PILED FOUNDATION
DESIGN & CONSTRUCTION

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http://www.gnpgeo.com.my
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- Preliminary Study
- Site Visit & SI Planning
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- Pile Installation Methods
- Types of Piles
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- Piling Supervision
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- Piling Problems
- Typical Design and Construction Issues
- Myths in Piling
- Case Histories
- Conclusions
Overview
What is a Pile Foundation

It is a foundation system that transfers loads to a deeper and competent soil layer.
When To Use Pile Foundations

• Inadequate Bearing Capacity of Shallow Foundations
• To Prevent Uplift Forces
• To Reduce Excessive Settlement
First floating condo turns for millionaires

SYDNEY: The world’s first floating condominium, The World, brought Sydney Harbour to a standstill yesterday as it performed a graceful pirouette to ensure all its millionaire apartment owners had their fair share of the view.

The super-rich pay between A$2mil (RM4.7mil) and A$7mil (RM16.4mil) for an apartment aboard the white-hulled 44,500-tonne giant liner. Yet for the past two days half of them have been staring out at the bleak facade of the 1980s-built Overseas Passenger Terminal in Sydney Cove where it is moored.

The rest have been enjoying what is probably the finest view of the famous harbour and the Sydney Opera House.

But tugs and police boats turned the tables yesterday, gingerly shepherding the huge ship out into the harbour, turning it 180 degrees and edging it back to its moorings, in a 30-minute operation which was the first of its kind in Sydney.

Extra charges for an apartment on The World range from A$100,000 (RM233,000) to A$340,000 (RM795,000) a year.

— Reuters
PILE CLASSIFICATION

● **Friction Pile**
  - Load Bearing Resistance derived mainly from skin friction

● **End Bearing Pile**
  - Load Bearing Resistance derived mainly from base
Friction Pile

Overburden Soil Layer
End Bearing Pile

Overburden Soil

Rock / Hard Layer
Preliminary Study
Preliminary Study

- Type & Requirements of Superstructure
- Proposed Platform Level (ie CUT or FILL)
- Geology of Area
- Previous Data or Case Histories
- Subsurface Investigation Planning
- Selection of Types & Size of Piles
Previous Data & Case Histories

Existing Development A

Proposed Development

Existing Development B

Bedrock Profile

Only Need Minimal Number of Boreholes
Challenge The Norm Thru Innovation To Excel
Factors Influencing Pile Selection

- Types of Piles Available in Market (see Fig. 1)
- Installation Method
- Contractual Requirements
- Ground Conditions (eg Limestone, etc)
- Site Conditions & Constraints (eg Accessibility)
- Type and Magnitude of Loading
- Development Program & Cost
- etc
TYPE OF PILES

DISPLACEMENT PILES

- TOTALLY PREFORMED PILES
  - Hollow
    - Small displacement
      - Steel Pipe
      - Concrete Spun Piles
  - Solid
    - Concrete Tube
    - Steel Tube
      - Closed ended tube concreted with tube left in position
      - Closed ended tube
      - Open ended tube extracted while concreting (Franki)

- DRIVEN CAST IN-PLACE PILES
  - Concrete
  - Steel H-piles (small displacement)
  - Bakau piles
  - Treated timber pile

NON-DISPLACEMENT PILES

- Bored piles
- Micro piles

FIG 1: CLASSIFICATION OF PILES

Restricted use due to environmental considerations
<table>
<thead>
<tr>
<th>SCALE OF LOAD (STRUCTURAL)</th>
<th>COMPRRESSIVE LOAD PER COLUMN</th>
<th>MAINLY END-BEARING (D=Anticipated depth of bearing)</th>
<th>BEARING TYPE</th>
<th>TYPE OF INTERMEDIATE LAYER</th>
<th>GEOTECHNICAL</th>
<th>SOIL WITH SOME BOULDERS / COBBLES (S=SIZE)</th>
<th>GROUND WATER</th>
<th>ENVIRONMENT</th>
<th>UNIT COST (SUPPLY &amp; INSTALL) RM/TON/M</th>
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</thead>
<tbody>
<tr>
<td>&lt;100 KN</td>
<td>√</td>
<td>√</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>0.5-2.5</td>
</tr>
<tr>
<td>100-300</td>
<td>√</td>
<td>√</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>0.3-2.0</td>
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<tr>
<td>20-30m</td>
<td>x</td>
<td>x</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>0.5-2.5</td>
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<tr>
<td>30-60m</td>
<td>x</td>
<td>x</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>0.5-2.5</td>
</tr>
<tr>
<td>WEATHERED ROCK / SOFT ROCK</td>
<td>x</td>
<td>x</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>0.5-2.5</td>
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<tr>
<td>ROCK (ROD &gt; 70%)</td>
<td>x</td>
<td>x</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>0.5-2.5</td>
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<tr>
<td>COHESIVE SOIL</td>
<td>SOFT SPT &lt; 4</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>?</td>
<td>0.5-2.5</td>
</tr>
<tr>
<td>M. STIFF SPT = 4 - 15</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>?</td>
<td>0.5-2.5</td>
</tr>
<tr>
<td>V. STIFF SPT = 15 - 32</td>
<td>?</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>?</td>
<td>0.5-2.5</td>
</tr>
<tr>
<td>HARD SPT &gt; 32</td>
<td>x</td>
<td>?</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>?</td>
<td>0.5-2.5</td>
</tr>
<tr>
<td>COHESIVELESS SOIL</td>
<td>LOOSE SPT &lt; 10</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>?</td>
<td>0.5-2.5</td>
</tr>
<tr>
<td>M. DENSE SPT = 10 - 30</td>
<td>?</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>?</td>
<td>0.5-2.5</td>
</tr>
<tr>
<td>DENSE SPT = 30 - 50</td>
<td>x</td>
<td>?</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>?</td>
<td>0.5-2.5</td>
</tr>
<tr>
<td>V. DENSE SPT &gt; 50</td>
<td>x</td>
<td>x</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>?</td>
<td>0.5-2.5</td>
</tr>
<tr>
<td>SOIL WITH SOME BOULDERS / COBBLES (S=SIZE)</td>
<td>S &lt; 100 mm</td>
<td>x</td>
<td>?</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>0.5-2.5</td>
</tr>
<tr>
<td>1000-1000mm</td>
<td>x</td>
<td>x</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>0.5-2.5</td>
</tr>
<tr>
<td>1000-3000mm</td>
<td>x</td>
<td>x</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>0.5-2.5</td>
</tr>
<tr>
<td>&gt;3000mm</td>
<td>x</td>
<td>x</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>0.5-2.5</td>
</tr>
<tr>
<td>GROUND WATER ABove PILE CAP</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>0.5-2.5</td>
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<tr>
<td>BELOW PILE CAP</td>
<td>x</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>?</td>
<td>0.5-2.5</td>
</tr>
<tr>
<td>UNIT COST (SUPPLY &amp; INSTALL) RM/TON/M</td>
<td>0.5-2.5</td>
<td>0.3-2.0</td>
<td>1.0-3.5</td>
<td>1.2</td>
<td>0.5-2.0</td>
<td>1.5-3.0</td>
<td>1.25</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

FIG 2: PILE SELECTION CHART
Site Visit and SI Planning
Site Visit

Things To Look For …

● Accessibility & Constraints of Site

● Adjacent Structures/Slopes, Rivers, Boulders, etc

● Adjacent Activities (eg excavation)

● Confirm Topography & Site Conditions

● Any Other Observations that may affect Design and Construction of Foundation
Subsurface Investigation (SI) Planning

- Provide **Sufficient Boreholes** to get Subsoil Profile
- **Collect Rock Samples for Strength Tests** (eg UCT)
- **In-Situ Tests to get consistency of ground** (eg SPT)
- **Classification Tests to Determine Soil Type Profile**
- **Soil Strength Tests** (eg CIU)
- **Chemical Tests** (eg Chlorine, Sulphate, etc)
Typical Cross-Section at Hill Site

- Ground Level
- Hard Material Level
- Very Hard Material Level
- Bedrock Level
- Groundwater Level
Placing Boreholes in Limestone Areas

- **Stage 1: Preliminary S.I.**
  - Carry out geophysical survey (for large areas)

- **Stage 2: Detailed S.I.**
  - Boreholes at Critical Areas Interpreted from Stage 1

- **Stage 3: During Construction**
  - Rock Probing at Selected Columns to supplement Stage 2
Pile Design
Allowable Pile Capacity is the minimum of:

1) Allowable Structural Capacity

2) Allowable Geotechnical Capacity
   a. Negative Skin Friction
   b. Settlement Control
 Structural consideration

• Not overstressed during handling, installation & in service for pile body, pile head, joint & shoe.

• Dimension & alignment tolerances (common defects?)

• Compute the allowable load in soft soil (<10kPa) over hard stratum (buckling load)

• Durability assessment
Pile Capacity Design

Structural Capacity

- **Concrete Pile**
  \[ Q_{all} = 0.25 \times f_{cu} \times A_c \]

- **Steel Pile**
  \[ Q_{all} = 0.3 \times f_y \times A_s \]

- **Prestressed Concrete Pile**
  \[ Q_{all} = 0.25 \left( f_{cu} - \text{Prestress after loss} \right) \times A_c \]

- **Notation**:
  - \( Q_{all} \) = Allowable pile capacity
  - \( f_{cu} \) = characteristic strength of concrete
  - \( f_y \) = yield strength of steel
  - \( A_c \) = cross sectional area of concrete
  - \( A_s \) = cross sectional area of steel

- \( \text{Prestress after loss} \) refers to the reduction in prestress due to losses occurring during installation and time.
Pile Capacity Design

Geotechnical Capacity

Collection of SI Data

Depth Vs SPT-N Blow Count

SPT Blow Count per 300mm Penetration

Depth (m)

Upper Bound

Lower Bound

Design Line (Moderately Conservative)
Pile Capacity Design

Geotechnical Capacity

Collection of SI Data

Depth Vs SPT-N Blow Count

Depth (m)

SPT Blow Count per 300mm Penetration

Upper Bound

Design Line

Lower Bound

Depth Vs SPT-N Blow Count

Depth (m)

SPT Blow Count per 300mm Penetration

Upper Bound

Design Line

Lower Bound
Moderately Conservative Design Parameters

**Eurocode 7 definition:**

- Characteristic value of a geotechnical parameter shall be selected as a cautious estimate of the value affecting the occurrence of the limit state

- In other words, moderately conservative
Moderately Conservative Design Parameters

If at least 10 test results are available:

- A value of \(0.5D\) below the mean of the test results provides a useful indication of the characteristic value

2. Extracted from Prof. Brian Simpson’s Course Note (2-day Course on Eurocode 7 Geotechnical Design to EC7, 13-14 November 2007, PJ, Malaysia).
0.5 SD below the mean?

Extracted from Prof. Brian Simpson’s Course Note (2-day Course on Eurocode 7 Geotechnical Design to EC7, 13-14 November 2007, PJ, Malaysia).
Pile Capacity Design

Geotechnical Capacity

• Piles installed in a group may fail:
  • Individually
  • As a block
Pile Capacity Design

Geotechnical Capacity

- Piles fail individually
  - When installed at large spacing
Pile Capacity Design

*Geotechnical Capacity*

- Piles fail as a block
  - When installed at close spacing
Pile Capacity Design

Single Pile Capacity
Factor of Safety (FOS) is required for:

- Natural variations in soil strength & compressibility
Factor of Safety (FOS) is required for different degrees of mobilisation for shaft and for tip.
Pile Capacity Design

Factor of Safety (FOS)

Partial factors of safety for shaft & base capacities respectively

- For shaft, use 1.5 (typical)
- For base, use 3.0 (typical)

\[
Q_{\text{all}} = \frac{\sum Q_{su}}{1.5} + \frac{Q_{bu}}{3.0}
\]
Global factor of safety for total ultimate capacity

- Use 2.0 (typical)
- \[ Q_{all} = \frac{\sum Q_{su} + Q_{bu}}{2.0} \]
Pile Capacity Design

**Factor of Safety (FOS)**

- Calculate using **BOTH** approaches (Partial & Global)
- Choose the **lower** of the $Q_{all}$ values
Pile Capacity Design

Single Pile Capacity

\[ Q_u = Q_s + Q_b \]

\( Q_u \) = ultimate bearing capacity

\( Q_s \) = skin friction

\( Q_b \) = end bearing

Overburden Soil Layer
Pile Capacity Design

**Single Pile Capacity: In Cohesive Soil**

\[ Q_u = \alpha \cdot s_{us} \cdot A_s + s_{ub} \cdot N_c \cdot A_b \]

- \( Q_u \) = Ultimate bearing capacity of the pile
- \( \alpha \) = adhesion factor (see next slide)
- \( s_{us} \) = average undrained shear strength for shaft
- \( A_s \) = surface area of shaft
- \( s_{ub} \) = undrained shear strength at pile base
- \( N_c \) = bearing capacity factor (taken as 9.0)
- \( A_b \) = cross sectional area of pile base
Pile Capacity Design

**Single Pile Capacity: In Cohesive Soil**

Adhesion factor ($\alpha$) – Shear strength ($S_u$)  
(McClelland, 1974)

![Graph showing the relationship between $C_\alpha/S_u$ and $S_u$](image)

- Preferred Design Line

---

**Adhesion Factor**

<table>
<thead>
<tr>
<th>$S_u$ (kN/m²)</th>
<th>$C_\alpha/S_u$</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>0.6</td>
</tr>
<tr>
<td>75</td>
<td>0.4</td>
</tr>
<tr>
<td>100</td>
<td>0.2</td>
</tr>
<tr>
<td>SPT N</td>
<td>Meyerhof</td>
</tr>
<tr>
<td>-------</td>
<td>----------</td>
</tr>
<tr>
<td></td>
<td>$f_{su} = 2.5N$ (kPa)</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>2.5</td>
</tr>
<tr>
<td>5</td>
<td>12.5</td>
</tr>
<tr>
<td>10</td>
<td>25</td>
</tr>
<tr>
<td>15</td>
<td>37.5</td>
</tr>
<tr>
<td>20</td>
<td>50</td>
</tr>
<tr>
<td>30</td>
<td>75</td>
</tr>
<tr>
<td>40</td>
<td>100</td>
</tr>
</tbody>
</table>
Pile Capacity Design

Single Pile Capacity: In Cohesive Soil

Correlation Between SPT N and $f_{su}$
Values of undrained shear strength, $s_u$, can be obtained from the following:

- Unconfined compressive test
- Field vane shear test
- Deduce based on Fukuoka’s Plot (minimum $s_u$)

Red Check: Deduce from SPT-N values based on Meyerhof

NOTE: Use only direct field data for shaft friction prediction instead of Meyerhof
Modified Meyerhof (1976):

- Ult. Shaft friction = $Q_{su} \approx 2.5N$ (kPa)
- Ult. Toe capacity = $Q_{bu} \approx 250N$ (kPa)

or 9 $s_u$ (kPa)

(Beware of base cleaning for bored piles – ignore base capacity if doubtful)
Pile Capacity Design

**Single Pile Capacity: In Cohesionless Soil**

Modified Meyerhof (1976):

- Ult. Shaft Friction = $Q_{su} \approx 2.0\text{N (kPa)}$
- Ult. Toe Capacity = $Q_{bu} \approx 250\text{N} - 400\text{N (kPa)}$
Pile Capacity Design

Single Pile Capacity: For Bored Piles

Semi-empirical Method (SPT-N)

Shaft: $f_{su} = K_{su} \times SPT-N$

Tip: $f_{bu} = K_{bu} \times SPT-N$

From Malaysian experience:

$K_{su} = 2.0$

$K_{bu} = 7.0$ to 60 (depending on workmanship)
Pile Capacity Design

*Single Pile Capacity: For Bored Piles*

- Base cleaning of bored piles
  - Difficult and no practical means of verification during construction available

- Base resistance require **large movement** to mobilise

- Base contribution in bored pile design **ignored** unless proper base cleaning can be assured and verified (or base grouting, etc.)
Rock Socket Design

Rock Socket Design Factors:

- **Socket Roughness** (*Shearing Dilation*)
- Intact Rock UCS, $q_{uc}$
- **Confining Stiffness** (*Rock mass fractures & Pile Diameter*)
- **Socket Geometry Ratio**

Socket Resistance, $f_s = \alpha \times \beta \times q_{uc}$
$\alpha$ - Factor (after Tomlinson, 1995)

Rock socket skin friction

$= f_s = \alpha \beta q_{uc}$

- Williams and Pells
- Rosenberg and Journeaux
- Horvath
$\beta$ - Factor (after Tomlinson, 1995)
Point Load Test
(UCS of Intact Rock)
Load Transfer Profile of Rock Socket

(after Pells & Tuner, 1979)
## Summary of Rock Socket Friction Design Values (updated from Tan & Chow, 2003)

<table>
<thead>
<tr>
<th>Rock Formation</th>
<th>Working Rock Socket Friction*</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limestone</td>
<td>300kPa for RQD &lt; 30%</td>
<td>Authors</td>
</tr>
<tr>
<td></td>
<td>400kPa for RQD = 30 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>500kPa for RQD = 40 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>600kPa for RQD = 55 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>700kPa for RQD = 70 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>800kPa for RQD &gt; 85%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>The above design values are subject to 0.05x minimum of (q_{uc}, f_{cu}) whichever is smaller.</td>
<td></td>
</tr>
<tr>
<td>Sandstone</td>
<td>0.10(q_{uc})</td>
<td>Thorne (1977)</td>
</tr>
<tr>
<td>Shale</td>
<td>0.05(q_{uc})</td>
<td>Thorne (1977)</td>
</tr>
<tr>
<td>Granite</td>
<td>1000 – 1500kPa for (q_{uc}) &gt; 30N/mm²</td>
<td>Tan &amp; Chow (2003)</td>
</tr>
</tbody>
</table>

Where:
- RQD = Rock Quality Designation
- \(q_{uc}\) = Unconfined Compressive Strength of rock
- \(f_{cu}\) = Concrete grade
End Bearing Design in Rock

Only designed when

- Dry Hole
- Base Cleaning & Inspection are possible
Pile Capacity Design

Block Capacity
\[ Q_u = 2D(B+L) \, s + 1.3(s_b \cdot N_c \cdot B \cdot L) \]

Where

- \( Q_u \) = ultimate bearing capacity of pile group
- \( D \) = depth of pile below pile cap level
- \( B \) = width of pile group
- \( L \) = length of pile group
- \( s \) = average cohesion of clay around group
- \( s_b \) = cohesion of clay beneath group
- \( N_c \) = bearing capacity factor = 9.0

(Refer to Text by Tomlinson, 1995)
No risk of group failure
if FOS of individual pile is adequate
Pile Capacity Design

*Block Capacity: On Rock*

No risk of block failure

if the piles are properly seated in the rock formation
Pile Capacity Design
Negative Skin Friction (NSF)
Compressible soil layer consolidates with time due to:
- Surcharge of fill
- Lowering of groundwater table
Pile Capacity Design

**Negative Skin Friction**

- **Clay**
- **Fill**
- **QGL**
- **Hf**
- **ρs**

Month

- 0
- 1
- 2
- 3 Month

Fill Capacity Design
Pile Capacity Design

Negative Skin Friction

Pile to length (floating pile)

- Pile settles with consolidating soil → NO NSF
Pile to set at hard stratum (end-bearing pile)

- Consolidation causes **downdrag** forces on piles as soil settles more than the pile
Design Considerations

- Skin Friction

Soil Settlement > Pile Settlement

Positive Skin Friction

Negative Skin Friction

Load

Original Ground Level
Negative Skin Friction

Soil Settlement > Pile Settlement

End-Bearing Crushing of Pile!!!
Negative Skin Friction

Soil Settlement > Pile Settlement

Load
Load
Load

Original Ground Level

Soil Settlement > Pile Settlement

Friction Pile – Excessive Settlement
Negative Skin Friction

Pile Settlement >
Soil Settlement

Load

Soil Settlement > Pile Settlement

Load

Positive Skin Friction

Load

Negative Skin Friction

End-Bearing Pile –
Crushing of Pile!!!

Load

Friction Pile –
Excessive Settlement
WARNING:

- No free fill by the contractor to avoid NSF
Effect of NSF …

Reduction of Pile Carrying Capacity
Effect of NSF ...
NSF Preventive Measures

- Avoid Filling
- Carry Out Surcharging
- Sleeve the Pile Shaft
- Slip Coating
- Reserve Structural Capacity for NSF
- Allow for Larger Settlements
Clay
Sand
OGL
Qba
Qneg
Sand
Clay
OGL
Qall = (Qsu/1.5 + Qbu/3.0)
Qall = (Qsu/1.5 + Qbu/3.0) - Qneg
Pile Capacity Design
Negative Skin Friction

Qall = (Q_{su}/1.5 + Q_{bu}/3.0)
Qall = (Q_{su}/1.5 + Q_{bu}/3.0) - Q_{neg}
Pile Capacity Design

**Negative Skin Friction**

**Increased Pile Axial Load**

Check: maximum axial load < structural pile capacity
Pile Capacity Design

Factor of Safety (FOS)

Without Negative Skin Friction:

\[
\text{Allowable working load} = \frac{Q_{\text{ult}}}{\text{FOS}}
\]

With Negative Skin Friction:

\[
\text{Allowable working load} = \frac{Q_{\text{ult}}}{\text{FOS}} - (Q_{\text{neg}} + \text{etc})
\]
Pile Capacity Design

Static Pile Load Test (Piles with NSF)

- Specified Working Load (SWL) = Specified foundation load at pile head
- Design Verification Load (DVL) = SWL + 2 $Q_{neg}$
- Proof Load: will not normally exceed
  
  DVL + SWL
Pile Settlement Design
Pile Settlement Design

*In Cohesive Soil*

- Design for *total* settlement & *differential* settlement for design tolerance
- In certain cases, *total* settlement not an issue
- *Differential* settlement can cause damage to structures
Pile Settlement Design

In Cohesive Soil

Pile Group Settlement in Clay

= Immediate / Elastic Settlement + Consolidation Settlement
**IMMEDIATE SETTLEMENT**

\[
p_i = \frac{\mu_1 \mu_0 q_n B}{E_u}
\]

by Janbu, Bjerrum and Kjaernsli (1956)

Where

- \(p_i\) = average immediate settlement
- \(q_n\) = pressure at base of equivalent raft
- \(B\) = width of the equivalent raft
- \(E_u\) = deformation modulus
- \(\mu_1, \mu_0\) = influence factors for pile group width, \(B\) at depth \(D\) below ground surface
Pile Settlement Design

*In Cohesive Soil*

**IMMEDIATE SETTLEMENT**

Influence factors (after Janbu, Bjerrum and Kjaernsli, 1956)
Pile Settlement Design

*In Cohesive Soil*

**CONSOLIDATION SETTLEMENT**

As per footing (references given later)
Pile Settlement Design

On Rock

No risk of excessive settlement
Pile Installation Methods
PILE INSTALLATION

METHODS

- Diesel / Hydraulic / Drop Hammer Driving
- Jacked-In
- Prebore Then Drive
- Prebore Then Jacked In
- Cast-In-Situ Pile
Diesel Drop Hammer Driving

Hydraulic Hammer Driving
Jacked-In Piling
Jacked-In Piling (Cont’d)
Cast-In-Situ Piles (Micropiles)

THE MICROPILE INSTALLATION PROCESS

1. Setting casing and drilling of bore hole over pile position.
2. Lowering the Down the Hole hammer for hard material drilling after ensuring hole is truly vertical.
3. Installation of the micropile structural member by lowering the steel bars into the drilled hole.
4. Checking to ensure drilled hole formed is washed and cleared before grouting.
5. Trench grouting in progress.
6. Pour bar micropile system ready to be incorporated into the pile cap.
Types of Piles
TYPES OF PILES

• Treated Timber Piles
• Bakau Piles
• R.C. Square Piles
• Pre-Stressed Concrete Spun Piles
• Steel Piles
• Boredpiles
• Micropiles
• Caisson Piles
R.C. Square Piles

- Size: 150mm to 400mm
- Lengths: 3m, 6m, 9m and 12m
- Structural Capacity: 25Ton to 185Ton
- Material: Grade 40MPa Concrete
- Joints: Welded
- Installation Method:
  - Drop Hammer
  - Jack-In
RC Square Piles
Pile Marking
Pile Lifting
Pile Fitting to Piling Machine
Pile Positioning
Pile Joining
Considerations in Using RC Square Piles ...

• Pile Quality
• Pile Handling Stresses
• Driving Stresses
• Tensile Stresses
• Lateral Loads
• Jointing
Pre-stressed Concrete Spun Piles

- Size: 250mm to 1000mm
- Lengths: 6m, 9m and 12m (Typical)
- Structural Capacity: 45Ton to 520Ton
- Material: Grade 60MPa & 80MPa Concrete
- Joints: Welded
- Installation Method:
  - Drop Hammer
  - Jack-In
Spun Piles
Spun Piles vs RC Square Piles

Spun Piles have …

- **Better Bending Resistance**
- **Higher Axial Capacity**
- **Better Manufacturing Quality**
- **Able to Sustain Higher Driving Stresses**
- **Higher Tensile Capacity**
- **Easier to Check Integrity of Pile**
- **Similar cost as RC Square Piles**
Steel H Piles

- Size: 200mm to 400m
- Lengths: 6m and 12m
- Structural Capacity: 40Ton to 1,000Ton
- Material: 250N/mm² to 410N/mm² Steel
- Joints: Welded
- Installation Method:
  - Hydraulic Hammer
  - Jack-In
Steel H Piles
Steel H Piles (Cont’d)
Steel H Piles Notes...

- Corrosion Rate
- Fatigue
- OverDriving
OverDriving
of Steel Piles
Large Diameter Cast-In-Situ Piles (Bored Piles)

- Size: 450mm to 2m
  (Up to 3.0m for special case)
- Lengths: Varies
- Structural Capacity: 80Ton to 2,300Tons
- Concrete Grade: 20MPa to 35MPa (Tremie)
- Joints: None
- Installation Method: Drill then Cast-In-Situ
Overburden Soil Layer

Bedrock

Drilling

Borepile Construction
Advance Drilling

Overburden Soil Layer

Bedrock

Borepile Construction
Overburden Soil Layer

Bedrock

Drilling & Advance
Casing
Borepile Construction

Drill to Bedrock

Overburden Soil Layer

Bedrock
Lower Reinforcement Cage

Overburden Soil Layer

Bedrock
Borepile Construction

Lower Tremie Chute

Overburden Soil Layer

Bedrock
Borepile Construction

Pour Tremie Concrete

Overburden Soil Layer

Bedrock
Completed Borepile

Overburden Soil Layer

Bedrock
Bored Pile Construction

BORED PILING MACHINE

BG22
Cleaning Bucket
Rock Reamer
Rock Auger
Rock Chisel

Harden Steel
Bored Pile Construction

DRILLING EQUIPMENT

Cleaning bucket

Coring bucket

Soil auger
BENTONITE PLANT

Bored Pile Construction

Desanding Machine

Water Tank

Mixer

Slurry Tank
Drilling
Lower Reinforcement
Place

Tremie

Concrete
Completed Boredpile
Borepile Cosiderations...

• Borepile Base Difficult to Clean
• Bulging / Necking
• Collapse of Sidewall
• Dispute on Level of Weathered Rock
Micropiles

- **Size**: 100mm to 350mm Diameter
- **Lengths**: Varies
- **Structural Capacity**: 20Ton to 250Ton
- **Material**: Grade 25MPa to 35MPa Grout
  - N80 API Pipe as Reinforcement
- **Joints**: None
- **Installation Method**:
  - Drill then Cast-In-Situ
  - Percussion Then Cast-In-Situ
Cast-In-Situ Piles (Micropiles)
TYPES OF PILE SHOES

• Flat Ended Shoe
• Oslo Point
• Cast-Iron Pointed Tip
• Cross Fin Shoe
• H-Section
Cross Fin Shoe

Do more harm in inclined rock surface!
Cast Iron Tip Shoe

Do more harm in inclined rock surface!
H-Section Shoe

Do more harm in inclined rock surface!
Piling Supervision
4. (1) A local authority may if it is of the view that any plan, drawing or calculation is beyond the competence of such qualified person submitting the same, require such person to submit a certificate from the relevant competent authority responsible for registering such qualified person, certifying that such plan, drawing or calculation is within the competence of such qualified person submitting the same.

(2) A local authority shall accept any returned plan, drawing or calculation if the same were re-submitted together with a certificate from the relevant competent authority responsible for registering such qualified person, certifying that such plan, drawing or calculation is within the competence of such qualified person submitting the same.

5. Where under these By-laws any plan, drawing or calculation in relation to any building is required to be submitted by qualified person, no erection or continued erection of that building shall take place unless that qualified person or any person duly authorised by him undertakes the supervision of the erection and the setting out, where applicable, of that building.

6. (1) All plans submitted shall be signed by the qualified person and by the owner or his agent and shall bear the full address of the owner.

(2) The local authority may, if satisfied that the owner of the premises has refused to or has failed to execute any work which is required under the Act to be executed by him, direct the owner of the premises in writing to execute such work.

7. (1) The qualified person submitting the plans shall be responsible for the proper execution of the works and shall continue to be so responsible until the completion of the works unless...
PILING SUPERVISION

• Ensure That Piles Are **Stacked Properly**
• Ensure that Piles are **Vertical During** Driving
• Keep **Proper Piling Records**
• Ensure Correct Pile Types and Sizes are Used
• Ensure that Pile Joints are Properly Welded with NO GAPS
• Ensure Use of Correct Hammer Weights and Drop Heights
PILING SUPERVISION
(Cont’d)

• Ensure that Proper Types of Pile Shoes are Used.
• Check Pile Quality
• Ensure that the Piles are Driven to the Required Lengths
• Monitor Pile Driving
FAILURE OF PILING SUPERVISION

Failing to Provide Proper Supervision WILL Result in Higher Instances of Pile Damage & Wastage
Pile Damage
Driven concrete piles are vulnerable to damages by overdriving.
Damage to Timber Pile
Damage To RC Pile Toe
Damage to RC Pile Head
Damage to RC Piles
Damage to RC Piles – cont’d
Damage to Steel Piles
Damaged Steel Pipe Piles
Piling Problems
Piling Problems – Soft Ground
Ground heave due to pressure relief at base & surcharge near excavation.

Pile tilts & moves/walks.
Piling Problems – Soft Ground
Piling in Kuala Lumpur Limestone

**Important Points to Note:**

- Highly Irregular Bedrock Profile
- Presence of Cavities & Solution Channels
- Very Soft Soil Immediately Above Limestone Bedrock

**Results in ...**

- High Rates of Pile Damage
- High Bending Stresses
Piling Problems in Typical Limestone Bedrock

- Cliff
- Overhang
- Pinnacle
- Floater
- Collapsed cavity
- Sinkhole
- Ground surface
- Limestone
- Kenny Hill
- Residual soil
- Cavity
Piling Problems – Undetected Problems

FIG 5: PILING PROBLEMS
Piling Problems – Coastal Alluvium

FIG 6: PILING PROBLEMS IN COASTAL ALLUVIUM
Piling Problems – Defective Piles

Seriously damaged pile due to severe driving stress in soft ground (tension)

Defect due to poor workmanship of pile casting
Piling Problems – Defective Piles

Defective pile shoe

Problems of defective pile head & overdriving!
Piling Problems – Defective Piles

Non-chamfered corners

Cracks & fractured
Pile head defect due to hard driving or and poor workmanship
Piling Problem - Micropiles

Sinkholes caused by installation method-dewatering?
Piling in Fill Ground

Important Points to Note:

• High Consolidation Settlements If Original Ground is Soft

• Uneven Settlement Due to Uneven Fill Thickness

• Collapse Settlement of Fill Layer If Not Compacted Properly

Results in . . .

• Negative Skin Friction (NSF) & Crushing of Pile Due to High Compressive Stresses

• Uneven Settlements
Typical Design and Construction Issues #1

**Issue #1**

Pile Toe Slippage Due to Steep Incline Bedrock

**Solution #1**

Use Oslo Point Shoe To Minimize Pile Damage
Pile Breakage on Inclined Rock Surface

No Proper Pile Shoe
Extension Pile

Pile Joint

Extension Pile
First Contact
B/W Toe and Inclined Rock
Pile Joint Breaks

Pile Body Bends

Toe “Kicked Off” on Driving
Pile Breakage on Inclined Rock Surface

Continue “Sliding” of Toe
Use Oslo Point Shoe to Minimize Damage
**Design and Construction Issues #2**

**Issue #2**
Presence of Cavity

**Solution #2**
Detect Cavities through Cavity Probing then perform Compaction Grouting
Presence of Cavity

Pile Sitting on Limestone with Cavity
Application of Building Load
Application of Building Load

Roof of Cavity starts to Crack …
Building Collapse

Pile Plunges!

Collapse of Cavity Roof
Issue #3
Differential Settlement

Solution #3
Carry out analyses to check the settlement compatibility if different piling system is adopted
Differential Settlement of Foundation

Original House on Piles

No Settlement

Soft Layer

Piles transfer Load to Hard Layer

No pile

Hard Layer

SPT>50

Cracks!!

SAFETY of Original Building Not Compromised

Renovation: Construct Extensions

Settlement
Eliminate Differential Settlement

Construct Extension with Suitable Piles

All Load transferred to Hard Layer – No Cracks!
Problem of Short Piles

- Cracks!!
- Construct Extensions with Short Piles

Soft Layer

Load from Original House transferred to Soft Layer

Soft!

Hard Layer

Load transferred to Soft Layer, Extension still Settles

Load from Original House transferred to Hard Layer

SPT>50
Cracks at Extension
Costly conventional piling design – piled to set to deep layer in soft ground

Solution #4

- Strip footings / Raft
- Floating Piles
Low Rise Buildings (Link Houses)

Conventional Pile System

Pile Strip/Raft System

25m to 30m
Very Soft to Soft Compressible Clay
($\mathbf{S_u}$ = 15 to 45 kPa)

Medium Stiff to Stiff Clayey Silt with Sand
(SPT’N = 5 to 35 Blows/ft)

Hard Stratum (SPT’N $\geq$ 50 Blows/ft)
“Conventional” Foundation for Low Rise Buildings
Foundation for Low Rise Buildings (Soil Settlement)
Exposed Pile Settlement

Settling Platform Detached from Building
Conceptual Design of FOUNDATION SYSTEM

1. Low Rise Buildings :-
   (Double-Storey Houses)
   = Strip Footings or Raft or Combination.

2. Medium Rise Buildings :-
   = Floating Piles System.
Low Rise Buildings on Piled Raft/Strips

Strip / Raft System

Fill

25-30m Soft Clay

Stiff Stratum

Hard Layer
Comparison

Building on Piles

Building on Piled Strips

- Fill
- 25-30m Soft Clay
- Strip System
- Stiff Stratum
- Hard Layer
Comparison (after settlement)

Building on Piles

Building on Piled Strips

- Stratum
- Hard Layer

Fill

25-30m Soft Clay

Strip System

Stiff Stratum

Hard Layer
Advantages of Floating Piles System

1. Cost Effective.

2. No Downdrag problems on the Piles.

Bandar Botanic at Night
Soft Ground Engineering

End Bearing System

2500-Ton Oil Storage Steel Tank

1.5m Sand Fill

30m Very Soft Compressible Marine Clay

12m Medium Soft Clay

Completed Tank Structure

Adopted

Floating System

2500-Ton Oil Storage Steel Tank

1.5m Sand Fill

30m Very Soft Compressible Marine Clay

12m Medium Soft Clay

2500 Ton Oil Storage Steel Tank

R.C. Tank Raft

Completed Tank Structure

Adopted
Typical Design and Construction Issues #5

Issue #5
Load test results far below predicted pile capacity

Solution #5
- Modifications to test set-up
- Change of pile installation method
- Adequate soil plug to prevent toe softening
Testing Set-up Using Reaction Piles
Testing Set-up

- Long reaction piles at close spacing used

- Case histories:
  - Load tests using reaction piles give ERRATIC results
Fig. 1. The result of 2 load tests on the same pile. Test 1 with anchor piles; test 2 with dead weight.

- Tested using anchor piles: \( \approx 1100 \text{kN} \)
- Tested using kentledge: \( \approx 2100 \text{kN} \)

Approx. 2 times smaller using reaction piles!

Ref: A.F. van Weele, 1993
Reaction piles

Zone of interaction with test pile

Test pile

Reaction piles
Testing Set-up

- Latest version of ASTM D1143
- Published April 2007

Designation: D 1143/D 1143M – 07


This standard is issued under the fixed designation D 1143/D 1143M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This standard has been approved for use by agencies of the Department of Defense.
Testing Set-up

- ASTM D1143
  - Clear distance of at least 5 times the maximum diameter
  - Caution on factors influencing results:
    - “Possible interaction ..........from anchor piles.......”
Drilling to the Casing Tip to Form “Bored Pile”
Drilling to Form “Bored Pile”

- Disturbance to soil at tip and surrounding the pile
- Potential hydraulic/basal heave failure resulting in lower soil strength
- Effect more severe for longer pile
Construction of “Bored Pile”

1. Install Permanent Steel Casing to Pile Toe

2. Removal of Soil within Steel Casing to Toe of Casing

3. Installation of Reinforcement and Concreting
Drilling to Form “Bored Pile”

- Pile behaviour COMPLICATED!
  - Influenced by steel casing which behave like **DRIVEN PILE**
  - Influenced by soil removal which behave like **BORED PILE**
SAND UPHEAVAL AFTER 3 HRS
Zone of Weakened Soil due to Installation of Steel Casing using Vibro-hammer

Further Soil Disturbance – Magnitude of Disturbance?????

Pressure from Drilling Fluid

Pressure from Soil + Water

Pressure from Soil + Water > Pressure from Drilling Fluid
Probable causes of erratic and unpredictable pile capacities:

- Testing set-up using reaction piles
- Drilling to the casing tip to form “bored pile”
Original Load Test

- 1\textsuperscript{st} Load Test – Failed at 90\% of WL
  - After 32 days

- 2\textsuperscript{nd} Load Test – Failed at 110\% of WL
  - After 94 days
Recommendations:

- Open-ended spun pile or steel pipe pile with adequate soil plug
- Use of impact hammer instead of vibro-hammer
- Trial piles for correlation between static load test and high strain dynamic load test
Pile performs satisfactorily within acceptable settlement limits!!!

Settlement at 1WL = 12.5mm
Load Test Results at P52W

- Result for Empty Casing
  - 1xWL: pile settlement = 20mm
    (residual settlement = 1mm)
  - 1.9xWL: pile settlement = 50mm
    (residual settlement = 3mm)

- Result for Cast Pile
  - 1xWL: pile settlement = 12.5mm
    (residual settlement = 1mm)
  - 2xWL: pile settlement = 33.4mm
    (residual settlement = 7mm)

The Pile is Stiffer after Concreting !!

Larger Residual Settlement due to Disturbance from RCD work !!
Load Test Results at P52W

- Research by Ng et al., 2001:
  - Elastic compression of large diameter bored piles:
    - $\frac{1}{2}$ PL/AE - Piles founded in soil
    - $\frac{3}{4}$ PL/AE - Piles founded in rocks
Result for Concreted Pile

Piles founded in SOIL: ½ PL/AE

Piles founded in ROCK: ¾ PL/AE

Settlement is in accordance to prediction!
ELASTIC COMPRESSION OF PILE

- Depends on:
  - E – Elastic Modulus of Pile Material
  - A – Cross-sectional Area of Pile
  - L – Pile Length

Elastic Compression = f (PL / AE)

Therefore, after concreting of pile:
- A increased significantly (composite E due to steel and concrete reduced slightly)
- Elastic compression will reduce
Pile Settlement Criteria

- Pile settlement criteria depends on
  - Pile Size
  - Pile Material (e.g. steel, concrete, etc.)
  - Pile Length

- Unrealistic to adopt same settlement criteria (e.g. 12mm) for all piles (regardless of length, size, etc.)
Myths in Piling
MYTHS IN PILING #1

Myth:
Dynamic Formulae such as Hiley’s Formula Tells us the Capacity of the Pile

Truth:
Pile Capacity can only be verified by using:
(i) Maintained (Static) Load Tests
(ii) Pile Dynamic Dynamic Analyser (PDA) Tests
Myth:

Pile Achieves Capacity When It is Set.

Truth:

Pile May Only “Set” on Intermediate Hard Layer BUT May Still Not Achieve Required Capacity within Allowable Settlement.
MYTHS IN PILING #3

Myth:

Pile settlement at 2 times working load must be less than certain magnitude (e.g. 38mm)

Truth:

Pile designed to Factor of Safety of 2.0. Therefore, at 2 times working load: Pile expected to fail unless capacity under-predicted significantly
Pile Capacity Design

*Factor of Safety (FOS)*

Global factor of safety for total ultimate capacity

- Use 2.0 (typical)
- \[ Q_{all} = \frac{\Sigma Q_{su} + Q_{bu}}{2.0} \]
CASE HISTORIES

- Case 1: Structural distortion & distresses
- Case 2: Distresses at houses
CASE HISTORY 1
Distortion & Distresses on 40 Single/ 70 Double Storey Houses

- Max. 20m Bouldery Fill on Undulating Terrain
- Platform Settlement
- Short Piling Problems
- Downdrag on Piles
Distresses on Structures
Prevention Measures

- **Design:**
  - Consider *downdrag* in foundation design
  - Alternative strip system

- **Construction:**
  - Proper QA/QC
  - Supervision
CASE HISTORY 2
Distresses on 12 Double Storey Houses & 42 Townhouses

- Filled ground: platform settlement
- Design problem: non-suspended floor with semi-suspended detailing
- Bad earthwork & layout design
- Short piling problem
Diagonal cracks due to differential settlement between columns

Larger column settlement
Sagging Ground Floor Slab
SAGGING PROFILE OF NON-SUSPENDED GROUND FLOOR SLAB

NON-SUSPENDED GROUND FLOOR SLAB BEFORE SETTLEMENT

BUILDING PLATFORM PROFILE AFTER SETTLEMENT

PILE

PILECAP

$\rho_S$ — ACTUAL FILLED PLATFORM SETTLEMENT

$V_e > V_c$

$V_c$

$V_c < V_e$
Distorted Car Porch Roof
Poor Earthwork Layout

Silt trap

Temporary earth drain

Legend:
- Mackintosh probe for Block 2
- Mackintosh probe for Block 1
Prevention Measures

- **Planning:**
  - Proper building layout planning to suit terrain (eg. uniform fill thickness)
  - Sufficient SI

- **Design:**
  - Consider filled platform settlement
  - Earthwork layout

- **Construction:**
  - Supervision on earthwork & piling
SUMMARY

- Importance of Preliminary Study
- Understanding the Site Geology
- Carry out Proper Subsurface Investigation that Suits the Terrain & Subsoil
- Selection of Suitable Pile
- Pile Design Concepts
SUMMARY

- Importance of Piling Supervision
- Typical Piling Problems Encountered
- Present Some Case Histories
CHALLENGING THE NORM
WITH TEAMWORK WE SHALL EXCEL TO HIGHER HORIZON

FERRARI'S PITSTOP WAS COMPLETED BY 15 MECHANICS (FUEL AND TYRES) IN 6.0 SECONDS FLAT.

54 PEOPLE TOOK PART IN THIS CONCERTED ACROBATIC JUMP.
Thank You for Your Attention