Direct on-seabed sliding foundations
(A.K.A. “slippery foundations”)

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Presentation Overview

➤ What are they?
➤ Motivation (why?)
➤ Design (how?)
   ● Key aspects
   ● Reliable geotechnical engineering
   ● System integration
➤ Summary
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A direct on-seabed sliding foundation

A sliding foundation

Repeated sliding over the seabed

Initial literature
Cathie et al. (2008)
Bretelle & Wallerand (2013)
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Julimar field*, Apache. www.apachecorp.com

*Just a freely available field layout – no sliding foundations as far as I’m aware.
Motivation – System Example

Pipeline

Pipeline End Termination (PLET)

Spool

Pipeline Termination Structure (PTS)
Motivation – System Example

Repeated axial movement of pipeline during operation

\[ \Delta L \]

\[ \Delta L \text{ can be 1 m or more} \]

\[ \Delta L \text{ repeated 100’s to 1000’s of times} \]

\[ \Delta L \text{ a function of:} \]
- Product (e.g. temperature and pressure)
- Pipeline properties (e.g. heat transfer)
- Pipeline design (e.g. buckle design strategy)
- Geotechnics (axial & lateral pipe ‘friction factors’)
PLET Options

**Fixed PLET**
- Fixed
- Large foundation to ‘anchor’ pipeline expansion

**Fixed foundation - sliding PLET**
- Pipe
- Spool
- Pipeline support slides on rails
- Pipeline support structure slides on ‘table-top’
- Pre-lay structure (‘table-top’)

**Direct on-seabed sliding**
- Slides over the seabed
- Maybe in-line installable

Smaller foundation
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Key design aspects

- **Capacity and Stiffness**: Sufficient for set-down, tie-in and external loading (e.g. cyclonic)
  - Set-down
  - Spool tie-in

- **Sliding resistance**: Should be minimised
  - Load shedding: Connector overstress

- **Settlement**: Should be minimised
  - $\Delta z$
Imposed forces

- Weight ($V_z$)
- Sliding resistance ($H_x$)
- Moment ($M_{yy}$, $M_{xx}$)
Imposed system forces

- Load shedding from PLET may cause overstress.
- System analysis and interaction with pipe engineering teams vital.
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Long term settlement focus

- Consolidation & creep
- Plastic sliding deformations
- Shakedown
Soil consolidation & creep

Consolidation
(hours or months?)

Creep
(years or decades?)

Time
Settlement

[Soil densification]
Plastic deformation while sliding

Soil interaction diagram

- Elastic
- Plastic

V1

H

V

ΔL

N_{stroke}

Settlement

[Soy removal]
Plastic deformation while sliding

Soil interaction diagram
Plastic deformation while sliding

Prevented by design: minimised $V/V_{ult}$ and soil-foundation interface strength

[analysis needs to consider VHM loading, Cyclic strength degradation, drainage, $N_{eq}$ etc]

[Soil removal]
Plastic deformation while sliding

Introduction of smoother interface (soil-foundation), extends ‘working’ surface

Prevented by design: minimised $\frac{V}{V_{ult}}$ and soil-foundation interface strength

[analysis needs to consider VHM loading, Cyclic strength degradation, drainage, $N_{eq}$ etc]
Cycle by cycle densification - shakedown

Shear stress, $\tau$, transferred to seabed

Increasing number of cycles

[Soil densification]
Cycle-by-cycle densification – Shakedown

[Diagram showing soil layers and displacement]

[DeJong et al. 2003, 2006]
Shakedown predictions

\[ N_{stroke} = 0 \quad \text{and} \quad N_{stroke} = 1000 \text{ (say)} \]

Modelling requires site specific test data and analysis

[shakedown a function of applied shear stress, soil void ratio, compressibility, 'state' c.f. CSL and PTL, movement rate etc.]

Deeks et al. 2014
(OMAE, 2014)
Shakedown predictions

- Cycle-by-cycle settlement assessment
- “Hardening” rule added to existing cyclic strength frameworks
- Prediction based on site specific soil element testing

Deeks et al. 2014 (OMAE, 2014)
Shakedown predictions

Deeks et al. 2014
(OMAE, 2014)
**Influence of soil state: example settlement calculations**

- **Load** vs. **Foundation Settlement**
- **Depth Below Seabed** vs. **Soil strength**
- Offsets represent consolidation component
- **Settlement limit?**
- **Decreasing load**
- **Nstroke**
- Stronger/stiffer seabed
- Weaker seabed
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System integration & modelling

- Validate pipeline-plet-spool-structure system integrity
- Interaction & iteration between pipeline, geotechnical, and structural team is vital for successful implementation
- Reliable analysis: consider appropriate LE/BE/HE combinations
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Summary

- Allowing direct on-seabed sliding can allow for smaller and lighter foundations which are cheaper to manufacture and install.
- Design team interaction is required for successful implementation.
- Shakedown (cycle-by-cycle densification) is typically the dominant cause of long-term settlement (and can be modelled on a site specific basis).
- Opportunities for design method optimisation.

- Other seabed interactions include:
  - Berm build up vs. axial movement history
  - Mobile seabeds (flexible/ moving scour protection)
  - Sand waves

Thanks for listening
& thank you to AG and industry colleagues