Identifying Defects in Large Diameter Bored Piles - Case Studies

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What makes a “Good Pile”?  

To perform successfully, a pile should:

• Have adequate soil resistance
• Be structurally sound

These are two separate requirements both must be satisfied
Quality Assurance of Foundations
- Design Aspects

Assess Loads

Site Investigation

Select Pile Type

Estimate Pile Length

SPT, Cone, Pressuremeter

Experience
Available Equipment Environment
Quality Assurance of Deep Foundations
Design Aspects

Estimate Pile Length

Static Analysis Method
Applicable Codes
Drivability
Constructability
Serviceability

Risk

Factor of Safety

QA/QC Program
- Initial
- Production

Static Load Test
Dynamic Load Test
Pile Integrity Test

Facts
Bored Pile Quality: Do the piles Always look like this?

On most sites, the reality is quite different.
How can we test the quality of bored piles?

Any of these piles could have major defects.
QA/QC:

- Unplanned Testing
  - In response to something gone wrong
  - Extra costs & project delays

- Planned Testing (Preferred)
  - Included in project specifications
  - Planned costs - normal pay item
Quality Assurance by Load Tests

- Installation Monitoring during construction
- Pile Load Testing – using dead load or anchor piles
  - Load carrying capacity – Geotechnical Quality
  - But these tests only confirm the safe load carrying capacity of the tested piles.

How to ensure that all piles are of desired quality?
Quality Assurance – Modern Tools

- Pulse Echo Method / Low Strain Pile Integrity Testing (PIT) - For Pile Integrity, structural quality

- Sonic Logging / Tomography Test - For Pile Integrity, structural quality

- Parallel Seismic Test - For Determining Unknown Foundation Depth

- High Strain Dynamic Load Testing - For Structural Quality, Assess Load Carrying Capacity
Load Testing

Static Load Testing
- Dead load Testing
  - React. piles/anchors
    - Bottom Applied-Osterberg Cells
Dynamic Load Testing
- Dyn. Formula - 1890
- Wave Equation - 1950
- PDA / CAPWAP - 1970 (ASTM D4945)
Static tests are costly and time consuming, so they are not always the best answer.
Pile Load Test using Anchor Piles – 700 tonnes capacity

At Commonwealth Games Village Complex, Delhi
Low Strain Pile Integrity Test (PIT)
Low Strain Integrity Methods

- PILE INTEGRITY TESTING (PIT)
  - Measure Pile Top Motion, Reflections from Defects

- CROSS-HOLE SONIC LOGGING (CSL)
  - Determines Concrete Quality Between Tubes in Shaft
  - For large diameter bored piles

- PARALLEL SEISMIC (PS)
  - Hit Pile, Measure Hydrophone in Parallel Tube
  - Determines only Pile Length
Why Do Pile Integrity Testing?

- prime function is to locate major defects *(to evaluate questionable shafts)*
- inexpensive, can test many piles *(good for quality assurance)*
- no advance selection required *(good for forensic purposes)*
Low Strain Pile Integrity Testing (PIT)
Preparation..

Pile top preparation is key to good data which is the key to best interpretation. Shortcuts cause questionable data.
Wave Propagation

Compressed Zone, races along pile at wave speed $c$

$c$ is the wave speed of the pile material

In a time $\Delta t$ the wave travels a distance $\Delta L = c \Delta t$
Pile Integrity Tester: PIT
Pulse Echo Method

Small hammer impact device

Accelerometer measures response

(defect)
PIT - Basic Interpretations

Normal test (pile top “free”)  800 mm bored cast in-situ pile

L = 25 m  (L/D = 31)
How many piles should I test?

PIT is fast & cheap- test ALL piles for best results!!
Any of these piles could have a defect....
PIT Limitations

- As per published literature, piles with L/D ratio up to 30 give reasonably good results.
- Highly non-uniform piles may be difficult to interpret.
- Cracks or mechanical joints block waves.
- Small defects or short length hard to find.
- Not always applicable: inconsistent or non-ideal data may be difficult to interpret.
- No direct correlation to pile capacity; but can help to identify which piles to load-test.
High Strain
Dynamic Pile Load Test
(HSDLT)
High Strain Dynamic Pile Testing with the Pile Driving Analyzer ®
PDA Benefits to Project

- Confirms safe pile capacity
- Great savings in time and cost – test more piles at the same cost, in less time

PDA can test piles to reduce costs and save time
Dynamic Pile Testing

Load is applied by impacting ram
Load is measured by strain transducers
Motion is measured by accelerometers
Attach sensors to concrete on a flat surface

4 sets of sensors
Ram: concrete filled pipe

“donut” ram on center guide

Ram: concrete filled pipe
Dynamic Pile Monitoring

For each blow, determine:

- **Safe Pile Capacity**
- **Pile Integrity**
- **Pile Stresses**
- **Hammer Performance**

Last three items detect or prevent problems in the piles as-installed
Dynamic Pile Test

- Recognized by ASTM, IRC Codes. Soon to be included in IS Codes.
- Uses available or easy-to-make drop hammers and minimal pile preparation
- Confirms safe pile capacity, even at large loads
- Reduced testing time with large cost savings *(cost may be 5 to 20 times less than static load tests)*
- 8 Channel PDA preferred for bored piles
- Results must be analyzed by trained PDA professionals!!
- Use in conjunction with static load tests
Cross-hole Sonic Logging & 3D Tomography
Cross-hole Sonic Logging (CSL)  
ASTM D6760

Place probes in bottom of tubes.  
(Same test for each tube pair)

Stress Waves, emitted in one tube are received in another one if concrete quality is satisfactory.
3D body view  2D vert. slice  2D horiz. slice of a defect

3D Tomography
Parallel Seismic Test
Parallel Seismic Method

The PS method is typically performed in a cased borehole of 1.5 inch I.D. or greater which is placed in the proximity of the foundation in question. The test can also be performed using a Cone Penetration Test Rig in soft soil environments.
Parallel Seismic Test

1. Impact Foundation

2. Lower Hydrophone in PVC pipe within 3 m of pile

3. Pick first arrival waves

4. Break in slope indicates foundation depth

- Determines unknown pile length
- Requires parallel bore installed
- Does not determine integrity
Case Study -1
High Rise Building
(66 Storeyed)
in Noida (UP)
Project Details

- 66-story residential tower- 240 m high
- Double Basement (9m below grade)
- 3,400 m² circular footprint
- Foundation System
  - Piled-raft;
  - 2.5m thick Raft @ 9m depth
  - 298 bored piles of 1m dia and 48m length
- Construction is presently underway!
Field Investigation

1 BH
1 PMT
1 CHST
Medium dense to dense alluvial sand to 37m depth

Hard clay to 41-50m depth

Very dense sands / silt (N>100) to 60 m depth

GW at 11m depth below OGL
Pressure meter Test Data

Corrected Curve
- Depth 20.0 m
- Depth 15.0 m
- Depth 10.0 m
- Depth 5.0 m

Deformation Modulus, $E_{dm}$ kg/cm²
Limit Pressure, $P_L$ kg/cm²

Reduced Level, m

50.00 m
Cross-hole Seismic Test Results
## Theoretical Pile Capacities

**Boundary Conditions:**
- 1m dia bored piles
- COL @ 10m depth (Basement Level)
- GWT considered @ COL

<table>
<thead>
<tr>
<th>Pile length below COL, m</th>
<th>Ultimate Pile Capacity, MN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Compression</td>
</tr>
<tr>
<td>44</td>
<td>11.6</td>
</tr>
<tr>
<td>46</td>
<td>12.2</td>
</tr>
<tr>
<td>48</td>
<td>13.2</td>
</tr>
</tbody>
</table>
Initial (Static Load Tests)

- 1m dia
- 25m long test piles
- COL ~ 2-3m below GL as against 10 m for working piles
- Pile Settlement < 25mm at 10 MN compressive load
Routine Static Load Tests

1m dia, 48m long production piles @ COL of 10m

Concrete blocks used as kentledge
High-Strain Dynamic Load Tests

- 20 MT drop hammer
- 0.5-3m drop heights
- 4-strain transducers, 2 accelerometers recommended

6 HSDLT were performed using PDA
Routine Pile Load Test Results

- Load test results are fairly consistent.
- However, pile performance is very poor as compared to theoretical estimates (13MN) and initial pile load test results on 25m long piles.
- Settlement of 48m long piles is almost twice as much as 25m test piles.
- Structural defects & ‘soft-toe condition’ suspected.

Very Good Match!!!
Low-Strain Pile Integrity Tests (PIT)

298 Piles

8 lbs hand-held hammer
PIT Results

- PIT on 298 production piles
- Generally speaking:
  - Significant impedance changes along the pile shaft
  - Bulging at shallow depths (2.5-4.5m) - confirmed by pile exposures
  - Weak toe response - possible ‘soft toe condition’ and low pile end bearing
PIT: Profile Analysis - Pile 1079

Pile No. 1079
Pile Coring- 1079

0m to 7.5m depth
Pile Coring - 1079

7.5m to 13.5m depth

Nil recovery 11.5m-12m
Pile Coring- 1079

13.5m to 19.5m depth
Pile Coring- 1079

19.5m to 28.5m depth
Pile Coring- 1079

28.5m to 35.0m depth
Pile Coring - 1079

Slush encountered below 44.5m depth - confirms suspected 'soft toe' condition

35.0m to 44.5m depth
PIT vs. Pile Coring - 1079

Necking

Necking

‘Soft Toe’
Design Ramifications

- Lowered pile stiffness was considered in the analysis (nil end bearing)
- Final design of the piled-raft system was updated with reduced ultimate pile capacities / stiffness
- Additional piles were constructed under the raft
Case Study - 2

Commercial / Hotel Building
at Dwarka, Delhi
Layout Plan
Commercial Complex / Hotel at Dwarka, New Delhi

- 5 star hotel-cum-commercial complex
- Three basements – basement floor at 15.5 m depth
- Planned as **TOP-DOWN** construction to speed up construction
Stratigraphy

- Indo-Gangetic Alluvium
- Deposits consist primarily of sandy silt (Delhi Silt) of low plasticity with minor silty sand layers
- SPT values:
  - 0-7 m depth: 14-36
  - 7-13 m depth: 30-47
  - 13-20 m depth: 39-66
  - 20-60 m depth: > 100

Groundwater Level: 21.2 m depth (Feb 2009)
## Design Profile

<table>
<thead>
<tr>
<th>Depth</th>
<th>Stratum</th>
<th>$c$ kN/m$^2$</th>
<th>$\phi^\circ$</th>
<th>$\gamma$ kN/m$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>Sandy Silt/Clayey Silt</td>
<td>Above Cut-off Level</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.0</td>
<td>Very dense Sandy Silt/Clayey Silt</td>
<td>300</td>
<td>0</td>
<td>19</td>
</tr>
<tr>
<td>25.0</td>
<td>Very dense Sandy Silt/Clayey Silt</td>
<td>0</td>
<td>31</td>
<td>19.5</td>
</tr>
<tr>
<td>40.0</td>
<td>Very dense Sandy Silt</td>
<td>0</td>
<td>33</td>
<td>20</td>
</tr>
</tbody>
</table>

Design Water Table level considered at 15 m depth
## Computed Static Pile Capacities

<table>
<thead>
<tr>
<th>Pile Dia. (mm)</th>
<th>Pile Length Below Cut-Off Level&lt;sup&gt;1&lt;/sup&gt; (m)</th>
<th>Computed safe axial compressive pile capacity&lt;sup&gt;2&lt;/sup&gt; (MN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1600</td>
<td>25 (40.5)</td>
<td>11.79</td>
</tr>
<tr>
<td></td>
<td>27 (42.5)</td>
<td>12.49</td>
</tr>
<tr>
<td></td>
<td>30 (45.5)</td>
<td>13.54</td>
</tr>
<tr>
<td></td>
<td>32 (47.5)</td>
<td>14.23</td>
</tr>
</tbody>
</table>

<sup>1</sup>-Pile cut-off level is considered at 15.5 m below Ground Level. Pile lengths from ground level are presented in brackets

<sup>2</sup>-Design safe working loads include a Factor of Safety of 2.5
Construction Sequence

- Install 1600 mm diameter deep bored cast in-situ piles from ground level
- After piles are installed, excavation for basement shall be taken up
- Portion of pile above basement level shall act as column, that below basement shall contribute to pile capacity
- Construction of superstructure shall be taken up simultaneously
Tests for Quality Assurance

TOTAL 55 PILES INSTALLED

1600 mm dia 47.5 m below EGL, 32 m below COL

- No initial pile load test conducted
- One Static Load Test conducted on working pile
- 37 Low Strain Pile Integrity Test (PIT)
- 5 High Strain Dynamic Load Test (HSDLT)
- 1 Osterberg Cell Load Test (O-Cell)
PIT Results

Minor Impedance reduction at 15 m depth

Impedance reduction below 17.5 m depth. Toe Response Weak
Integrity Doubtful
Impedance reduction below 22 m depth. Integrity Doubtful

Impedance reduction below 36 m depth. Weak Toe Response
Integrity Doubtful
<table>
<thead>
<tr>
<th>Pile No.</th>
<th>Pile Diameter (mm)</th>
<th>Total Pile Length (m)</th>
<th>Test Load 1 (MN)</th>
<th>CAPWWAP Ultimate Pile Capacity 1 (MN)</th>
<th>Design Safe Working Load (MN)</th>
<th>F.O.S</th>
</tr>
</thead>
<tbody>
<tr>
<td>E41</td>
<td>1600</td>
<td>48.3</td>
<td>21.34</td>
<td>20.6</td>
<td>14.23</td>
<td>1.45</td>
</tr>
<tr>
<td>F51</td>
<td>1600</td>
<td>48.3</td>
<td>21.34</td>
<td>8.5</td>
<td>14.23</td>
<td>0.6</td>
</tr>
<tr>
<td>E52</td>
<td>1600</td>
<td>47.0</td>
<td>21.34</td>
<td>7.2</td>
<td>14.23</td>
<td>0.5</td>
</tr>
<tr>
<td>A41</td>
<td>1500</td>
<td>48.3</td>
<td>18.63</td>
<td>18.1</td>
<td>12.42</td>
<td>1.45</td>
</tr>
<tr>
<td>C1-43</td>
<td>1500</td>
<td>44.5</td>
<td>18.63</td>
<td>8.4</td>
<td>12.42</td>
<td>0.7</td>
</tr>
</tbody>
</table>

1 After eliminating shaft friction for the top 15.5 m to account for basement excavation
CAPWAP Analysis: Pile E-52

Interpreted Ultimate Capacity: 7.2 MN
Osterberg Cell Bi-Directional Load Test

- Test pile – boring done to 48.8 m depth, concreting done to 8.3 m depth below GL
- Pile length 39.6 m, effectively 33.3 m below COL
- O-Cells installed at 40.5 m depth below GL i.e. 8.3 m above pile toe
Interpreted Ultimate Capacity

- Interpreted ultimate capacity of lower shaft and base = 7.38 MN
  - 3.62 MN contribution of lower shaft,
  - 3.76 MN contribution of base
- Lower Shaft failed at 2.5 MN, net settlement 16 mm
- Base carried 2.6 MN, settlement approaching 160 mm

Interpreted Ultimate Pile Capacity = 9 MN
## Summary of Load Test Results

<table>
<thead>
<tr>
<th>Method of Analysis</th>
<th>Interpreted Ultimate Pile Capacity(^1) (MN)</th>
<th>Allowable Safe Working Pile Capacity(^2) (MN)</th>
<th>F.O.S(^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static Load Test</td>
<td>16</td>
<td>6.4</td>
<td>1.12</td>
</tr>
<tr>
<td>Osterberg Cell Load Test</td>
<td>9.0</td>
<td>3.6</td>
<td>0.63</td>
</tr>
<tr>
<td>HS Dynamic Load Test</td>
<td>7.2 to 20.6</td>
<td>2.9 to 8.2</td>
<td>0.5 - 1.45</td>
</tr>
</tbody>
</table>

\(^1\) Based on Load test extrapolation of upper bound hyperbolic curve for upper portion of the pile  
\(^2\) Assuming a Factor of Safety of 2.5 on ultimate pile capacity  
\(^3\) Factor of Safety for estimated ultimate pile capacity against current safe working capacity (14.2 MN)
Pile Above Basement Level
Quality of Piles Exposed above Basement Level

- Pile diameter not uniform, substantial necking / bulging observed in some piles
- Reinforcement exposed, bent
- Centre of pile / column at basement floor level was off by over 500 mm in some cases
- Some piles were visually out of plumb, so using as column was aesthetically unpleasant
Reinforcement Exposed
Repair Work in Progress
Safe Pile Capacities De-Rated

- Additional piles installed below basement level
- Piled-Raft analysis done to assess the overall settlement and safety of the foundation system
- Of course it led to contractual issues:
  - Blame all involved – soil consultant, structural consultant, building contractor, piling agency – all were under scrutiny
  - **Client suffered!!** – Project delayed, resulted in direct & indirect losses
Case Study -3
PIT for a Mall in Noida (UP)
Case Study 3: Noida Mall

800 mm dia Bored Cast in-situ piles in sand

- Initial Cyclic Pile Load Test:
  - $Q_{\text{ult}} = 270$ MT
  - $Q_{\text{safe}} = 135$ MT

- 14 PIT were performed on initial and routine piles
Case Study 3: Noida Mall

Original Ground Level

Excavated Level, Pile COL

Pile Toe Level

<table>
<thead>
<tr>
<th>SYMBOL</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fine sand (SP-SM)</td>
</tr>
<tr>
<td></td>
<td>Silty fine sand (SM)</td>
</tr>
<tr>
<td></td>
<td>Sandy silt (CL)</td>
</tr>
<tr>
<td></td>
<td>Water Table</td>
</tr>
</tbody>
</table>
Case Study 3: Noida Mall

Major defect at 16~18 m depth (or short pile)
Case Study - 4
Parallel Seismic Test
to determine Pile Length
of a Bridge in New Delhi
A view of the Bridge

Test location prior to excavation

Retaining wall

(After excavation of Trial Pit)

Test Location prior and after excavation of Trial Pit
Testing in Progress
Test Results

Parallel Seismic Test

Arrival Time, microsec

Depth below Pile COL, m

Estimated Pile Length = 12 m below COL
Concluding Remarks
“There is many a slip twixt the cup and the lip”

- A well-planned, comprehensive & robust QA program for the foundations is essential to ensure adequate performance and avert disaster
- Keep the geotechnical engineer the and structural engineer involved throughout the foundation construction process
- More testing justifies lower F.S., leading to significant cost savings
Just doing the tests is not enough!

- Proper interpretation of the test results by an independent agency
- Correlate all information and test results - geotechnical data, pour card information, test results, etc.
- Improve the design as well as the construction methodology in parallel to get maximum benefit
- Many reliable test methods available, but results are only as good as the testing agency!!
What are the consequences of insufficient testing?

- failed structure (loss of use, life??)
- high remediation costs
- increased insurance costs

Can we afford to skip installation monitoring and eliminate follow-up NDT?
Let us strive to achieve quality in pile construction

THANK YOU...

Cengrs Geotechnica Pvt. Ltd