PHILLIP COOPER, INTECSEA, UK, SHOWS US HOW ADVANCED NUMERICAL SIMULATIONS ARE UNRAVELLING DEEPWATER DESIGN CHALLENGES.

DEEPWATER DESIGN CHALLENGES

As oil and gas developments move into extreme water depths approaching 2 km or more, a host of challenges arise for subsea system designers. Conventional design tools have shortcomings that include the difficulty of assessing accurate pipe-soil interactions and limited non-linear and dynamic analysis capabilities. As a result, these conventional tools tend to provide conservative estimates, thereby necessitating more complex pipeline structures and increasing project costs.

With this in mind, the technical staff of INTECSEA undertook analyses of several common deepwater design challenges including prediction of the consolidation settlement of shallow foundation structures on very soft soil, fatigue design of flowline systems with slug flow, the bending capacity of pipe bends and pipe-in-pipe lateral buckling under deepwater conditions.

For all of these challenges, the INTECSEA team utilised ABAQUS Finite Element Analysis (FEA) 3D software allowing detailed evaluation of the problems and establishing cost-effective solutions without compromising integrity, target safety or reliability measures.

Analysis of a pipeline end structure's foundation settlement

Consolidation settlement is defined as the time-dependent process of volume change in the soil as the water is squeezed from the pores. The settlement process takes years to fully develop, so cannot be determined by surveys during construction, and must be predicted during the design phase. Long term settlement imposes significant loads on attached tie-in spools, so conservative estimates can lead to unduly large and complex spool designs.

Complex load conditions are inherent in a deepwater flowline termination assembly (FTA). These loads are generated from the substantial self-weight of the structures, pipeline and tie-in spool and additional loads from pipeline thermal expansion. Besides overestimating the consolidation settlement, the conventional 1D analytical method has further limitations in accounting for eccentric loadings, permeability and the complexity of the structure assembly.

Deepwater developments typically feature very soft normally consolidated clay soils, with low bearing capacity and significant compressibility.

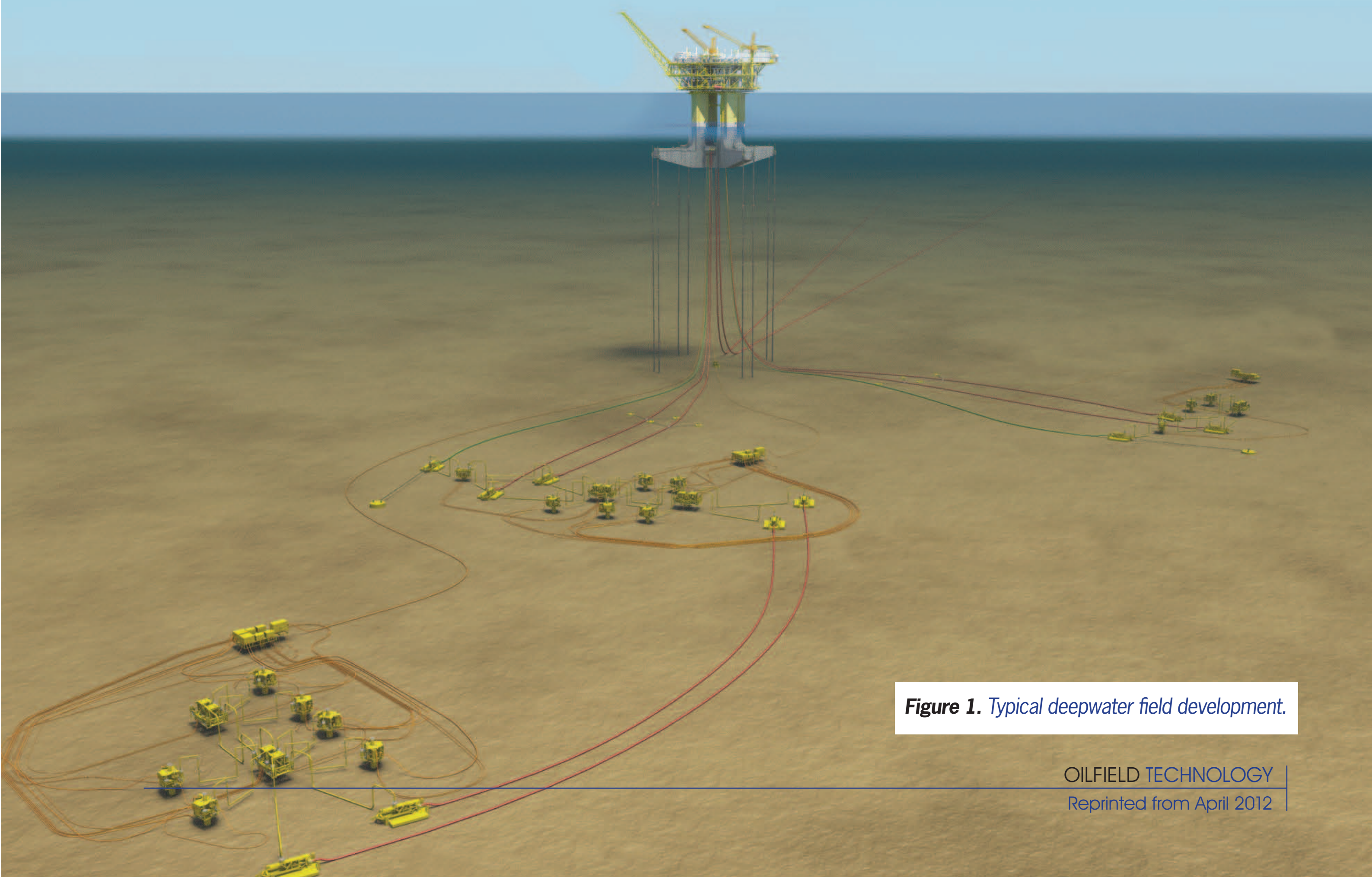


Figure 1. *Typical deepwater field development.*

While void ratio and permeability are difficult to determine accurately, efforts were made to minimise uncertainly for these restrictions. Sensitivity studies showed that a reduction in void ratio could lead to a corresponding increase in predicted settlement for both a 1D analytical solution as well as a 2D FEA analysis.

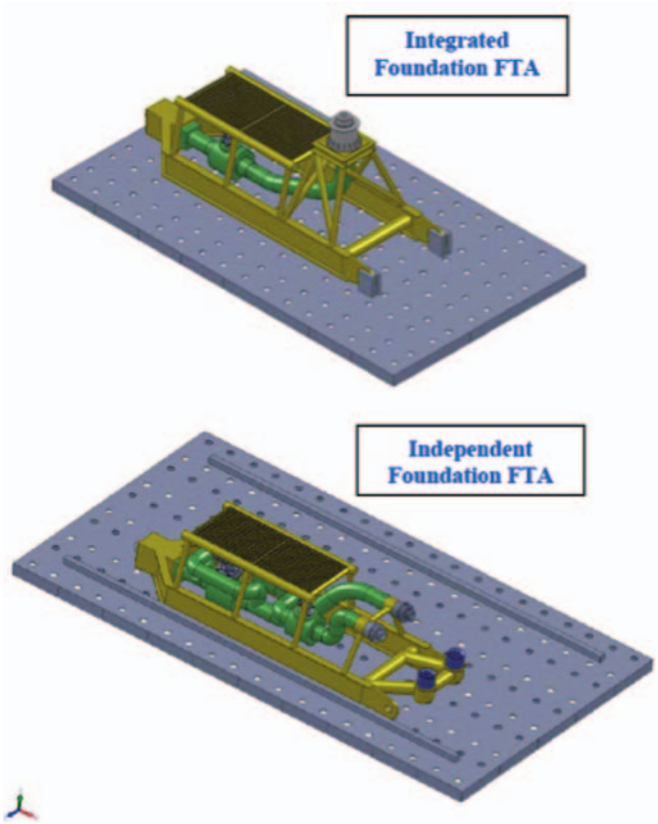


Figure 2. *FTA case studies.*

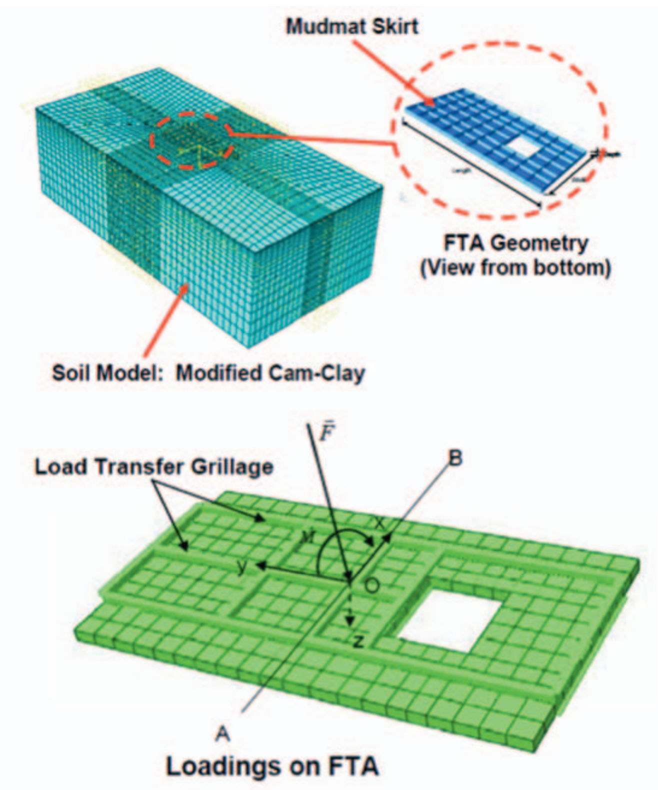


Figure 3. *3-D FEA model.*

An order of magnitude change in permeability can change end of life settlement by +12% to -25%.

The team considered two FTAs in its case studies: one integrated foundation and one independent (pre-installed) foundation. The independent foundation FTA was larger than the integrated foundation FTA, in order to accommodate pipeline lay-down tolerances, and had the potential for larger eccentricity. Thus, rotational effects were more critical.

Using a 2D FEA model to calibrate the mesh density and other pertinent parameters of the FTAs, the team first determined the sensitivity of the parameters to ensure that the results were comparable with those from a 1D analytical solution before undertaking the more complex 3D FEA. This approach provided an optimised computer model, capable of solving the complex 3D problem in a reasonable time, without undue loss of accuracy.

The 3D FEA model used the modified Cam-clay soil model (Roscoe and Burland, 1968) based on the critical state plasticity theory to give an accurate determination of the consolidation settlement.

Compared with the conventional 1D analytical method, the 3D FEA application gave the team a more accurate representation of consolidation settlement and a more realistic three-dimensional view of structural modelling, loading and stress distributions.

While there are currently no physical or experimental results to verify the FEA results obtained, the 3D analysis showed clear evidence of lower consolidation settlement with a 70% reduction in vertical movement indicated, due mainly to the accurate representation of vertical stress distributions with soil depth and width in the 3D model. This difference could have a significant impact on the design of the FTA's associate components, namely spools and connectors.

Fatigue design of flowline systems with slug flow

Multiphase flowlines have a high potential for slug formation and pipeline designers are cognisant of the tremendous effect slug-induced fatigue damage can have on the spans, especially at tie-in spools or flowline terminations. Spans introduced by lateral buckling mitigation features can also be particularly difficult to protect against slug-induced fatigue.

Since most oil reservoirs will yield fluids containing a mixture of oil, gas and water at some stage during the life of the field, there is a high potential for slug flow. Slug flow results when the liquid and gas phases separate into a 'slug' of liquid and a 'bubble' of gas. The bubble is accompanied by a variable quantity of liquid in a 'film.' The lengths of slug and bubble are variable and difficult to measure or predict, but they are typically in the range of 10 m to 100 m, which is comparable to a typical span length. Prediction models often indicate slug frequencies of 100 per hour or more. For a typical 20 year design life, this leads to a fatigue cycle count approaching 20 million.

The density of the slug and bubble also has a strong effect on the fatigue design. Although dependent on local flow conditions and fluid composition, typical average density for slug and bubble are around 900 kg/m^3 and 100 kg/m^3 respectively.

The hydraulic flow regime alone can generate slug flow conditions – uneven well discharge or terrain effects are not required. In fact, economic sizing of flowlines tends to lead to a flow velocity well within the slug flow regime and will result in slug flow under normal operating conditions.

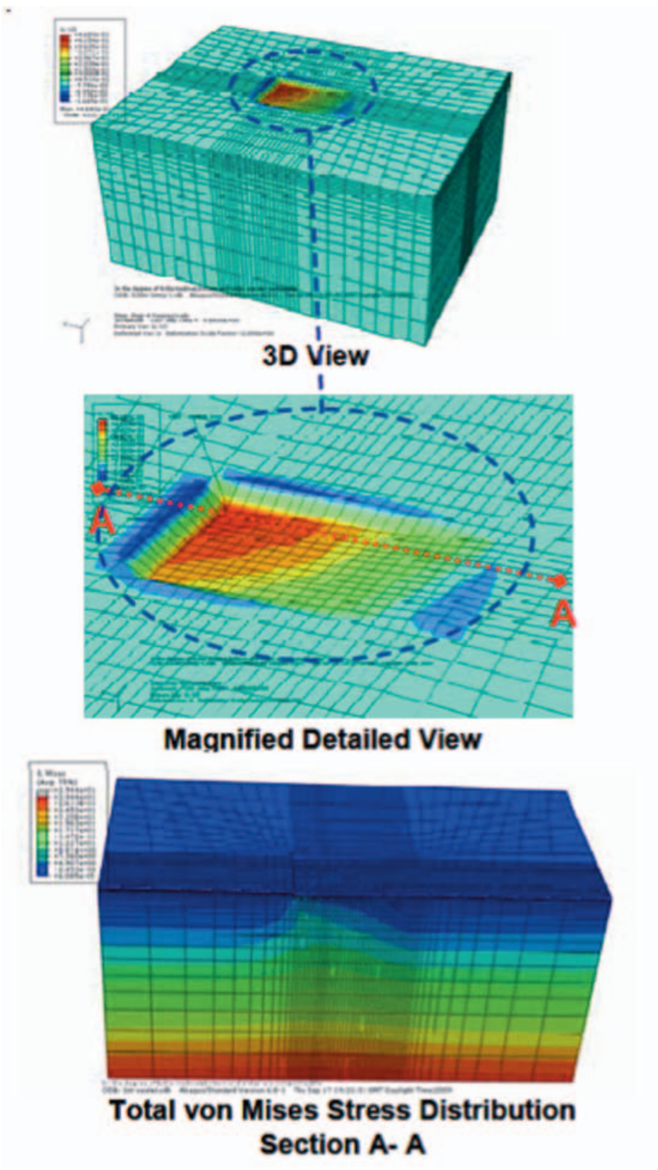


Figure 4. *Soil deformation and stress distribution around the integrated foundation FTA.*

Multiphase flowlines typically operate with flow velocity of approximately 10 m/sec., therefore the slugging condition is likely to be 'chronic,' affecting a major part of the design life of the flowline system.

Because of high cycle fatigue loads associated with continuous slug flow, the design of the flowline system is subject to rather restrictive allowable fatigue stress ranges.

As a result, the team incorporated slug-induced fatigue into allowable pipeline span calculations along with the standard criteria of VIV, static strength and bar buckling. Static FEA was used to evaluate fatigue stress ranges for isolated idealised spans, taking account of seabed stiffness and effective axial force effects. Subsequent development work by company engineers has refined this procedure to include full dynamic and moving mass effects, to provide even more accurate span response predictions.

A similar approach was used to assess fatigue stresses at 'engineered' spans introduced at pipeline end structures, crossing supports and buckle mitigation sleepers. The known geometry of the specific features was modelled using FEA to provide an accurate estimate of fatigue stress ranges due to slug flow. Static analysis also was used with a selection of slug/bubble configurations selected to generate the most severe stress range at critical locations along the span.

Stiffeners applied to reinforce the stem pipe connecting the pipeline to the FTA require careful design, as the span formed at this location is exposed to slug fatigue effects. Detailed FEA was used by the team to refine stiffener designs and demonstrate adequate fatigue resistance.

Dynamic FE analysis of rigid spools

The team also used the ABAQUS software as a design tool to determine slugging flow fatigue on rigid spools that connect adjoining flowline segments. Using either vertical or horizontal diverless connection systems, these spools generally span from hub to hub and eliminate an interface with the seabed, which complicates design, metrology, fabrication and installation. However, this floating spool configuration is vulnerable for dynamic loads, including slug flow.

A seabed-supported spool configuration is required if a free-spanning spool cannot be designed to tolerate stress ranges associated with dynamic loads. While the support provided by the seabed reduces the stress range in the spool, the spool flexibility is also reduced leading to higher static stresses and connector loads when expansion movements occur.

Resonance may occur when the spool is subjected to the dynamic loads caused by the slugging passage. Using the ABAQUS implicit dynamic solver, the potential structural resonance was examined by performing a time-domain analysis, including both variable weight effects and impulse loads as slugs pass through bends. Results showed that spools with a high central elevated section (included to relieve static loads) were subject to more structural resonance when slugging occurred.

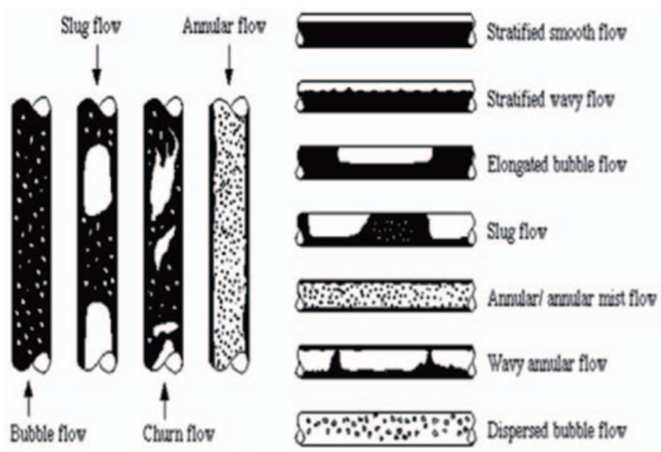


Figure 5. *Two phase flow regimes.*

Bending capacity of pipe bends

Currently, there is no comprehensive guidance to enable the calculation of the maximum capacity under combined bending and external pressure loading. DNV's standard on submarine pipeline systems (DNV OS-F101, 2010) provides some conservative guidance, but the proposed approach leads to excessively large wall thickness requirements in very deepwater applications.

The team used a nonlinear FE method featuring ABAQUS to evaluate the ultimate capacities of induction-heating formed bends. The method took into account the combined effects of non-linear material properties, initial ovality, wall thinning/thickening, net external or internal pressure, internal CRA cladding and temperature change on the ultimate moment capacity of the bend.

Results from the FE modelling showed that the maximum bending strength was increased by as much as 57% compared to corresponding values that were calculated ignoring the contribution of the CRA material.

Additionally, the FE modelling showed that increasing the levels of initial ovality by approximately 25% decreased the calculated maximum bending strength by approximately 7%. The level of ovality was shown to increase from an initial value of 2.5% to approximately 7.2% at the ultimate load condition due to a closing bending moment.

The team concluded that modelling using three layers of elements brings the accuracy of the FE-calculated results well within engineering accuracy. This level of detail delivers an acceptable simulation turn-around time, enabling it to be used as a practical design tool for deepwater bends.

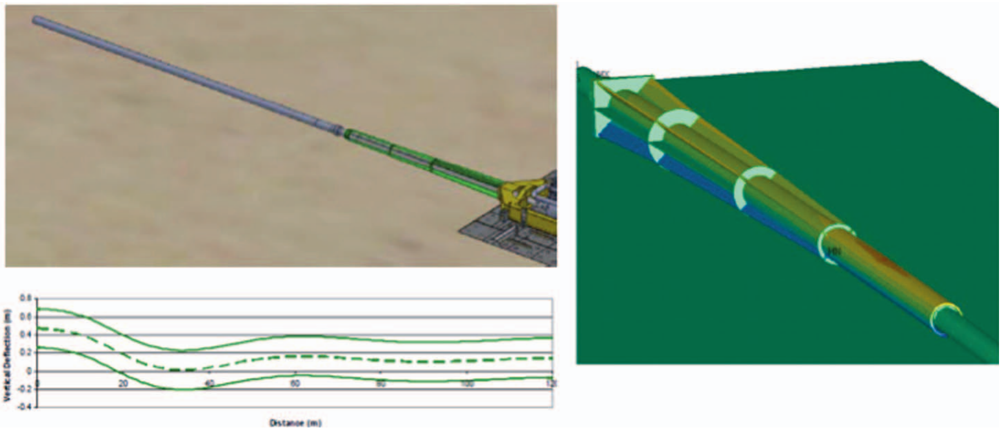


Figure 6. *Typical span at flowline structure connection.*

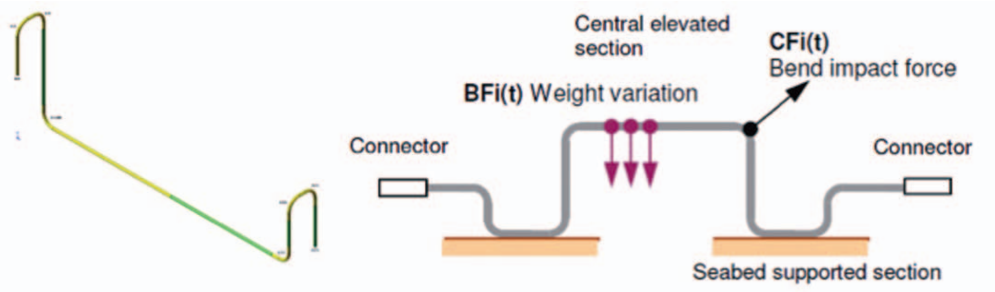


Figure 7. *Schematic diagram of slug dynamic forces applied on a spool.*

Pipe-in-Pipe (PIP) lateral buckling

The high operating temperatures in deepwater developments necessitate highly insulated PIP systems, which can be subject to buckling on the seabed.

Since these flowlines cannot be buried due to difficulties in trenching and backfilling operations, the flowline is engineered to buckle laterally in a controlled manner and assure the strain encountered remains within fatigue and ultimate limit states.

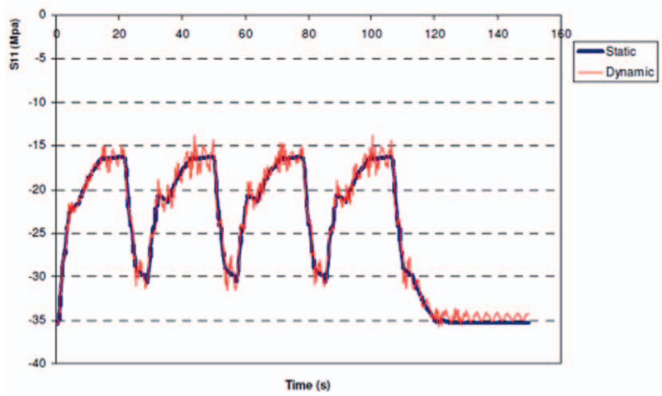
Using FEA, the team analysed PIP lateral buckling to account for the actual seabed profile and complex non-linear soil friction in the axial and lateral directions, which affect the buckle initiation and post-buckle cyclic response.

Treatment of termination and in-line structures, forged pipeline components such as J-lay collars and bulkheads, and mechanical interaction of inner and outer pipe also presented significant analysis and design challenges.

In 2D laboratory pipe-soil test results, the buckle lobe became almost completely restrained after only a few cycles of lateral movement. The high levels of associated lateral friction led to rather high peak strain levels when incorporated in a design simulation, and increased mitigation requirements.

The team then implemented a cyclic friction model into the ABAQUS FEA code, capable of representing a defined increase in lateral resistance with swept distance.

Using revised cyclic friction parameters to account for 3D effects, the effective lateral friction forces reduced to much



Figures 8. *Typical dynamic/static longitudinal stress history at connectors.*

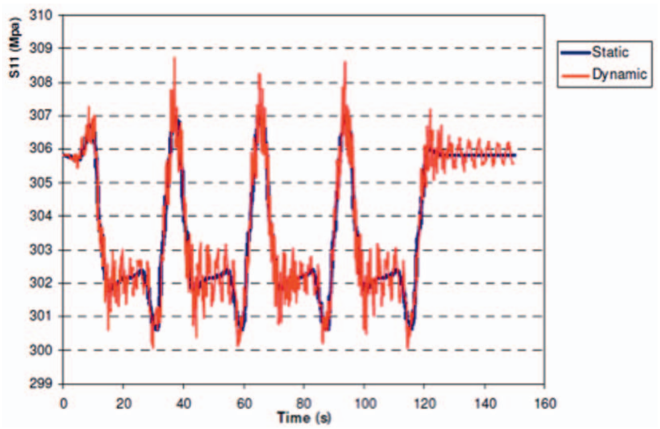


Figure 9. *Typical dynamic/static longitudinal stress history at central elevated section.*

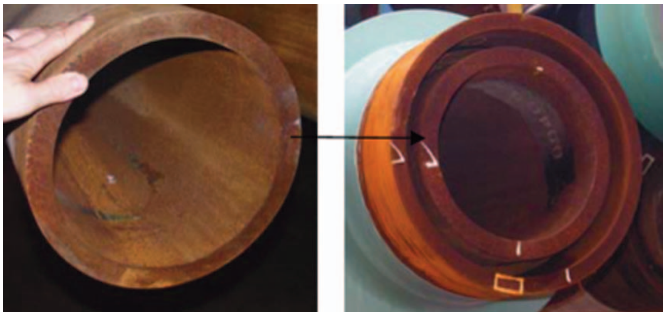


Figure 10. *Heavy deepwater PIP cross section.*

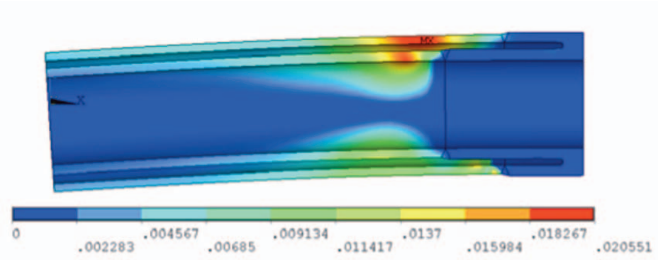


Figure 11. *Nonlinear FEA for limit state design of an intermediate bulkhead.*

less onerous levels with corresponding reductions in peak and cyclic strain levels. This, in turn, led to significant reductions in buckle mitigation requirements and less stringent weld defect acceptance criteria.

Since pipe-soil interaction presents the greatest uncertainty in lateral buckling design and is less understood for heavy PIP flowlines resting on soft soil, deepwater projects need to recognise that the correct modelling requires complex user-defined friction models capable of capturing 3D effects due to 'diving' pipe response and ensure the necessary data and analysis tools are available at an early stage of the project.

Conclusion

For each of these deepwater challenges, the FEA modelling and design tools used by the company brought new insight. The company hopes its continuing research will help unlock the increasingly complex field development challenges expected in future years.

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