On Mooring Systems for *Oil & Gas vs Floating Wind*

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Presented at the Offshore Engineering Society
Wednesday, 10th January 2018
Institution of Civil Engineers
One Great George Street, London SW1P 3AA
Agenda

- Introduction
- Macroscopic Observations
- History of Moored Production Floaters – Oil & Gas and Wind
- A Tale of Two Floaters
- Mooring Fundamentals
- Design Topics
- Why Redundancy?
- Tolerability of Risk
- Concluding Remarks

Acknowledgements to:
- David Bignold
- Roberto Longo
- James Luo
- Philip Smedley

- But all errors are mine
Introduction - LOC

• Established 1979
• Premier marine warranty surveying firm in O&G
• No.1 marine warranty surveying firm with >30 Offshore wind farms warranted
• Design engineers and analysts on >30 OWFs through sister company Longitude
• Just completed the Infrastructure & Logistics scope for the Carbon Trust Floating Wind JIP for 500MW Farm
• Currently running the MWS on one of the largest FIDs ($37bn) taken in 2016.
Macroscopic Observations

- Mooring lines fail
- Conventional 3-leg moorings is an oxymoron
- Oil & Gas TLPs don’t count in hundreds
- But they all have mooring redundancy – more than 1-tendon per corner
- Consequences of system failure of unmanned structures is not negligible
- If you think mooring line redundancy costs – try system failure
- When in doubt increase the number of lines and not the size
History of floating production O&G
Floater types now used in O&G
History of Floating Wind

- **HYWIND DEMO (SPAR-2.3MW)**: 2009
- **WINDFLOAT DEMO (SEMI-2MW)**: 2010
- **FUKUSHIMA MIRAI (SEMI-2MW)**: 2013
- **FUKUSHIMA HAMAKAZE (SPAR-5MW)**: 2015
- **FUKUSHIMA SHIMPUU (SEMI-7MW)**: 2015
- **HYWIND SCOTLAND (SPAR 5 X 6MW)**: 2016
- **HYWIND DEMO (SPAR-2.3MW)**: 2017
Contemplated substructure types for offshore

Courtesy: www.offshore-mag.com
Observations from History

- Offshore O&G has learnt a lot from 42 years of floating production history – c.250 one-offs + c.250 floating drilling!
- Concepts proliferate and are still being put forward – most recently, the successful cylindrical FPSOs
- No convergence – no automatic choice
- Allowed industry to march to ultra deep record at 2912m (Shell Stones FPSO)
- Floating Wind is recent ~8 years
- Don’t expect imminent convergence of substructures for offshore wind

![Diagram showing the percentage of O&G Floaters compared to Wind Floaters. O&G Floaters account for 98% while Wind Floaters account for 2%.]
A Tale of Two Floaters......

Courtesy: The Scotsman and Statoil
The Locations
## Key Data for the Tale of Two Floaters

<table>
<thead>
<tr>
<th>Particulars</th>
<th>O&amp;G – Buchan Alpha*</th>
<th>Wind – Hywind Scotland**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installed</td>
<td>North Sea, 1981 (Decommissioned 2017)</td>
<td>North Sea, 2017 (50nm away!)</td>
</tr>
<tr>
<td>Substructure Type</td>
<td>Semi</td>
<td>Spar</td>
</tr>
<tr>
<td>Displacement</td>
<td>19,400t</td>
<td>12,000t</td>
</tr>
<tr>
<td>Draught</td>
<td>20-22m</td>
<td>75m</td>
</tr>
<tr>
<td>Water depth</td>
<td>118m</td>
<td>95-120m</td>
</tr>
<tr>
<td>No. of Moorings</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>Line Length</td>
<td>3570m</td>
<td>900m</td>
</tr>
<tr>
<td>Breaking Strength</td>
<td>340t</td>
<td>2159t</td>
</tr>
<tr>
<td>Material</td>
<td>70mm 6x36 IWRC Wire</td>
<td>147mmØ Chain (plus 60t weight)</td>
</tr>
<tr>
<td>Total Line Weight</td>
<td>715t</td>
<td>1200t</td>
</tr>
<tr>
<td>Anchors</td>
<td>Drag embedment</td>
<td>Suction, 16m x 5mØ, 300t</td>
</tr>
</tbody>
</table>

* Data from Mobile Offshore Production Unit Register, Clarksons Research
Mooring Strategy
Some observations from “A Tale of Two Floaters”

- The two structures experience(d) extremely similar conditions
- One has had 36 years of exposure – 2 or 3 mooring failures
- The mooring philosophy is different – “many-light vs few-heavy”
- What are the features?
- At the permanent states – manufacture and in-place – “many-light”
- In the temporary states – transport and installation – “few-heavy”

<table>
<thead>
<tr>
<th>Many - light</th>
<th>Few - heavy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longer installation due to numbers</td>
<td>Lesser installations, speedier and useful when scaled</td>
</tr>
<tr>
<td>Safer installation due to lighter materials and connectors</td>
<td>More bespoke, focused activity</td>
</tr>
<tr>
<td>Easier production – not pushing at limits</td>
<td>Lowering competitiveness</td>
</tr>
<tr>
<td>System reliability high</td>
<td>Weak system reliability</td>
</tr>
<tr>
<td>Compliance</td>
<td>Less Compliance</td>
</tr>
</tbody>
</table>
Mooring Fundamentals

- Originally catenary – it is weight that held station
- As we got further offshore, wave effects became significant
- **Chain elasticity** is crucial to making moorings work offshore. This also means that paradoxically moorings in shallow waters is tougher than in deep waters
- Important to make the moorings **compliant**; don’t interfere with the moored structure’s wave frequency response
- Beating wave effects are important – **slow drift**. Wasn’t an issue for massive parts of maritime history but became important
- **Line dynamics** is not what you think it is. When you don’t understand fundamentals, you hide behind simulations…..
- Always ask what the **natural periods** are
Design Topics

- ISO Establishes Consequence Categories
- In the UK, HSE sets expectations
- ISO & Class Societies establish design standards
# ISO Standard Offshore Structures

<table>
<thead>
<tr>
<th>Life Safety Category</th>
<th>Consequence category</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C1 High</td>
</tr>
<tr>
<td>S1 Manned non-evacuated</td>
<td>North Sea O&amp;G</td>
</tr>
<tr>
<td>S2 Manned Evacuated</td>
<td></td>
</tr>
<tr>
<td>S3 Unmanned</td>
<td></td>
</tr>
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</table>
Regulatory expectations on moorings for floating wind and marine devices (HSE & MCA) (Aug 2017) states

• The design of the OREI and its mooring should ensure that:
  • it can withstand such forces acting on it as are reasonably foreseeable;
  • its construction, commissioning, operation, modification, maintenance and repair of the installation may proceed without prejudicing its integrity;
  • it may be decommissioned and dismantled safely;
  • in the event of reasonably foreseeable damage to the installation or its moorings, it will retain sufficient integrity to enable action to be taken to safeguard the health and safety of persons on or near it.

• Reasonable foreseeable considerations include:
  • Environmental conditions, e.g. winds, waves, water depth, tidal and current conditions;
  • Loads during operational conditions including normal operation, contact loads from access boats and temporary loads maintenance operations.
  • Moving the OREI including tow out to site;
  • The weight of the installation and anything on it, buoyancy, drag and inertia forces from movement of the OREI;
  • Unplanned incidents including vessel impact; and
  • Mooring failure (thereby becoming a navigational hazard to third parties).
# Code & Standards Requirements

<table>
<thead>
<tr>
<th>Key Issues</th>
<th>Oil &amp; Gas</th>
<th>Floating Wind</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Return Period</strong></td>
<td>100, 10,000-year</td>
<td>50-, 500-year</td>
</tr>
<tr>
<td><strong>Design Life</strong></td>
<td>No minimum</td>
<td>≥ 20-years</td>
</tr>
<tr>
<td><strong>Intact SF</strong></td>
<td>1.67/2.00*</td>
<td>1.67</td>
</tr>
<tr>
<td><strong>Damaged SF</strong></td>
<td>1.25/1.43*</td>
<td>1.25</td>
</tr>
<tr>
<td><strong>Transient SF</strong></td>
<td>1.05</td>
<td>1.05</td>
</tr>
<tr>
<td><strong>Non-Redundant Penalty</strong></td>
<td>infinity</td>
<td>1.2</td>
</tr>
<tr>
<td><strong>Polyester Penalty</strong></td>
<td>None</td>
<td>1.09-1.14</td>
</tr>
<tr>
<td><strong>Other Fibre Penalty</strong></td>
<td>None</td>
<td>1.09-1.14</td>
</tr>
<tr>
<td><strong>Fatigue SF</strong></td>
<td>3</td>
<td>2,5,3,10**</td>
</tr>
</tbody>
</table>

* Higher safety factors if quasi-static analysis
** Depends on redundancy and inspectability
*** Move from normal to high safety class
# Approximate estimate from partial safety factors
Increasing safety factors to counter lack of redundancy?
Why Redundancy?

Oil & Gas – Redundant Mooring

Floating Wind – 3-leg mooring
System failure can lead to

**Oil & Gas**
- Personnel Risk
- Hydrocarbons on Board
- Riser Damage
- Pipeline Damage
- Collision
- Business Interruption
- Public Relations Damage

**Floating Wind**
- Personnel Risk
- Hydrocarbons on Board
- Riser Cable Damage
- Pipeline/Cable Damage
- Collision
- Business Interruption
- Public Relations Damage
Lack of people & hydrocarbons – does it provide a decisive reduction in consequences?

- 2004-5 was transformative for Gulf of Mexico risk perception
- Until then shutdown and personnel evacuation meant, risk perceived as *medium*
- Drilling rig moorings designed to site specific 5-year return conditions!
- Pre-hurricane production was not restored until 5-years later (Loss of $15bn in revenues)
- Pipeline damage due to dragged moorings
- Most production risers survived…

https://www.eia.gov/outlooks/steo/special/pdf/2010_sp_03.pdf
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<tr>
<td>S2 Manned Evacuated</td>
<td>GoMex</td>
</tr>
<tr>
<td>S3 Unmanned</td>
<td>Fixed/Floating Wind?</td>
</tr>
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</table>
### Historical Mooring Failure Probabilities – A Survey

<table>
<thead>
<tr>
<th>Source</th>
<th>Failure Probability/line/annum</th>
<th>Failure Probability/Asset/Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ahilan et.al. (1997)</td>
<td>0.014</td>
<td>0.13</td>
</tr>
<tr>
<td>DNV HSE – 1980-98 (2001)</td>
<td></td>
<td>0.119*</td>
</tr>
<tr>
<td>Kvitruud et. al (2006)</td>
<td>0.01</td>
<td>0.1</td>
</tr>
<tr>
<td>Morandini &amp; Legerstee (2009)</td>
<td></td>
<td>0.14</td>
</tr>
<tr>
<td>OGP (2014)</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>PTIL (2014)</td>
<td>0.088</td>
<td>0.1</td>
</tr>
<tr>
<td>Noble Denton HSE RR444 (2006)</td>
<td></td>
<td>0.11</td>
</tr>
<tr>
<td>Fontaine et. al. (2014)</td>
<td>0.0025</td>
<td>0.021</td>
</tr>
</tbody>
</table>

* Derived from combining Semi (0.14), FPSO (0.155) and FSU (0.034) frequencies
Reasonable to conclude failure rate/asset/year ~ 0.02-0.1
Tolerability of Risk in Wind

Probability of Failure vs $ Consequence

Line failure probability vs consequence
Cable failure probability vs consequence
A Consequence of Mooring Failure

Now you see it

Now you don’t....

Concluding Remarks

- Consequences of system failure of unmanned structures is not negligible
- When in doubt increase the number of lines and not the size
- Installing redundancy may not be as expensive as you think
- Increased factor of safety does not always mean increased safety
Roll on, thou deep and dark blue Ocean, roll!
Ten thousand fleets sweep over thee in vain;
Man marks the earth with ruin; his control
Stops with the shore;
- Byron
References/Bibliography/Websites

• Fontaine et. al. (2014). Industry Survey of Past failures, Pre-emptive Replacements and Reported Degradations for Mooring Systems of Floating Production Units, OTC25273-MS
• Morandini C, F Legerstee, 2009, Consistent Integrity of Mooring Systems, ISOPE, Osaka, Japan.

• Websites accessed for pictures: theengineer.co.uk, windpower.com, statoil.com, hitachiglobal.com, gov-online.go.jp, offshorewind.com and others acknowledged with thanks.