.3 Basic principles of techniques

Cross-hole Sonic Logging (CSL) is a derivative of the Ultra-sonic Pulse Velocity (UPV) test. The sound wave velocity in concrete (V) is a function of the density and Young Modulus of concrete (Finno and Osborn 1997) as presented in the following Equation.

$$V = \sqrt{\frac{E(1-\mu)}{\rho(1+\mu)(1-2\mu)}} \tag{1}$$

Where,

E = Young's modulus (MPa);

p = Density (kilogram per cubic meter); and.

μ = Poisson's ratio.

The CSL method is an ultrasonic test that involves measuring the propagation time of ultrasonic signals between two probes in vertical tube /ducts in a shaft. These tubes were casted into a shaft during construction of cast in-situ pile.

The difference in signal coming time permits one to calculate and identify areas of low compactness of concrete. For the case of good concrete, pulse velocity is on the order of 4000 m/sec, depending on its ingredients. Concrete consists of soil, gravel, betonies or honeycombing which causes lower propagation velocity so that the presence of these irregularities is immediately observable. Signal reduction is sign of unsound quality zones because more energy is transmitted through sound concrete than through poor concrete.

The dynamic Young's modulus of elasticity (E) of the concrete may be determined from the pulse velocity and the dynamic Poisson's ratio using the following relationship (I S: 13311 1992):

$$E = \frac{\rho(1+\mu)(1-2\mu)V^2}{(1-\mu)} \tag{2}$$

Where,

E = Young's Modulus of concrete in MPa;

= Density in kg/m^3; and.

V = Pulse velocity in km/second.

The value of the dynamic Poisson's ratio varies from 0.20 to 0.35, with recommended value of 0.25 is adopted for calculation in this present study.

A typical defect identification and first time arrival is shown in Fig. 1.

1.4 Objectives and approach

The purpose of the present study is to present a method developed to detect the exact location of the defects after performing the CSL test at 7 days of concreting to determine E value of concrete and non-uniform cross sections at different depths of drilled shaft. To accomplish these objectives, a drilled shaft sample of around 100 m long pile with 2.5 m diameter was constructed with arrangement of cross hole sonic pipe arrangement (Four steel Pipes of 40 mm diameter). and O-Cell arrangement for CSL test and O-Cell Test. O-Cell test was conducted at 28 days of concreting.

The objectives of this present paper is also to determine unit skin friction for both uniform and non-uniform values of E and pile cross-section and preparation of equivalent top down loading graph and recommendation of pile capacity for both cases.

1.5 Quantity of concrete used

A pile of 100 m long and 2.5 m diameter was constructed. Excavation of soil was carried out using rotary Equipment with reverse air circulation method. Length of excavation was recorded using boring pipe of length segment of 2.5–3.0 m as shown Fig. 2 with sequence of numbering as shown in Fig. 2 so that exact depth of pile can be constructed. Length of

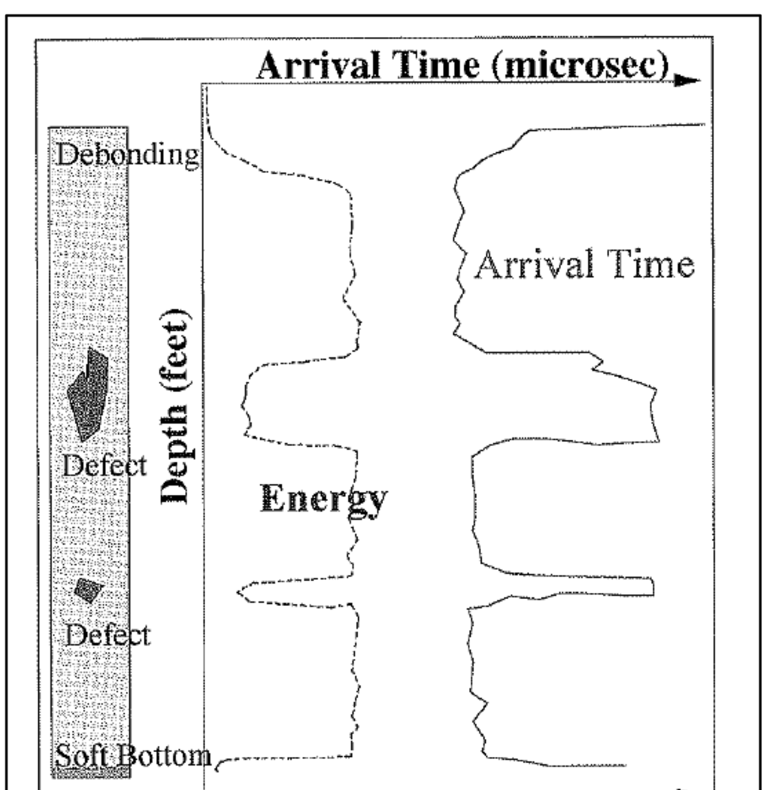

Fig. 1 Defect and FTA Graph

Fig. 2 Checking Excavation and Concrete Pouring Depth

excavation, after excavation of soil, before concrete works and after pouring each 49.1 m^3 with wire rope arrange for cross checking the depth of concreting. Volume of concreting recorded using wire rope method as shown in Fig. 2.

Concrete volume is noted after 10 m depth of pouring and presented in Table 1 and comparison of concrete volume with theoretical volume is presented in Fig. 3.

1.6 Cross hole test method

The principle of cross hole sonic testing has been applied for quality control of deep excavation. Although the sensitivity of the sensor is well known and often causes some difficulties in achieving reasonable results, the lack of a better solution has led to the method becoming well accepted and used worldwide where excavations must be supported by a fluid (Clean Water or like as water). In order to improve the actual state-of-the-art, Bauer has developed the Sonic Meter "RSM-SY8" which, amongst many other features self-calibrates over depth and thus gives more reliable results this Sonic meter follow the code ASTM- D 6760–02.

In order to test the ultrasonic integrity test of a completed bored pile, the ultrasonic signal of compression waves is analyzed between four parallel pipes, as shown in Fig. 4. Four Pipes are used to conduct this test.

Table 1 Volume and area of concrete executed

Pile length(m)	Cumulative Theoretical volume (m^3)	Cumulative Actual volume (m^3)	Actual cross section (m^2)
0	0	0	–
10	49.1	49.1	4.91
20	98.2	98.2	4.91
30	147.3	152.2	5.4
40	196.4	205.2	5.3
50	245.5	257.2	5.2
60	294.6	310.2	5.3
70	343.7	367.2	5.7
80	392.8	418.2	5.1
90	441.9	470.2	5.2
100	491	517.2	4.7

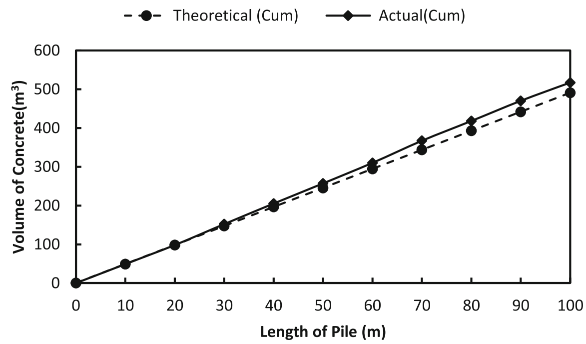

Fig. 3 Theoretical and Actual Volume of Concrete

1.7 Pre - preparation and execution of ultrasonic testing of bored piles

Special steel pipes (inner Ø 40 mm, outer Ø 44 mm) were installed on the reinforcement cage 2.5 m diameter of pile. The number and the position of the pipes recorded on the drawings. In no instance should the pipes be allowed to reduce the clear distances required for concrete flow. Since the initiation of the concrete pour is often critical to the quality of the whole placement it is recommended to curtail the pipes 50 cm above the cut of level of pile.

Pipes must be watertight at their base and joints. A reduction in the inner diameter is avoided, an additional sealing over the joints may affect the ultrasonic signal. Therefore,

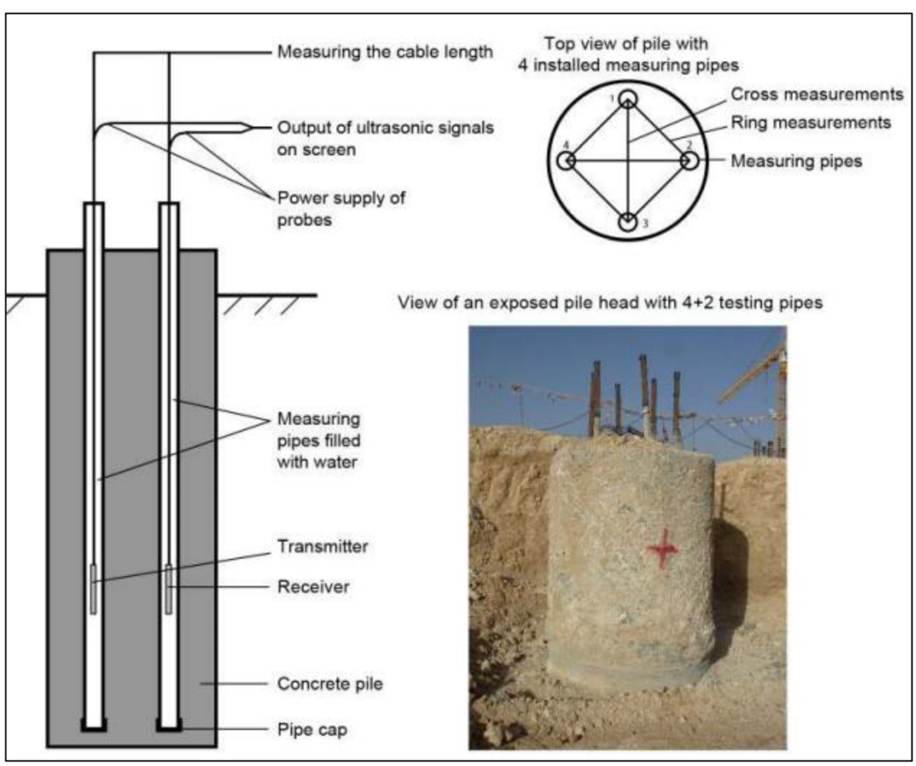

Fig. 4 Setting for Ultrasonic Integrity Testing of a Bored Pile

the position of the joints should also be recorded. Steel pipes with welded caps and crimped connections have proved effective.

Before concreting the pipes were be closed at their top.

After concreting, and before testing, the following steps are adopted:

- Cutting the testing pipes 5 cm–10 cm above the cut of level of pile.
- Measuring and recording of the actual distances between pipes at the accessible top of the pile.
- Checking the continuity of the pipes by using a steel bolt.
- Measuring and recording the maximum depth of each pipe.
- Filling of the pipes with clean water.

Closing the pipes until testing is commenced.

Typical photograph showing the progress of the test is shown in Fig. 5.

The testing commences after lowering both sensor to the designated lower reference elevation. The sensor are slowly (0.5 m/s) pulled upwards with a rope system. The same elevation of the sensor was verified frequently and any deviations recorded. The technical measurement regulations should follow the relevant standards (eg ASTM D6760–02).

In suspicious areas repeated or additional measurements were carried out.

1.8 Apparatus for test

Apparatus for Allowing Internal Inspection (Steel Pipe): Before concreting, access pipe typically have an internal diameter from 38 to 50 mm.

Apparatus for Determining Physical Test Parameters

- Weighted Measuring Tape
- Magnetic Compass

Apparatus for Obtaining Measurements:

- Sensor (Probes): Probes were allowed a generated or detected pulse within 100 mm of the bottom of the Steel pipe. The weight of each probe was in all cases to be

(1) (2)

Fig. 5 Progress of Cross Hole Sonic Test sufficient to allow it to sink under its own weight in the Steel pipe. The probe housing was waterproof to at least 1.5 times the maximum depth of testing.

- Transmitter Probe—the transmitter probe was generated an ultrasonic pulse with a minimum frequency of 30,000 Hz.
- Receiver Probe—the receiver probe was a similar size and compatible design to the transmitter probe and used to detect the arrival of the ultrasonic pulse generated by the transmitter probe.
- Signal Transmission Cables—the signal cables used to deploy the probes and transmit data from the probes were sufficiently robust to support the probes' weight. The cable was to be abrasion resistant to allow repeated field use and maintain flexibility in the range of anticipated temperatures. All cable connectors or splices were watertight

Apparatus of Wave Machine (RSM-SY8) for Processing Data—The apparatus for processing the data was a digital computer or microprocessor capable of analyzing all data to identify at least the first arrival and energy of the transmitted ultrasonic pulse at the receiver probe for each depth interval. The data were then be compiled into a single ultrasonic profile for each duct pair.

Apparatus Wave Machine (RSM-SY8) for Display of Measured Data—the apparatus was capable of displaying the raw receiver ultrasonic pulses to confirm data quality during acquisition. After data acquisition, the apparatus was capable of displaying the raw data of each ultrasonic pulse along the entire pile length. The apparatus displayed the processed ultrasonic profile.

1.9 Start test on selected pile

Check that the apparatus is functioning correctly prior to mobilizing to site.

Date of Testing—The tests were performed no sooner than 7 days after casting of concrete.

Preparing Steel pipe for Testing—the steel pipe was exposed and the protective top caps removed. Use a weighted measuring tape to measure and record the length of each pipe to the nearest 10 mm. The pipes were filled to the top with clean water.

Steel Pipes Documentation—Assign a systematic reference label to each pipe and prepare a reference sketch of the pipe layout using the magnetic compass or a site plan diagram. The as-built details of the pipe layout were recorded including measuring the center-to-center separations of the exposed pipes, make sequence number as clock wise like as 1–2, 2–3. 3–4, 4–1 or 1–2, 2–3, 3–4, 4–1, 1–3, 2–4, and measuring the pipe length exposed above the concrete. Typical diagram is shown in Fig. 6.

Sensor (Probe) Preparation—to obtain a good acoustic coupling between the sensors (probes) and the water in the pipes, the sensors (probes) were clean and free from all contaminants.

Check that test equipment and sensors (probes) are functioning correctly prior to actual testing by placing the sensors (probes) in two adjacent water filled access ducts of one pile just below the level of the shaft concrete and verifying that ultrasonic pulses are received in the recording apparatus.

Obtaining Measurements with the Apparatus:

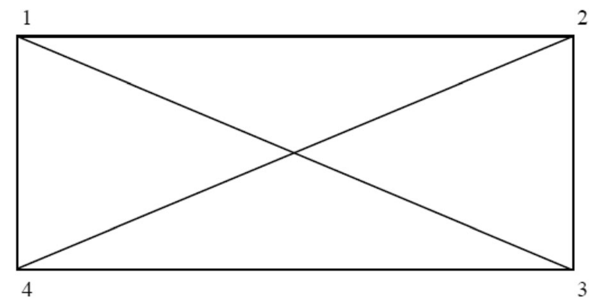

Fig. 6 Positions of Pipes

Pay due regard to safety and any special instructions or manufacturer's procedures pertaining to the particular apparatus employed.

Document the pair of access ducts being tested. Place the sensor (probe) cable pulley guides into the pipe. Insert the transmitter and receiver sensor into these pipes ensuring that the cables are engaged over the respective cable pulley guides fixed at the pipes tops.

Zero the depth-measuring device if required by the recording apparatus.

Carefully lowered the sensor (probes) down the pipes at a steady rate not exceeding 0.5 m/s, always keeping them at the same level, until one sensor (probe) reached the bottom of the pipe. Temporarily secure the cables at that level with the cables remaining in equal tension.

Sensor cable connect the Wave Machine, then power on & select program. Input the data such as Pile information (diameter, length of pipe, concrete grade etc) and steel pipe (access duct) information (inner diameter, outer diameter, length of pipe, bottom level, through speed, lift up speed etc).

Adjust the test apparatus, if necessary, selecting the power settings required for the pipe separation distance and concrete characteristics encountered such that an ultrasonic pulse with good amplitude can be consistently obtained in a portion of pile shaft of good quality.

Begin recording the ultrasonic pulses as the sensor (probes) are raised. Lift all probes by steadily pulling the sensor (probe) cables simultaneously at a speed of ascent slow enough to capture one ultrasonic pulse for each depth interval specified. If an ultrasonic pulse is not obtained for any depth interval, then the sensor (probes) was lowered past that depth and the test repeated until all depth intervals have an associated ultrasonic pulse.

1.10 Data quality checks

After completing data acquisition, view the ultrasonic profile obtained. Check the ultrasonic profile quality.

Compare the length of the measured ultrasonic profile with the measured access duct length. In comparing these measurements a correction should be made to account for the length between the bottom of the probe assembly to the exact point of the transmitter and receiver on the probe. The difference between the corrected measurements shall not exceed 1% of the measured length or 0.25 m, whichever is larger.

Ensure that the captured data is labeled with the pile identification, identification of the all access ducts for the data set, date of test, identification of the test operator, and any further necessary project information such as site and location details as requested by the specified. Store the data and information safely.

1.10.1 Completing the test

If the ultrasonic profile indicates an exception, then the suspect exception zone may be further investigated by special test procedures such as fan shaped tests, tests with the sensors (probes) raised at a fixed offset distance, or other tomographical techniques. The sensors (probes) shall be lowered to a depth of at least 1 m below the anomaly and raised to a depth of at least 1 m above the anomaly.

Cross-Hole Sonic Logging test was conducted just 1 day before conducting O-Cell load test. Based on ultrasonic pulse velocity, density of concrete and Poisson ratio of concrete, E Values at different depths were calculated using Eq. 2 and presented in Table 2 and Fig. 7.

Strains were measured during O-Cell load test which was conducted at 28 days of concreting. Strains were recorded for each load increment and plotted and shown in Fig. 8.

Unconfined compressive strength at 28 days, Fc was tested in the project site laboratory and test results was found to be 52.1 MPa and this strength was converted to cube strength by multiplying a factor, 0.8. Unit weight of concrete was found to be 2405 kg/m^3. E value is calculated using following ACI formula as mentioned below:

$E = 0.043\ ɣ^{1.5}\ fc^{0.5} = 0.043 \times 2405^{1.5} \times 42.3^{1.5} = 32{,}992$ MPa.40 mm diameter, 32 bar used and equivalent cross section is found = $(3.1.14/4) \times 2500 \times 2500 + [280/(3 \times 13-1)(3.1.14/4) \times 40 \times 40 \times 32 = 5{,}102{,}341\ mm^2$.

Forty millimeters diameter steel with 32 numbers were used in pile caging and pile stiffness, AE was calculated and found to be 168,340 MN. Unit skin friction has been determined from O-Cell test results and cross hole sonic logging test and presented in Table 3. Distribution of skin friction for the case of CSL is presented in Fig. 9. Similar graph can be plotted based on O-Cell Test Results. Strains of two adjacent strain gauges are considered and converted to compressive load using following formula, load = εAE(ε = Strain, AE = stiffness' of pile) as obtained from Eq. 3. The differences in compressive load and self-weight are used to determine skin friction from the theory of force equilibrium.

2 Result interpretation

The explanation of CSL results requires understanding of the proficiencies and restrictions of the method. Pile integrity calculation from CSL is based on the FAT of the

Table 2 E Value at different depth

Pile depth(m)	Average Velocity (km/S)	E (MPa)
0	–	–
10	4.1500	34,445.00
20	4.1400	34,279.20
30	4.1500	34,445.00
40	4.1700	34,777.80
50	4.1550	34,528.05
60	4.1673	34,733.33
70	4.1667	34,722.22
80	4.1600	34,611.20
90	4.1667	34,722.22
100	4.2067	35,392.09
Average=		34,685.93

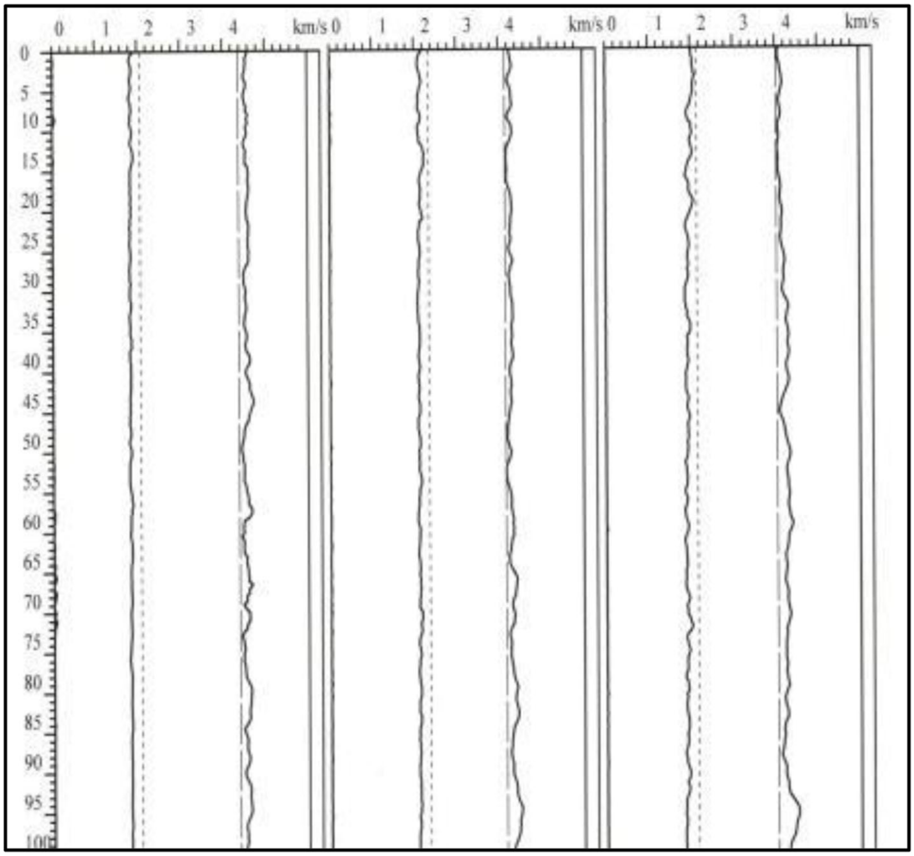

Fig. 7 Wave Speed VS Sound Speed

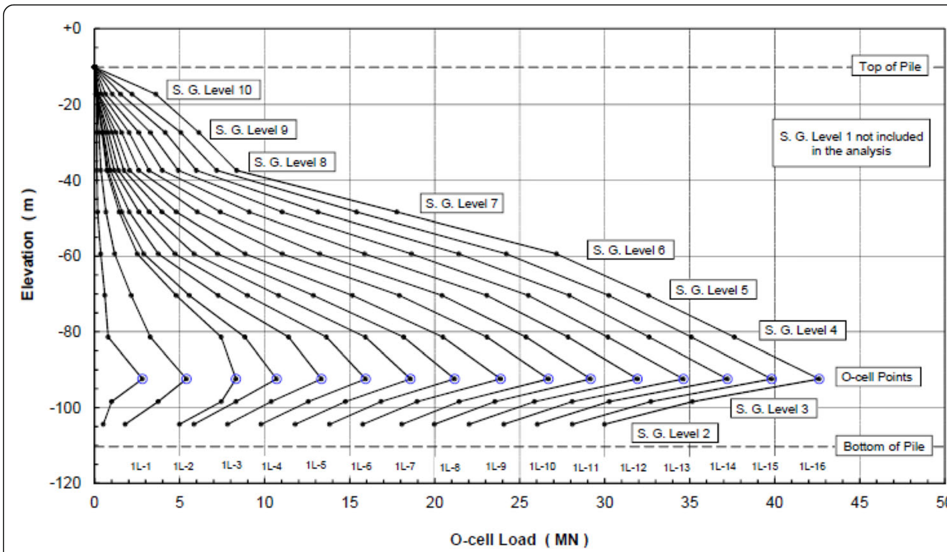

Fig. 8 Strain Recorded during O-Cell Load Test

Table 3 Comparison of unit skin friction

Description	Level	O-Cell Skin Friction (KPa)	Cross hole sonic skin friction (KPa)
Concrete top	12.33		
SG 10	17.26	25.56	25.70
SG 9	27.41	40.74	40.81
SG 8	37.41	26.06	30.60
SG 7	48.41	58.22	65.38
SG 6	59.41	102.57	104.73
SG 5	70.41	149.23	158.34
SG 4	81.41	94.49	124.47
O-Cell	92.41	15.68	40.23
SG 3	98.41	62.99	53.49
SG 2	104.41	129.69	142.35
SG 1	109.91	306.19	225.74
Average (KPa)=		91.95	91.99

Average values are found to be very close and hence Unit skin distributions are comparable

signal. The pulse velocity in concrete can be determined by dividing the distance between the pipes by the FAT.

Quality of concrete is determined based on rating mentioned in Table 4 (I S: 1311–1992). Considering Tables 2 and 4, it is observed that good quality of concrete was used in the construction of pile. Hence pile integrity is found to be satisfactory.

The cross-sectional area of the concrete directly influences the stiffness of the test pile. To estimate the cross-sectional area of the concrete, the volume of pouring concrete was recorded along the depth of the shaft, as shown in Fig. 3. Based on volume of concrete pouring, cross section has been estimated 10 m interval and presented in Table 1.

Ultrasonic Pulse velocity has been determined @ 10 m interval taking average velocity from CSL Test and E value concrete is also determined @ 10 m interval using Eq. 2 and presented in Table 2. E value is comparing with ACI Method and it is observed that E value obtained from CSL is slightly higher than ACI Method. Uniform stiffness used for O-Cell calculation and non-uniform stiffness obtained from CSL is used to determine unit shear skin friction. The friction values for both cases are presented in Table 3 and presented in Fig. 9 for the case of CSL Method.

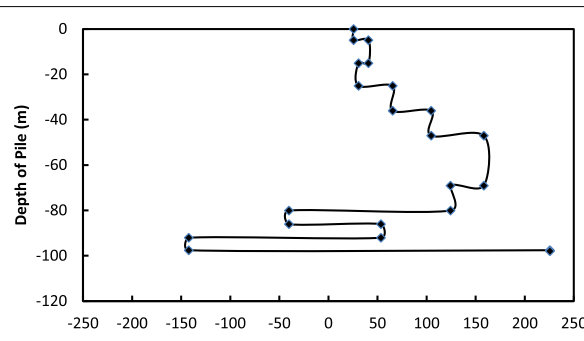

Fig. 9 Unit Skin Shear from Cross Hole Sonic Test Results

Table 4 Velocity criterion for quality of concrete

Pulse velocity (km/Sec)	Grading of concrete quality
> 4.5	Excellent
3.5 4.5	Good
3.0–3.5	Fair/Medium
< 3.5	Doubtful

Friction force has been determined both cases and it was found to be 32.5 MN from O-Cell load case and 34.8 MN for the case of CSL method. Design capacity of pile is found to be 30.5 MN for the case of O-Cell results and 31.1 MN for the case of CSL. Both capacities are comparable and only 2% variations are noticed. Therefore, it may be concluded that proposed method may be considered for O-Cell test result analysis.

3 Construction of equivalent top down load

The bidirectional test results are considered as upward and downward load-settlement curves with respect to Osterberg-cell. In the case of upward deflection is less, extrapolation is required using hyperbolic curve. It is expected that the upward load-displacement behavior is governed by the skin resistance of the test pile above the O-cell and that the downward behavior is governed by the skin friction and toe resistances below the O-cell. The original method for constructing Equivalent Top Load (ETL) curves suggested by Osterberg (1995). In the initial development, the uphill and downhill settlement curves are adding combing the upward and down- ward loads for same settlement. The upward and downward force represents the skin friction force (Qs) and toe bearing capacity (Qb) above and below the Osterberg-cell respectively, noting that Qb also includes the skin friction i.e., by the adjacent soil below the O-cell. Elastic shortening (δc) of the foundation material is considered in estimating pile capacity.

The actual field O-Cell tested curve with the smaller displacement should be extrapolated to generate a resulting curve up to the applied load. Hyperbolic curve fitting method can be used.

The revised simplified method is based on settlement at the head consists of both the toe settlement and the elastic shortening of the foundation material. In Osterberg-cell tests, the settlement of the lowest plate considers the base settlement and the flexible shortening of the foundation below the O-cell. Hence, there is no need of elastic shortening consideration below the Osterberg-cell but foundation section above the O-cell, the elastic shortening is required for determination of equivalent top-down load test mostly exceeds that in O-cell tests (England 2009). Elastic shortening has been determined using following Equation:

$$\delta = \frac{CQ_s}{AE} \times L \tag{3}$$

Where,

δ=Elastic Shortening;

L = Length of pile above O-Cell;

AE = Stiffness of Pile;

Qs = Upward force; and.

C = Factor, 0.5 for rectangular distribution of skin shear and 0.33 for triangular distribution.

Load deflection curve was prepared and calculated based on following steps:

1. Choose a known deflection and find out downward force and upward force and add both to get top down load for summing up both deflection .
2. Similarly choose a second deflection and calculate load deflection as mentioned in Step 1. Generally upward movement is less and this maximum upward deflection and load will be considered until downward deflection will more than upward maximum deflection.
3. Beyond this deflection as mentioned in Step 2, it will calculates as per method as mentioned Step1.

Load deflection curves are prepared and presented in Fig. 10.

Length of pile above top of the O-Cell is 80 m. Elastic shortening above O-Cell is considered. It is found rectangular skin shear developed as shown Fig. 9 and C value is taken 0.5 and finally Equivalent Top Load presented in Fig. 11.

Movement after elastic shortening for the case of non-uniform values of E and cross section are also calculated and elastic shortening is more than 0.1 mm i.e., close to value of uniform case i.e., results obtained from O-Cell results. Therefore, proposed method is comparable with conventional method.

4 Conclusions

Cross-hole sonic logging test is conducted to determine quality of concrete for deep pile and identifies the defect location based on ultrasonic pulse velocity. Generally unit skin friction can be determined CSL and strain captured during O-Cell pile load test. This paper presents this method and compares skin friction force /ultimate pile capacity and compares O-Cell test result. It is found that both methods are comparable and analysis may be carried out using proposed method. Based on the results and analysis presented herein, following conclusions may be drawn:

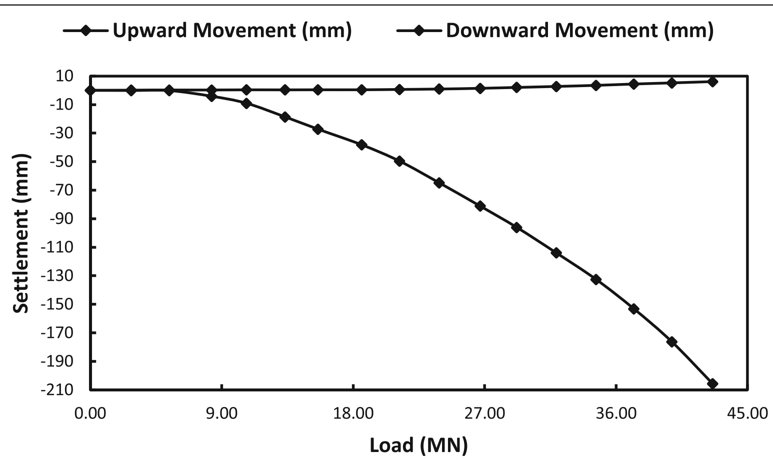

Fig. 10 Actual Load Settlement Curve from O-Cell Test Results

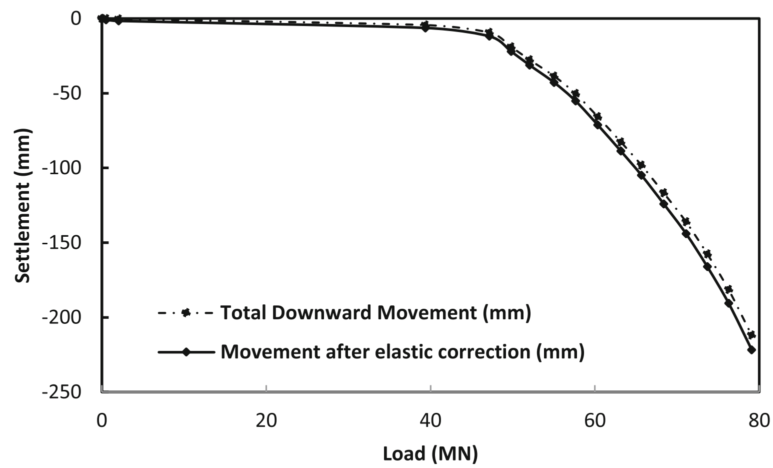

Fig. 11 Equivalent Top Load

- Actual cross section can be determined based on concrete consumed during concreting. This is carried out using wire rope method.
- Cross-hole sonic logging test results can be used to determine pile capacity when same pile is tested using O-Cell.
- E value of concrete can be determined using formula as mentioned in Eq. 2 and it may be used for O-Cell test results analysis.
- Quality of concrete in pile will be determined based on ultrasonic pulse velocity and quality of concrete grade as mentioned in Table 4.
- Strains at different depths of pile can be found from strain gauge reading. Uniform pile cross section - A, E value and non-uniform cross sections and non-uniform E values can be used to determine unit shear skin friction as proposed method mentioned in this paper.
- Skin friction forces obtained by both methods may be used for ultimate capacity of pile.
- Proposed methodology is found to be suitable and may be used for O-Cell test results analysis and comparison.
- Determination of Equivalent top down load has been simplified and same may be used for analysis.

Abbreviations
CSL: Cross-hole Sonic Logging; FTA: First Time Arrival; NDT: Non Destructive Testing; ASTM: American Society for Testing Material; C T: Cross-hole Tomography; MN: Mega Newton; ETL: Equivalent Top Load

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Data share
No objection for data sharing.

Authors' contributions
S K BAGUI: Main Author-Collection of field data, literature review, preparation of document. S K PURI: Guide team member for document preparation, cost variation of project, estimation of base grout quantity. K Subbiah: Document collection from Institute, Methodology for field testing. The author(s) read and approved the final manuscript.

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