DESIGN CONSIDERATIONS FOR OFFSHORE SHALLOW FOUNDATIONS

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OFFSHORE FOUNDATION DESIGN

MOTIVATION FOR STUDY

- Offshore foundations are subject to combined VMH loads
- Conventional bearing capacity theory predicts conservative ultimate limit states under VMH loading
- Industry guidelines are based on conventional theory
- Results in over-conservative and inefficient foundation designs for offshore structures
- Offshore foundations are VERY expensive therefore the financial consequences of the conservatism is significant
1. OFFSHORE FOUNDATION DESIGN

> ENVIRONMENTAL LOADING

- offshore structures are subject to considerable lateral and overturning loads from the wind, waves and currents
1. OFFSHORE FOUNDATION DESIGN

**>> FOUNDATION LOADS**

- Offshore foundations are therefore required to carry general combined vertical, moment and horizontal loads (VMH)

\[
\text{Self-weight of superstructure and foundation system (V)} \quad + \quad \text{Wind & wave & current forces acting on legs (H, M)} \quad = \quad \text{VMH foundation loads}
\]

\[
M = f(Hh)
\]

\(H\)

\(M\) (often in the region of 500m)
OFFSHORE FOUNDATION DESIGN

>> SKIRTED FOOTINGS
- shallow footings with a circumferential skirt penetrating the seabed (sometimes called ‘bucket foundations’)
- during undrained moment loading suctions are developed within the skirt providing an uplift capacity, allowing moment loads to be withstood at low vertical loads

>> CONVENTIONAL SURFACE FOOTING
- uplift of footing from seabed
OFFSHORE FOUNDATION DESIGN

APPLICATIONS

- **TrollA**: gravity based structure (up to 500m)
- **SnorreB**: vertically tethered tension leg platform (up to 1500m)
- **TrollOlje**: anchored semi-submersible (> 1500m)
OFFSHORE FOUNDATION DESIGN

COMPARISON WITH ONSHORE

- Troll A Platform: 470 m (1410 feet) tall
OFFSHORE FOUNDATION DESIGN

COMPARISON WITH ONSHORE

maximum storm loads

<table>
<thead>
<tr>
<th>Load Type</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>2006 MN</td>
<td>1500 MN</td>
</tr>
<tr>
<td>H</td>
<td>495 MN</td>
<td>29 MN</td>
</tr>
<tr>
<td>M</td>
<td>18850 MNm</td>
<td>3255 MNm</td>
</tr>
</tbody>
</table>

35% extra V
1600% extra H
500% extra M

foundation plan

<table>
<thead>
<tr>
<th>Area 1</th>
<th>Area 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>9173 m²</td>
<td>3692 m²</td>
</tr>
</tbody>
</table>

150% bigger foundation area

168 m

Taywood Seltrust

213 m

One Shell Plaza
Houston

29 MN

495 MN

183 m

52 m

71 m

3255 MNm

18850 MNm
OFFSHORE FOUNDATION DESIGN

>> THE PROBLEM

- offshore design guidance is based on experience and empiricism from onshore, despite the considerable differences in the conditions
- reflected in poor predictions of ultimate limit states for load conditions relevant to offshore foundation designs

>> AREAS FOR STUDY

- failure of shallow foundations for conditions typically encountered offshore to quantify the degree of conservatism introduced by conventional theory (as proposed in design guidelines) and to try and identify possible practical alternative approaches
2 CONVENTIONAL BEARING CAPACITY THEORY

BASIC EQUATION

- ultimate uniaxial vertical load of a strip footing resting on the surface of a homogeneous material

\[ V_{ult} = ASuN_c \]

‘infinitely long’ footing

Terzaghi (1943)

- \( V_{ult} \): unit vertical bearing capacity
- \( A \): area of the foundation
- \( Su \): undrained shear strength (uniform with depth)
- \( N_c \): vertical bearing capacity factor of a strip footing

\[ = 5.14 \text{ (Prandtl, 1921)} \]
CONVENTIONAL BEARING CAPACITY THEORY

>> CORRECTION FACTOR

- non-verticallity of load i.e. inclination or eccentricity
- finite foundation length

\[ V_{\text{ult}} = A_S u N_c K_c \]

**correction factor**

\[ K_c = 1 - i_c + s_c \]

load orientation factor
\[ i_c = 0.5 - 0.5 \sqrt{(1 - H/A'Su)} \]

foundation shape factor
\[ s_c = s_{cv}(1 - 2i_c)B'/L \]

Petroleum and natural gas industries - Offshore structures Part 4
2 CONVENTIONAL BEARING CAPACITY THEORY

LOAD ORIENTATION CORRECTION

- based on solutions for load eccentricity and load inclination

**Effective Width**

\[ B' = B - 2e \]

**Effective Area**

\[ A' = B' \times L \]

Meyerhof (1953)

**Ultimate Load**

\[ V_{ult}/A_{Su} = 0.5 + 0.5\sqrt{(1-H/ASu)} \]

Green (1954)
2 CONVENTIONAL BEARING CAPACITY THEORY

3D FOUNDATION GEOMETRY CORRECTION
- semi-empirical reduction factor to account for end effects

![Diagram showing 3D foundation geometry correction]

CIRCULAR FOOTINGS
- assume equivalent area and areal moment of inertia

\[
\begin{align*}
BL &= A = \frac{\pi D^2}{4} \\
B^3L &= I_{xx} = \frac{\pi D^4}{12} \\
D &\equiv 1.128B
\end{align*}
\]
DESIGN CONSIDERATIONS FOR OFFSHORE SHALLOW FOUNDATIONS

>> 3 FINITE ELEMENT ANALYSES (FEA)

ABAQUS (HKS 2002)

SOIL - soft clay
homogeneous
linear elastic
tresca plastic
Eu/Su=500, \( \nu = 0.49 \)

FOOTING - concrete
linear elastic
\( E = 10^7 \)Eu, \( \nu = 0.15 \)

- bonding on footing/seabed interface models uplift capacity
**3. FINITE ELEMENT ANALYSES (FEA)**

**LOAD PATHS**
- combined VMH and (VM-H)

- ultimate limit failure loads from each analysis combines to form a continuous failure locus
**Design Considerations for Offshore Shallow Foundations**

## 4 Failure Loci

### H & M Loadspace at Constant V Load

- **H/M Loadspace**
  - Load space non-dimensionalised by footing geometry and undrained shear strength.

- **Equation**
  
  \[ A = \pi D^2 / 4 \]

- **Diagram**
  - Illustration of a structure submerged in water with load vectors indicating the H/M loadspace.
  - Footing geometry and undrained shear strength denoted.

- **Graph**
  - Axes for H/ASu and M/ASu with values ranging from -1 to 1.
  - Labels for H/M and -H/M load conditions.
BASELINE CASE V=0 (idealised situation as implies weightless structure)

- Locus is asymmetric
- Ultimate moment corresponds to zero lateral load
- Maximum moment mobilised in conjunction with lateral load

\[ M_{\text{ult}}, \text{i.e. at } H=0 \]

\[ M_{\text{max}} \]
>> 4  FAILURE LOCI - FINITE ELEMENT ANALYSES (FEA)

>> NON-ZERO VERTICAL LOAD
- constant intervals

- maximum capacity at V=0
- diminishing load capacity with increasing vertical load
- shape of locus is function of V load

![Diagram showing the relationship between vertical load (V) and horizontal load (H) for different values of V ratio to ultimate capacity (V/V_ult). The diagram illustrates the non-zero vertical load failure loci with the shape of each locus being a function of the V load.](http://www.cofs.uwa.edu.au)
>> 4  FAILURE LOCI - CONVENTIONAL CALCULATION (ISO)

>> V = 0.5V_{ult}
  - maximum capacity at V = 0.5V_{ult} due to 'lift-off' at lower V

- symmetry reflects neglecting the difference in modes of H & M
- quasi-linearity indicates inadequacy of representation of simultaneous load inclination and eccentricity
>> 4 FAILURE LOCI- CONVENTIONAL CALCULATION (ISO)

>> CHANGES IN VERTICAL LOAD

- diminishing load capacity with increasing vertical load

Graph showing the relationship between $V_{ult}$ and $H/AS_u$ with different values of $V$: $V=V_{ult}$, $V=0.9V_{ult}$, $V=0.75V_{ult}$, and $V=0.5V_{ult}$. The graph illustrates how the load capacity diminishes with increasing vertical load.
>> 4  FAILURE LOCI - CONVENTIONAL CALCULATION (ISO)

>> CHANGES IN VERTICAL LOAD
- diminishing load capacity with increasing vertical load

AND with DECREASING vertical load
- zero moment capacity at zero vertical load
COMPARISON - ISO vs FEA RESULTS

- ZERO load capacity at zero vertical load
- MAXIMUM load capacity at zero vertical load

OVERLOOKED LOAD CAPACITY

- oversight of tension capacity at low vertical loads
uplift of footing from the seabed under moment loading at low vertical loads

- uplift of footing from seabed

- the reduced bearing area due to uplift causes reduced capacity
- vertical loads in excess of $0.5V_{ult}$ are sufficient to maintain foundation contact with the seabed
- ... but many offshore foundation systems would operate at working loads less than half their ultimate vertical capacity
V = 0.5V_{ult}  
- i.e. like comparison: no uplift  

ISO: \(M_{\text{max}} = M_{\text{ult}}\) at \(H=0\)  
FEA: \(M_{\text{max}} (>M_{\text{ult}}), H>0\)

- inadequacy of superposition of VH and VM solutions (quasi-linearity)  
- neglect of difference between VHM and V-HM modes (symmetry)
>> 5 COMPARISON - ISO vs FEA RESULTS

>> ECCENTRIC OR INCLINED LOADS (VM or VH)
- conventional theory is based on solutions for load inclination and vertical load eccentricity and breaks down under superposition

- eccentrically applied vertical load
- centrally applied inclined load
- eccentrically applied inclined load

![Graphs showing comparison between ISO and FEA results for eccentric and inclined loads.](http://www.cofs.uwa.edu.au)
5. COMPARISON - ISO vs FEA RESULTS

- SYMMETRY: VHM vs V-HM
  - conventional method reflects locus from VHM quadrant for negative H
  - VHM is NOT physically equivalent to V-HM
SUMMARY

For the conditions investigated (i.e. undrained bearing failure of a circular footing on a homogenous soil):

- conventional bearing capacity theory inadequately represents the shape of the failure loci and underestimates the magnitude of the bearing capacity of shallow foundations under general combined VMH loading

- superposition of solutions for inclined (VH) and eccentric (VM) loading failing to represent the response to inclined eccentric (VMH) loading in conjunction with the neglect of the differences between the H & M modes of loading (i.e. HM and -HM)

- conservatism is exacerbated for conditions of low vertical load as the conventional bearing capacity theory does not account for tensile capacity achieved with foundation skirts