Introduction

- Case Studies on
  - Pile Heave and Displacement of Driven Pile Installation
  - Failure of Piled Supported Wall under Extreme Lateral Loading
  - Pile Test Interpretation
    - Global Strain Measurement for Compressive & Tensile Loading

- Conclusions & Recommendation
Overview

- Common problems of installing displacement piles in soft ground
- Design robustness of piled supported wall
- Common overlooked issues of pile testing instrumentation

Case 1: Pile Heave & Lateral Soil Displacement

- Rapid pile installation in incompressible soft soil induces
  - Vertical heave in shallow depth (relatively less confinement from weight of overburden soils)
  - Lateral displacement in deeper depth (with soil confinement)

- Consequences:
  - Up-heaving soil movement causes tensile stress on pile & toe lift up during driving & downdrag after pore pressure dissipation
  - Lateral soil displacement causes flexural stress on pile & pile deviation
  - Excessive combined tensile and flexural stresses lead to pile joint dislodgement
  - Excessive foundation settlement in post construction (pile toe uplifting & downdrag settlement)
Pile Joint Dislodgement

- Pile joints could be dislodged due to excessive flexural and tensile stresses induced by ground heave and radial soil displacement
- Detectable using High Strain Dynamic Pile Test (HSDPT)

Mechanism of Pile Heave & Soil Displacement
Case Study - HSDPT

- Monitoring of pile top settlement during the HSDPT re-strike tests is summarised as below:

<table>
<thead>
<tr>
<th>Cumulative Pile Top Settlement (mm)</th>
<th>Pile C</th>
<th>Pile A</th>
<th>Pile B</th>
<th>Pile D</th>
<th>Pile E</th>
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</thead>
<tbody>
<tr>
<td>Upon resting 7-ton hammer on pile top</td>
<td>80</td>
<td>98</td>
<td>125</td>
<td>103</td>
<td>92</td>
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<tr>
<td>At the end of Restriking Test</td>
<td>275</td>
<td>399</td>
<td>497</td>
<td>186</td>
<td>182</td>
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Case Study - HSDPT

- Pile B
- Initial Blow

One Pile Length (12m) was DETECTED with Major Discontinuity at ‘toe’ (reflection)
Case Study - HSDPT

- Pile B
- Blow No. 4

First Joint Discontinuity closed up after few blows; Two Pile Lengths was revealed with another Major Discontinuity at new ‘toe’ (reflection)

Case Study - HSDPT

- Pile B
- Blow No. 17

Second Major Joint Discontinuity also disappeared; Total of Three Pile Lengths was observed
Case Study - HSDPT

- Pile B
- End of Blow

Minor velocity reflections were observable at first and second pile joints.

Pile Heave Monitoring Program
Summary of Case 1

- **Ground heave & radial soil displacement** due to rapid installation of displacement pile in soft incompressible soft clay can pose serious integrity problem on pile foundation.

- **Solutions**:
  - Use larger pile spacing & reduce rate of clustered pile installation for adequate time for dissipation of excess pore pressure
  - Simultaneous pile installation at mirror pile location from centre *outwards* to minimise net lateral displacement, but this improves nothing on ground heave
  - Stronger pile structural strength & joint to withstand tensile & flexural stresses
  - Staggered pile installation sequence or install piles at alternate locations
  - Restrike all piles with HSDPT to detect pile integrity if ground or soil heave is observed.
Case 2: Case study on Piled Supported Wall Failure

- **8m RS Wall + 2m L-Shaped RC Wall**
  - Foundation: Vertical piles + Raked Piles (3 rows each)
  - 400mm thick RC Slab
  - 3~3.5m RC Monsoon Drain in front of Wall

- **Failure occurred on 4 Jan 2007**
  - When RS Wall reached soffit of L-Shaped RC Wall
Site Conditions

- **Soil Conditions**
  - Top 4~5m Fill: medium stiff clayey Silt and clayey Sand (N = 6 to 10)
  - 4~8m very soft to soft Clay (S_u = 40kPa)
  - 8~18m Stiff Sandy Silt (N= 10~30)
  - Fill Platform: Cohesive lateritic soils
  - Wall Backfill: Granular Materials

- **Groundwater Level**
  - RL14m to RL18m

- **Rainfall Records**
  - Intense antecedent rainfall from 10 Dec 06 to 29 Dec 06 before failure
  - Triggering midnight rainfall (20mm/hr) on 3 Jan 07

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### Rainfall - ARI

<table>
<thead>
<tr>
<th>Rainfall Season</th>
<th>Month</th>
<th>Recorded Max Rainfall (mm)</th>
<th>CF Reference Station</th>
<th>Intensity, I (mm/hr)</th>
<th>ARI (Year)</th>
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<tr>
<td>10/10/06-11/11/06 (Oct)</td>
<td>107</td>
<td>109</td>
<td>137</td>
<td>Stn JPS JE (1)</td>
<td>4.45</td>
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<tr>
<td>11/11/06-11/12/06 (Nov)</td>
<td>67</td>
<td>103</td>
<td>131</td>
<td>Stn JPS JE (1)</td>
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<tr>
<td>11/12/06-11/17/07 (Dec)</td>
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<td>477</td>
<td>Stn JPS JE (1)</td>
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<tr>
<td>12/13/07-3/10/07 (Jan)</td>
<td>234</td>
<td>351</td>
<td>364</td>
<td>Stn JPS JE (1)</td>
<td>2.33</td>
</tr>
</tbody>
</table>
Rainfall Record

Site Observation

- Panels
  - Wet panels & traces watermark shown water seeping out at the panel joints
  - The highest level of observed water seeping was immediately below 2m high L-shaped RC wall
    \[ \therefore \text{Evidence of high water table behind the wall panel} \]

- Pile Foundation
  - Flexural damage of pile body at 1.75m to 2m below slab soffit level
  - Significant rotation of upper part of pile above the plastic hinge
    \[ \therefore \text{Likely due to excessive lateral load on piles} \]
3/29/2010

**Precast Precast RC panel**

**Water seepage sign**

**RL 27.0m**

**2m top RC panel**

**Monsoon Drain**

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**Damaged Foundation Piles**

**RL 18.6m**

1.5m

**Raked pile**

1.8m

**Damaged condition**
Investigation Approach

- Examine induced Axial & Lateral Forces and Moments on Piles at **Design Condition & Failure**
- Use of Lateral earth pressure theory
- Piglet to compute pile group load distribution
- Check FOS against
  - Pile axial capacity
  - Pile lateral capacity
  - Pile structural adequacy (Moment & Shear)
Design Scenario A (GWT at Monsoon Drain)
# Design Scenario A Results

**GWT at Top of Monsoon Drain (RL20.18m)**

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<tr>
<th>File no.</th>
<th>Axial loads [kN]</th>
<th>Status</th>
<th>Lateral loads [kN]</th>
<th>Lateral Resistance [kN]</th>
<th>FOS</th>
<th>Moments [kNm]</th>
<th>Ultimate Moment Resistance [kNm]</th>
<th>Load Factor</th>
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</table>

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# Design Scenario B (1/3 GWT)

- **Finished Ground Profile**
- **Surcharge = 30kPa**
- **Original Ground Profile**
- **Temporary Ground Profile During Piling & Wall Construction**
- **RL20.18m**
- **RL22.0m**
- **RL27.0m**
- **RL28.5m**
- **RL19.0m**
- **RL18.6m**
- **RL17.1m**
### Design Scenario B Results

**GWT at 1/3 of Retained Height (RL22.0m)**

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<th>Pile</th>
<th>Axial loads (kN)</th>
<th>Status</th>
<th>Lateral loads (kN)</th>
<th>Lateral Resistance (kN)</th>
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<th>Moments (kNm)</th>
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</table>

**Graph:**

- **Global Load Factor of Group Pile**
- **Load Back Calculated Load Factor of Individual Pile**

**Chart:**

- **Moment (kNm)**
- **Axial Load (kN)**
### Failure Scenario (GWT at Top Panel)

- **Original Ground Profile**
- **Temporary Ground Profile During Piling & Wall Construction**
- **Finished Ground Profile**

### Failure Scenario Results

#### GWT at Top RS Wall Panel (RL27.0m)

<table>
<thead>
<tr>
<th>Pile no.</th>
<th>Area Loads (kN)</th>
<th>Status</th>
<th>Lateral Loads (kN)</th>
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<td>41.80</td>
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</table>
Investigation Findings

- **At Failure**
  - Prolonged intense antecedent rainfall + Triggering rainfall on 3 Jan 2007 caused rising of water table above top RS wall panels
  - Excessive imposed lateral stress exceeds the pile lateral capacity resulting formation of plastic hinge of piles leading to collapse of central portion of wall & pulling the adjoining RS wall

- **At Service Condition**
  - The foundation pile design complies to design requirements (Adequate safety factors)
Conclusions

• Main causation:
  • Excessive lateral wall force due to high water table rise from prolonged intense rainfall

• Foundation design under service condition is acceptable

• Attention shall be given to brittle behaviour of concrete piles taking lateral load with rapid increase of earth pressure when rise of groundwater table within the wall.

29 December 2006 - Johor was the worst hit. Heavy rain – the highest recorded in 100 years – caused floods in Johor Baru and several major towns this month.
Summary of Case 2

- Need careful evaluation of design robustness of vertical and sub-vertical piles in taking lateral foundation loading

Solutions:

- Use more raked piles utilising more robust axial pile strength to resolve lateral imposed loading
- Extra drainage capacity for temporary drains for large flat retained platform
- Timely backfilling of suitable fill over granular fill of RS wall
Pile Test Interpretation
(using Global Strain Measurement)

- **Facts on Axially Tested Pile:**
  - Free standing portion – No friction interference
  - Embedded portion – Constant or linearly varying shaft friction with depth
  - Tensile cracking in tensile loading affecting axial stiffness of composite pile section

- **Factors affecting accuracy of pile instrumentation:**
  - Linearity of load-strain calibration
  - Pile shaft resistance profile assumed
  - Instrument locations for pile axial load measurement
  - Numbers of pile segment movement measurement
  - Gauge length of strain measurement (global / local strain measurement)

- **Consequences:**
  - Interpreted pile axial load at location assigned within the gauge length can be unjustified (unless no interference of shaft friction)

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Pile Instrumentation & Interpretation Approaches

- **New Method**
  - Glostrext Method
  - Traditional Method

- Identify pile-soil friction profile (Constant/ or Varying friction with depth)
- Measure movements of instrumented pile segments & pile top load with load-strain calibration
- Derive pile axial load at mid-point from global strain measurement & average mobilised pile-soil friction over gauge length
- Load-movement relationship of each pile segment for load transfer mechanism

- Identify pile-soil friction profile
- Measure localised pile strain and movement of instrumented pile segments independent extensometers & pile top load with load-strain calibration
- Derive localised pile axial load, interpolated pile movement profile & mobilised pile-soil friction
- Load-movement relationship of each pile segment for load transfer mechanism

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- Derive localised pile axial load, interpolated pile movement profile & mobilised pile-soil friction
- Load-movement relationship of each pile segment for load transfer mechanism
Load Transfer of Test Pile

\[ f_s = \text{Constant} \]

\[ f_s = f_{s,0} + mZ \]

\[ P_i \quad P_{i+1} \quad P_i \quad P_{i+1} \]

\[ \delta_i \quad \delta_i \quad \delta_i \quad \delta_i \]

\[ \delta_{i+1} \quad \delta_{i+1} \quad \delta_{i+1} \quad \delta_{i+1} \]

\[ F_{s,i} \quad F_{s,i} \quad F_{s,i} \quad F_{s,i} \]

\[ P(z) \]

\[ \varepsilon(z), \delta(z) \]

\[ \text{Linear} \quad \text{Quadratic} \quad 3^{rd} \text{ Degree Polynomial} \]

\[ \text{Tensile Pile Test} \]

\[ \% \text{ of Pile Diameter} \]

\[ \text{Tension Load (kN)} \]

\[ \% \text{ of Top Imposed Load} \]

\[ \text{Displacement (mm)} \]
Summary of Pile Instrumentation

- Proper planning of instrumented segment of test piles with due consideration of soil stratification, pile resistance profile (constant or varying profile with depth)
- Tensile cracking of concrete under tensile test load leading to irreversible stiffness alteration shall be carefully assessed for proper load transfer

Solutions:
- Identify expected profile of pile-soil friction based on stratification, soil consistency,
- Gauge length shall be reasonably small where practical for proper axial load interpretation, instrumented segment assigned for pile load and movement
- Minimum one axial load measurement per material stratum preferably at the either sides of the stratum interface
- For material strata with varying pile-soil friction with depth, more instrumented segments are needed for refined interpretation of axial load & movement (for best fitting the pile movement profile)
- At least one axial load measurement near to pile base for load transfer of mobilised base resistance

Thank You