Use of Limit State Design in Foundation Engineering
(Patrick Wong 17 April 2012)
Presentation Outline

1. Working Stress Design Method
2. Limit State Design Method
3. Comparison between the two methods
4. Case Study (Barangaroo South)
5. Conclusions
Working Stress Design Method

Structural Engineers often ask the Geotechnical Engineers to provide:

- “allowable” bearing pressure for footings
- “allowable” shaft friction and “allowable” end bearing pressure for piles
But what does “Allowable” mean? Is it:

- Ultimate Capacity / Factor of Safety (FOS)?
  or FOS can be rewritten as:
- FOS = Ultimate Capacity / Working Load
But what is the appropriate FOS (2, 2.5, 3)?

- FOS = \( \frac{R_{ug}}{P_w} \) should be dependent on allowable deformation & stiffness of the foundation.
Choice of FOS is also affected by uncertainty in material properties

Legend
- Concrete
- Soil
- Mean strength
Working Stress Design Summary:

- “Allowable” load = Ultimate Capacity / FOS
- FOS should be dependent on:
  - tolerable deformation
  - foundation stiffness (linear or non-linear?)
  - uncertainties in material properties/behaviour
But these factors are rarely considered adequately in Working Stress Design

Example of “Allowable” Design Parameters given in a Recent Site Investigation Report (settlement <1% footing width)

<table>
<thead>
<tr>
<th>Rock Class</th>
<th>Rock Strength</th>
<th>Allowable End Bearing Pressure (kPa)</th>
<th>Allowable Shaft Adhesion (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IV Shale</td>
<td>Extremely low to very low</td>
<td>800</td>
<td>80</td>
</tr>
<tr>
<td>III Shale</td>
<td>Medium strength</td>
<td>3000</td>
<td>300</td>
</tr>
<tr>
<td>II Shale</td>
<td>High strength</td>
<td>8000</td>
<td>800</td>
</tr>
</tbody>
</table>
Why Limit State Design?

1960’s identified two specific classes of problem not adequately addressed by working stress designs:

• Failures under extreme low probability events
• Over-design in redundant structures
Failures under low probability events
Failures under low probability events

DESIGN WIND LOAD

Self weight less overtuning = net compression

frictional resistance
Failures under low probability events

- **DESIGN WIND LOAD**
  - Self weight less overtuning = net compression
  - Frictional resistance

- **EXTREME WIND LOAD**
  - Self weight less overtuning = net uplift
  - Sliding

- **BUCKLE AND COLLAPSE**

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Coffey Geotechnics
Specialists managing the Earth
Redundancy and indeterminate structures
Foundation Engineering

Definition of the Ultimate Limit State (ULS)

Definition in Austroads 1992 for foundations:

a. a limit state at which a mechanism is formed in the ground

b. a limit state which involves a loss of static equilibrium or rupture of a critical section of the structure due to movements in the ground
Definition of the Serviceability Limit State (SLS)

• Similar to working stress loads BUT strength of the structure is not directly considered.
• Acceptance criteria relate to the structure being able to perform its intended function in terms of deflections, crack widths, appearance etc.
The Ultimate Limit State Inequality Formula

\[
\text{ULS Loads} \leq \text{Design Geotech Resistance}
\]

\[
S^* = \Psi S \leq \Phi_g R_{ug} = R_{ug}^*
\]
The Ultimate Limit State Inequality Formula

\[ S^* = \Psi S \leq \Phi_g R_{ug} = R_{ug}^* \]

Load factor typically >1
The Ultimate Limit State Inequality Formula

\[ S^* = \Psi S \leq \Phi_g R_{ug} = R_{ug}^* \]

(Resistance)
Strength factor typically < 1
The Ultimate Limit State Inequality Formula

\[ S^* = \Psi S \leq \Phi_g R_{ug} = R_{ug}^* \]

- Assumes probability approximates to a constant factor
- Assumes loads and resistance are independent
Idealised Probability Distribution

Load Factor ~ 1.8
Strength Factor ~ 0.6
Probability of failure

Factor of Safety ~ 3.0
More Realistic Probability Distribution

"Realistic" Probability distributions of a simple loading including 5% characteristic values

Higher probability for smaller loads
Confusions In Terminology

Structural Engineer: “ULTIMATE LOAD”
(= ULS Load = S*)
Confusions In Terminology

Structural Engineer: “ULTIMATE LOAD”
(= ULS Load = S*)

Geotechnical Engineer: “ULTIMATE CAPACITY”
(= R_{ug})
Confusions In Terminology

Structural Engineer: “ULTIMATE LOAD”
(= ULS Load = S*)

Geotechnical Engineer: “ULTIMATE CAPACITY”
(= $R_{ug}$)

$S^* \leq R_{ug}^* = \Phi_g \cdot R_{ug}$

=> Out by a factor of
$\Phi = 0.4$ to $0.8$?
Confusions In Terminology

Geotechnical Engineer:
“ALLOWABLE LOAD”
(= $R_{ug}/FOS$)
Confusions In Terminology

Structural Engineer: “???”
(S or S* ?)

Geotechnical Engineer: “ALLOWABLE LOAD”
(= R_{ug}/FOS)
Confusions In Terminology

Structural Engineer: “???”
(S or S* ?)

Geotechnical Engineer: “ALLOWABLE LOAD”
(= R_{ug}/FOS)

\[ \Psi \cdot S = S^* \leq R_{ug}^* = \Phi_g \cdot R_{ug} \]
⇒ Out by a factor of
\[ \Psi = 1.2 \text{ to } 1.5? \]
Quick Recap:

Limit State Design Requirements

Part 1 - Strength Limit State

\[ R_{ug}^* \geq S^* \]

\[ \Phi_g R_{ug} \geq \Psi S \]

Failure mechanism does not form due to deflections
The Limit State Design Requirements

Part 2 - Serviceability Limit State

Under the serviceability loading, the resulting deflection does not exceed the tolerable limit.
Comparison with Working Stress

- Shallow Square Pad Footing Problem on a Stiff Clay
Comparison with Working Stress

Working Stress:

\[ \frac{R_{\text{ug}}}{\text{FoS}} \geq S \]

e.g. \( \frac{R_{\text{ug}}}{3.0} \geq S \) for a shallow footing

Limit State:

\[ R_{\text{ug}*} \geq S^* \]
\[ \Phi_g R_{\text{ug}} \geq \Psi S \]
\[ \frac{R_{\text{ug}}}{(\Psi/\Phi_g)} \geq S \]

For typical \( \Psi = 1.3 \) and \( \Phi_g = 0.7 \), \( (\Psi/\Phi_g) = 1.86 \)

\[ \frac{R_{\text{ug}}}{1.86} \geq S \]

But the design is not quite finished!
For the this example:
- \( S = 1200\text{kN} \)
- \( S^* = 1.3 \times 1200 = 1560\text{kN} \)
- Rug = 600kPa

**Working stress:**
- Rug/3 = 200kPa
- B = 2.45m
- E at working stress = 20MPa
- Settlement = 22mm

**Limit State:**
- Rug* = Rug × 0.7 = 420kPa
- B = 1.95m
- Serviceability stress = 316kPa
- E at this stress level = 16MPa
- Settlement = 35mm (may need to increase footing width if settlement is unacceptable)
Deformation is a Key Design Issue

In both methods, likely settlement should be assessed but rarely done in Working Stress Design

Why?
Case Study – Barangaroo South (the site)
Case Study – Barangaroo South (site plan)

~ 4 ha
Case Study – Barangaroo South (geotech conditions)
Case Study – Barangaroo South (Rock Levels)
(top of rock RL0m to -28mAHD)
Case Study – Barangaroo South (design parameters)

1. Geotechnical investigation commissioned on a competitive basis

2. Standard brief requested the provision of “design parameters”

3. Report provided geotechnical design parameters based on well known guide used in Sydney (Pells et al, 1998)

4. Both “Limit State” and “Serviceability” design values provided in geotechnical investigation report
Case Study – Barangaroo South (design parameters)

<table>
<thead>
<tr>
<th>Sandstone Rock Class</th>
<th>Unit</th>
<th>Working Stress Design Values</th>
<th>Limit State Design Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Allowable End Bearing Pressures (MPa)</td>
<td>Allowable Shaft Adhesion (kPa)</td>
</tr>
<tr>
<td>V</td>
<td>4A</td>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td>IV</td>
<td>4B</td>
<td>1.5</td>
<td>150</td>
</tr>
<tr>
<td>III</td>
<td>4C</td>
<td>3.5</td>
<td>400</td>
</tr>
<tr>
<td>II</td>
<td>4D</td>
<td>8</td>
<td>800</td>
</tr>
</tbody>
</table>

Note FOS ranges from 3 to 10
Case Study – Barangaroo South (Pile Design Loads)

Building C4
## Building C4 – Typical Loads & Settlement Limits

<table>
<thead>
<tr>
<th>Pile Diameter (m)</th>
<th>ULS (MN)</th>
<th>SLS (MN)</th>
<th>Pile Toe Settlement Limit at SLS (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.4 to 17.5</td>
<td>7.2 to 14.4</td>
<td>3</td>
</tr>
<tr>
<td>1.18</td>
<td>20.5 to 28</td>
<td>16.7 to 23</td>
<td>3.5</td>
</tr>
<tr>
<td>1.5</td>
<td>26.9 to 32</td>
<td>24.2 to 25.9</td>
<td>4.5</td>
</tr>
<tr>
<td>2.4</td>
<td>90.5 to 101.4</td>
<td>72.6 to 81.4</td>
<td>7.2</td>
</tr>
</tbody>
</table>
Case Study – Barangaroo South (Design)

1. Preliminary design using “allowable” design values resulted in long socket lengths (e.g. 10m in Class II for 2.4m diameter piles)

2. Detailed design using Limit State Design method, with rock socket settlement performance analysed using numerical methods:
   - Base alone would achieve adequate “Strength” for the ULS load
   - Design was governed by “serviceability” limits
   - Rock socket required to provide sufficient stiffness
   - Rock socket lengths reduced to 50% to 60% of the preliminary design lengths
Case Study – Barangaroo South (Design)

Why is there a difference?

Note: this curve for allowable design values is an assumption, based on limited experience on pad footings.
Case Study – Barangaroo South (Design Example)

1.5m Diameter Bored Pile (Group of 2)
(2m Socket in Class IV and 2m Socket in Class III Sandstone + Various Socket in Class II Sandstone)

Load (MN) vs Pile Toe Settlement (mm)

Socket Length into Class II Sandstone:
- 0.3% of Pile Diameter = 4.5mm
- 0m Class (I)
- 0.5m Class (II)
- 1m Class (II)
- 1.5m Class (II)
- 2m Class (I)
- 2.5m Class (II)
- 3m Class (II)
Case Study – Barangaroo South (Design Example)

2.4m Diameter Bored Single Pile

(2m Socket in Class IV and 2m Socket in Class III Sandstone + Various Socket in Class II Sandstone)

- Class IV Sandstone
- Class III Sandstone
- Class II Sandstone

Pile Tip Settlement (mm)

Socket Depth in Sandstone (m)

- 72.5 MN (Working Load)
- 80 MN (Working Load)
- 80.6 MN (Working Load)
- 77.2 MN (Working Load)
- 75 MN (Working Load)
- 81.4 MN (Working Load)

0.5% Pile Diameter Settlement = 7.2mm
Case Study – Barangaroo South (Construction)

1. Rough side walls and clean pile bore base considered to be vital to achieve design stiffness and capacity

2. Contractor method statement critically reviewed

3. Independent site monitoring by geotechnical staff

4. Pile load testing to validate design assumptions
Case Study – Barangaroo South (Load Testing)

Prototype Pile Load Testing using O-Cells

2 x 0.75m dia piles designed to be loaded to 17.4MN bi-directionally (i.e. total 34.8MN)
Case Study – Barangaroo South (test pile BAR-19)

Test pile designed to mobilise ~75% of estimated ultimate shaft resistance, and ~50% of estimated ultimate base resistance.
Case Study – Barangaroo South (great project for big toys)
Case Study – Barangaroo South (rock auger tool)
Case Study – Barangaroo South (boring bucket)
Case Study – Barangaroo South (boring bucket)
Case Study – Barangaroo South (cleaning bucket)
Case Study – Barangaroo South (Happy snaps with O-Cell)
Case Study – Barangaroo South (O-Cell being lowered)
Case Study – Barangaroo South (O-Cell installed)
Case Study – Barangaroo South (O-Cell Test Results)

Final load was 26MN (i.e. 52MN total) at 65mm shaft deflection but O-Cell not calibrated beyond 17.4MN

Mobilised values in Class II Sandstone:
- End bearing pressure > 59MPa
- Shaft friction > 2,000kPa, but non-linear beyond 1,200kPa
Conclusions

1. The design principles for both Working Stress and Limit State methods are similar, if done properly ....

2. Limit State Method has the following advantages:
   • Partial factors for different levels of uncertainties
   • Designers are “reminded”, or “forced” to consider the key issues of “Deformation” as well as “Strength”, and hopefully also “Uncertainties”
   • Ability to optimise design based on both strength and serviceability criteria rather than lumping these together using an arbitrary FOS
Conclusions (Con’t)

3. Standard geotechnical investigation and reporting commissioned under competitive bidding arrangement is more likely to result in “conventional” or “ordinary” results.

4. Better results can be achieved by collaborative approach between the structural and geotechnical engineers, with the latter providing input on detailed foundation assessment, validation testing, and construction monitoring.

5. “I am not advocating reducing safety factors - I am advocating replacing arbitrary safety factors”

Prof. Malcolm Bolton, Cambridge University - 52nd Rankine Lecture 2012
Clear communication and close working relationship between geotechnical and structural engineers is essential.