Pipeline stability revisited

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THE STABILITY assessment of the 40-in North Rankin A trunkline, operated by Woodside Energy Ltd, has provided better insight into fluid-soil-pipe interactions during extreme storm events. The resulting conclusion of the work is that the trunkline, a major subsea natural gas artery in Australia's Northwest Shelf since its installation in 1982, can continue to be operated safely for the next 30 years from a hydrodynamic stability point of view. This conclusion was reached after substantial study and physical model testing was performed considering the tripartite interaction between fluid, seabed, and pipeline.

To provide vital information feeding into the stability analysis, a physical model testing programme was developed, and a new world-class hydrodynamic testing facility designed, constructed, and commissioned at the University of Western Australia. This facility allows the replication of near-seabed conditions during tropical cyclones in controlled laboratory conditions, and observation of the interaction between ocean, seabed, and pipeline. Tests were performed using a range of pipeline embedment profiles, storm realizations, and pipe fixity conditions simultaneously to model hydrodynamic loading onto the pipeline and seabed scour. This data were then used in the three-dimensional numerical modelling of pipeline response using finite-element analyses, which included the effects of seabed instability.

THE 134-km long, 40-in diameter, and 23.8-mm wall thickness North Rankin A (NRA) trunkline was constructed by Woodside Energy Ltd in 1982 based on a design life of 30 years. The gas pipeline links the NRA Platform to the North West Shelf Venture gas plant on the Burrup Peninsula (Fig.1) Primary stabilization is provided in the form of a concrete weight coating. In the area of interest, the concrete weight coating is 64 mm thick and has a density of 3,043 kg/m^3, and the corrosion coating comprises a 6-mm thick layer of asphalt enamel with a density of 1,281 kg/m^3; the contents' density for stability design purposes is 90 kg/m^3, and consequently the specific gravity (SG) of the pipeline in this area is 1.23 relative to seawater. The current practice, 30 years after the NRA trunkline was installed, is for large-diameter pipelines to be designed in similar water depths with a much thicker (and sometimes much higher density) concrete weight coating, with much higher SG values. This assists considerably in achieving on-bottom stability without the need for applying secondary-stabilization measures.

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Along the first 22.8 km from shore, the trunkline is covered with a minimum of 2.5 m of quarried rock to provide protection from accidental external impacts. From KP 22.8 to KP 123.8 the pipeline was post-trenched by ploughing in loose and variably cemented carbonate marine sands and silts. The plough formed an open V-shaped trench below the pipeline with the intention that the depth of the trench would place the top of the pipeline at or below the natural seabed level.

In April 1989, a severe Tropical Cyclone (TC) Orson caused significant changes to the seabed bathymetry along the trunkline, which resulted in the distinct V-shaped ploughed trench shape disappearing. Consequently, the required sheltering which the trench previously offered was no longer present everywhere along the pipeline route. Typical data from a survey undertaken after TC Orson in 1989 are shown in Fig.3, reconstructed to provide a three-dimensional visualization of the degree of burial along a typical length of the trunkline.

Upon discovering the changed bathymetry of the seabed in relation to the trunkline, a remedial stabilization programme was developed and implemented between 1990 and 1992. This comprised rock dumping along selected sections of the pipeline, both to improve pipeline stability and to also stabilize the seabed either side of the pipeline.

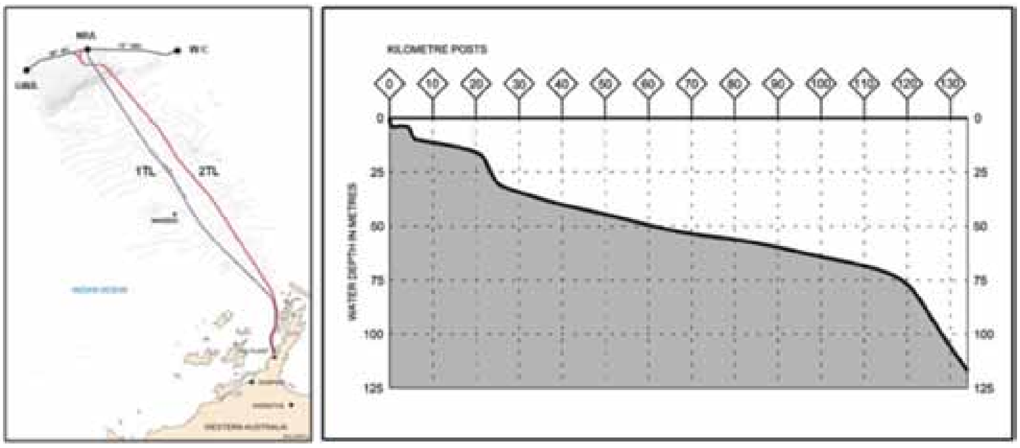

Fig.1. The NRA trunkline.

The desire to extend the lifespan of the trunkline beyond 2012 triggered the need to undertake a rigorous engineering assessment of this asset. It included a study of the hydrodynamic stability of the system for the next 30 years.

A screening process indicated that the critical area that needed thorough review was the section along the Continental Shelf, between the 26 m and 73 m water depth contours, or between KP 22.8 and KP 116. The two adjacent pipeline sections were either stabilized by quarry rock (the shore approach) or stable under the pipeline's own weight (the platform approach).

The challenges faced by the pipeline engineers who carried out the assessment were the following:

- The trunkline comprises sections with highly variable levels of embedment in sediments, ranging between 0% (of pipeline diameter) to 100% or more.
- Along many of these areas, the level of embedment either side of the trunkline is not the same; in some areas there is as much as 100% embedment on one side with little to no embedment on the other side.
- At the commencement of the assessment there was insufficient clarity as to the degree of instability of the seabed in the immediate vicinity of the trunkline.
- The SG of the trunkline (1.23 in seawater) along the area of interest is relatively low.
- A review of existing 3D pipeline-stability software packages indicated that they would be inadequate to undertake the assessment accurately in the given seabed conditions, unless considerable modifications were made to the software to account for the effects of seabed instability onto the pipeline-response model.
- The Northwest Shelf of Western Australia comprises carbonate soils, and international pipeline codes and recommended practices are written on the basis of any seabed sand being siliceous.

In summary, the assessment required an unconventional methodology in view of the nature of the sediments, the potential effects of seabed instability, and the pipeline embedment levels, which are not compatible with the existing codes and recommended practices.

At the time when the assessment commenced (2006) the only available and reliable recommended practice was DNV RP E305 [1], which:

- does not provide guidance on pipe-seabed interaction forces for pipelines on carbonate soils;
- does not allow for the effect of pipeline embedment on soil resistance and hydrodynamic loading; and
- does not consider the effects of seabed instability within the response of the pipeline during storm loading.

The successor to DNV RP E305, published in 2007, is DNV RP F109 [2]. This updated code does allow for some effects of pipeline embedment; however it does not consider asymmetrical embedment levels, and also does not provide quantitative guidance for carbonate soils. Both recommended practices focus on pipeline on-bottom stability with relatively low embedment levels, and are not suited to the assessment of highly embedded pipeline sections.

In addition, none of the existing codes and recommended practices considers the effects of the changes in seabed bathymetry and characteristics during a storm event – i.e. when subjected to the wave- and current-induced hydrodynamic loads – on pipeline stability. Such changes can include sediment scour and deposition, excess pore pressure build-up and dissipation and, sometimes, liquefaction.

The pipeline engineers who undertook the assessment considered these effects of great importance. It has been mentioned before that the seabed, if it comprises a fine- or medium-sized uncemented material, will lose strength and become mobile during the ramp-up period of a storm, long before the pipeline becomes unstable [3], depending on the SG of the pipeline. Whilst the recommended practices and guidelines do not incorporate these effects within their methodologies, many pipelines that are in operation have a track record of losing contact with the seabed over sometimes

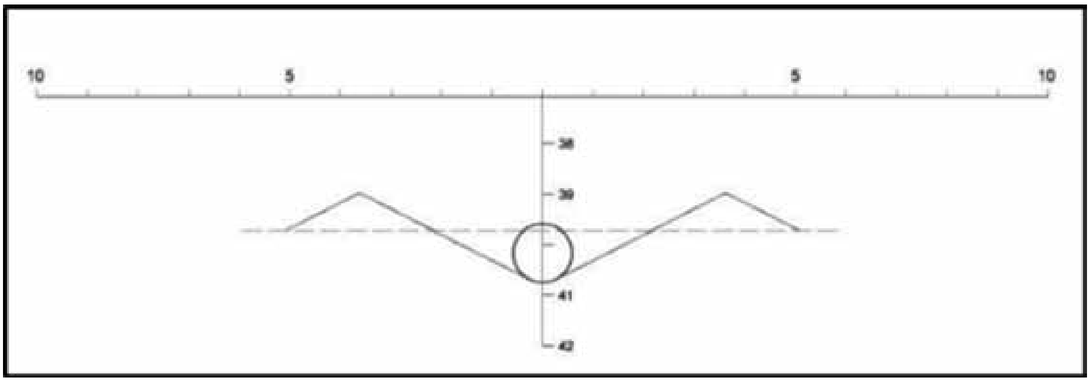

Fig.2. Typical as-built post-lay ploughed trench profile.

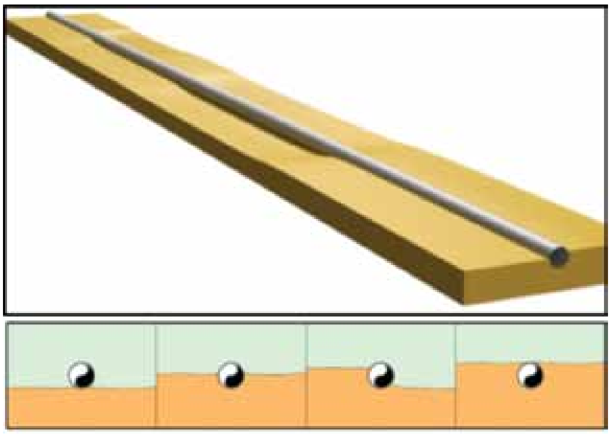

Fig.3. Various levels of pipeline embedment post-Tropical Cyclone Orson.

significant lengths in areas of loose sediments through the forming of scour holes. The forming of scour holes along a pipeline can sometimes be so extensive that the pipeline, depending on its SG, experiences self-burial over time.

Methodology

As a consequence of the limitations in the design codes and recommended practices, an unconventional methodology was developed for this case (Fig.4). The aim of the stability assessment was to develop an understanding of the processes contributing to the stability (or instability) of the trunkline and to assess whether satisfactory evidence can be gathered to demonstrate that the risk of future trunkline instability is sufficiently low.

The following main steps were identified when developing the methodology of the stability assessment of the NRA trunkline.

Overview of the assessment

Input data gathering

The NRA trunkline had previously been the subject of much study, in particular in relation to its hydrodynamic stability. A significant amount of data had been collected over more than two decades, including survey data from annual and post-tropical cyclone inspections. Also, past studies which had assessed the potential of the seabed sediments along the pipeline route to liquefy and/or scour were studied. Mechanical design properties of the trunkline were also collated to create an overall picture of the asset and its environment.

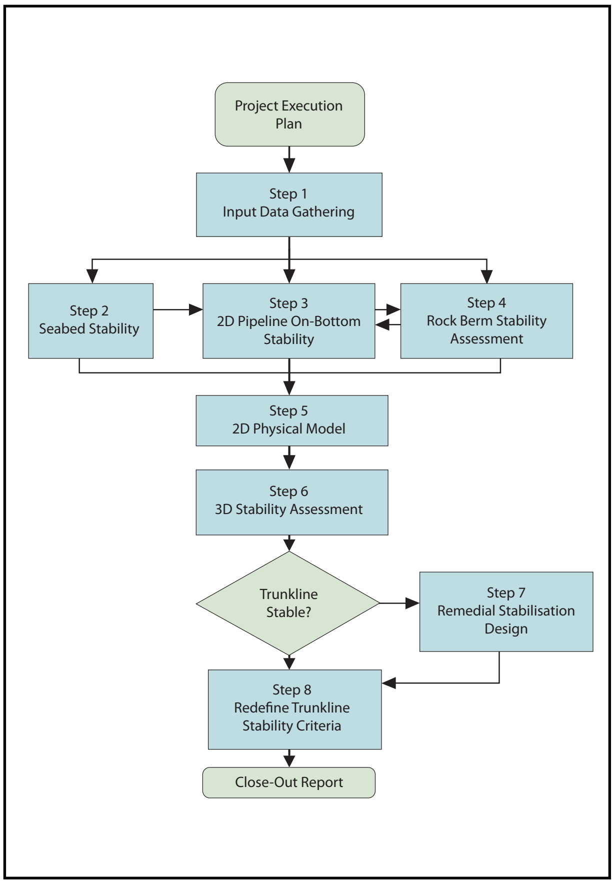

Fig. 4. The assessment process.

Table 1 presents the metocean data applicable to the section of the pipeline route between KP 52 and KP 63. The seabed along this section of the pipeline route comprises a 1 - 2 m thick layer of fine- to medium-carbonate sand overlying a calcareous rock pavement. The sand has a D50 of 150 - 200 microns.

Description	Symbol	Value
Significant wave height	H_s	12.94 m
Peak period	T_p	14.76 s
Water depth	d	55.8 m
Significant wave-induced current (perpendicular to pipeline)	U_s	1.62 m/s
Steady-state current (perpendicular to pipeline)	V_R	0.52 m/s
Maximum wave-induced current (perpendicular to pipeline)	U_{max}	2.46 m/s

Table 1. NRA trunkline 100-year RP design metocean data (from KP 52 to KP 63).

Seabed stability assessment

The pipeline engineers who undertook the assessment recognized that the overall stability of the pipeline depends on the tripartite interaction between the hydrodynamic loads induced by tropical cyclones, the seabed – comprising predominantly calcareous sediments – and the trunkline. Consequently, an in-depth study of these processes was undertaken.

As a starting point, the interaction between the hydrodynamic loads and the seabed was assessed. Specialists were engaged to undertake seabed liquefaction and scour analyses.

The seabed liquefaction analysis performed for this project, which used the methodology described by Bonjean *et al.* [4] concluded that, although the large hydrostatic pressure fluctuations caused by tropical-cyclone-induced waves do not have the capacity to induce free-field seabed liquefaction, it is likely that loose and fine sediments deposited within the open trench would have liquefied during a significant storm event (such as TC Orson in 1989). This would have caused lift of the pipeline by several tens of centimetres. The end result, after a significant storm, created a picture which was perceived at the time by many as a general lowering of the seabed (due to regional scour), while in reality it could well have been the pipeline which had risen.

This trench backfill material liquefaction theory is considered to be the most likely explanation for the observed change in the burial of the NRA trunkline. It casts doubt onto the validity of the broadly accepted regional-scour theory, or at least the depth extent of such seabed erosion and its effect on submarine structures such as pipelines in this region. The seabed-liquefaction assessment also concluded that where soils are classified as sand, excess pore pressure build-up around the pipeline during an extreme load condition is expected to be small (5 - 10%), which is not expected to impact pipeline stability. However, where soils are classified as silty sand, excess pore pressure build-up around the pipeline can be much higher under extreme load conditions (60 - 70%) which may be expected to cause localized partial flotation of the pipeline.

Excess pore pressure build-up will result in soil softening and reduced soil passive resistance, and could result in partial pipeline flotation where significant excess pore pressures are generated. However, it is difficult to precisely correlate a decrease in lateral soil resistance to a value of excess pore pressure. Although excess pore pressures generated in the region where the pipeline stability has been analysed in detail are not expected to have a significant effect, sensitivity load cases have been performed in the 3D FEA analysis using reduced soil passive-resistance values to assess the potential effects of excess pore pressure build-up on pipeline stability.

A regional (free-field) scour analysis was also performed. Two independent methods were used: the first used the Soulsby method [5] to determine the volume of sediment suspended in the water column, while the second assessed the possibility of sheet flow, using the Flores and Sleath method [6] to estimate the regional (free-field) scour depth.

The regional scour analysis indicated that over the long term, the regional scour depth is likely to be limited to less than 0.1 m along the NRA trunkline route in the area of interest.

Local scour was assessed using the computational-fluid-dynamic (CFD) package *SCOUR-2D* developed by the Hydraulics Research Group, led by Professor Liang Cheng at the University of Western Australia. It is believed that local scour did occur during TC Orson in 1989, whereby the spoil banks of the ploughed trench (and other unconsolidated, cohesionless, fine-grained sediments) were deposited on and around the pipeline inside the V-shaped ploughed trench. Following the suspected liquefaction of this material during the same and/or subsequent tropical storms, and rise of the pipeline through this material, further local scour of this seabed material is likely to have occurred alongside the trunkline.

The results of the seabed-stability assessment indicate that both liquefaction and scour have played a significant role in the stability of the trunkline. Also, now that the pipeline is exposed at the seabed, (predominantly) local scour is likely to have a significant influence on the stability of this pipeline.

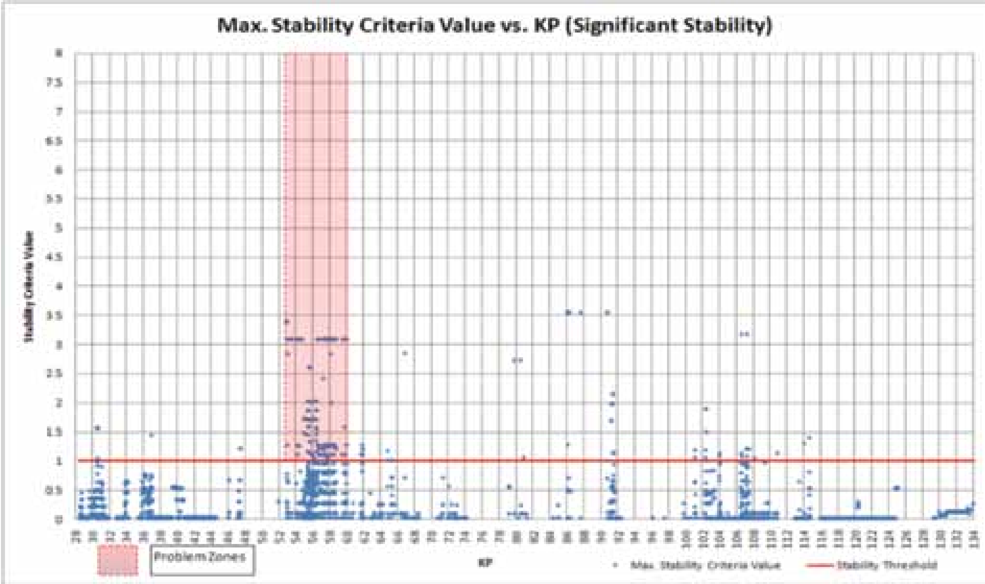

Fig.5. Pipeline significant stability results between KP 28 and KP 124.

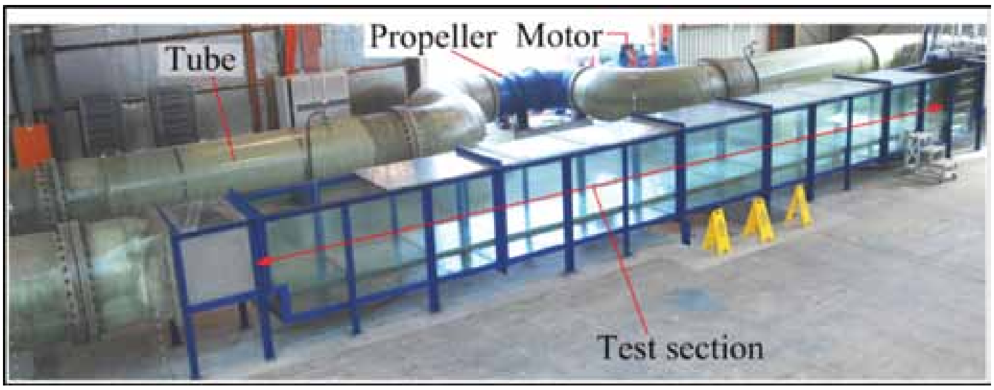

Fig.6. The O-tube hydraulic testing facility at UWA.

2D pipeline-stability assessment

The limitations of the available pipeline-stability recommended practices [1, 2] were assessed in great detail. It was decided that, initially, a 2D analysis using a modified RP F109 approach would be performed based on absolute stability criteria. In view of the relatively low pipeline SG and the fact that the pipeline had been trenched following installation, it was a safe assumption that should pipeline break out occur, instability had been reached to an unacceptable degree. It was recognized that this was a conservative approach, with the aim of identifying which areas of the trunkline needed further assessment. Thus, the results from the 2D stability analysis would then be utilized to prepare the scope of work for a more-realistic, but also more-complex, 3D FEA analysis.

The results of the 2D stability assessment are summarized in Fig.5. The region between KP 52 and KP 63 was identified as the most likely to experience instability: this 11-km route section was consequently used as the basis for the physical model testing programme and subsequent 3D dynamic stability assessment.

Rock-berm stability assessment

In parallel with the pipeline-stability assessment, the stability of the rock berms (which were installed as part of the remedial stabilization project in 1991) was re-analysed using the industry's latest reliable software. The rock-berm stability software package *PROBED* [7] was used to calculate the minimum rock-armour layer D_{50} values that would be statically stable for the 100-year return period conditions.

The *PROBED* software package has been developed by Delft Hydraulics and is based on tests performed on schematized structures. It allows for the design of graded rock structures that are subjected to a combination of steady-state currents and oscillating currents induced by non-breaking waves. The software uses empirical and semi-empirical design equations

Fig.7. Extract of test results (example).

based on wave height, critical Shields parameter, shear stress, and other inputs to calculate a D_{50} rock particle size. Some engineering judgement is required as graded rock structures are essentially a collection of graded rock particles, and the ability of an individual rock particle to withstand the design hydrodynamic load depends not just on the weight and dimensions of the particle, but also on the level of protrusion and interlocking with adjacent particles.

The analysis performed using *PROBED* indicated that the rock berm along the trunkline met the design functional requirements.

Physical model testing

The 2D pipeline-stability analysis provided information as to which sections of the pipeline along the area of interest were critical from a hydrodynamic-stability point of view. It was identified that within the limitations of existing design codes it was not possible to demonstrate that the pipeline satisfied on-bottom stability requirements. However, it was recognized that these limitations overlooked potentially beneficial effects from seabed mobility. To allow such effects to be incorporated in the design assessment, it was decided that physical model testing would be performed to provide additional information specific to the conditions relevant to this pipeline. To achieve the required results the minimum parameters of a testing facility were defined, which resulted in the following main conclusions:

- It was considered impractical to build a facility which would enable testing a 40-in weight-coated pipeline at the prototype scale. To practically model the tripartite interaction between hydrodynamics, seabed soils, and pipeline, scaling would need to be limited to a maximum of 1:5 – 1:6; the quantification of scour processes around pipelines become increasingly difficult to model at smaller scales.
- At such a scale, the use of an open wave and current flume would be impractical, requiring a flume depth of at least 10 m with the ability to concurrently model wave-induced, as well as steady-state, currents. Existing conventional open flumes are plagued by wave breaking and non-linear affects.
- U-tubes, which have commonly been used in the past for similar work, have significant limitations in relation to varying the wave periods as well as including steady-state currents. It is difficult to control the frequency in a U-tube much away from its natural frequency.
- After several meetings in which the physical model testing aspects were discussed, the concept of the O-tube [8] was developed by the University of Western Australia specifically for this project. To obtain the additional required funding to construct such an ambitious facility, Woodside formed a collaboration with Chevron Australia with the aim of undertaking additional testing over and above that required for the NRA trunkline's stability assessment. In addition, federal funding was successfully applied for through the Australian Research Council.

A number of scaled physical model tests were performed in the O-tube facility for various symmetric and asymmetric initial embedment profiles. The tests were performed using an appropriately scaled representation of a 100-year return period irregular wave-induced and steady-state current storm time series. Seven realizations of complete on-bottom wave and current velocity storm time series were generated. The storm realization with the largest peak flow velocity was selected as the base-case flow velocity time series for use in the physical model testing programme.

The following key data were measured from each test for use in the subsequent 3D FEA stability model:

- The lateral and vertical hydrodynamic loads were measured during each test as a function of time.
- In addition, the profile of the artificial seabed, created using sediments sourced from the Northwest Shelf, was monitored and measured throughout each test using a small echo-sounder.

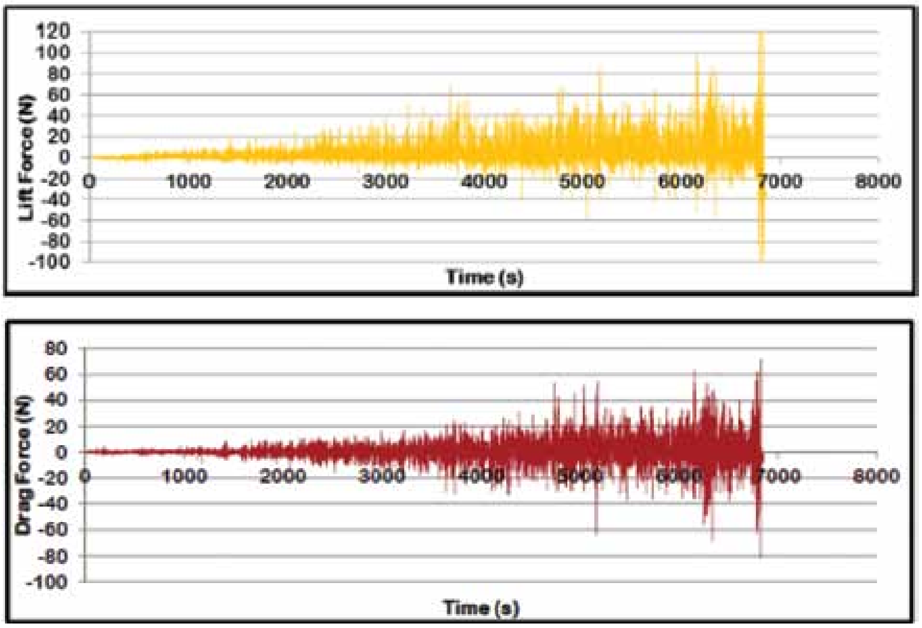

Fig.8. Extract of test results (example), lift force (top), and drag force (bottom).

Ancillary tests were also performed to provide additional information needed for the stability analysis, including:

- Hydrodynamic loading of the test pipe on a rigid seabed, to obtain lift and drag forces for a range of KC numbers.
- Pull-out tests to define a pipe-soil resistance model specific for this pipeline and soil type.

It is recognized that the 1:5.8 scaling used for the testing programme introduced several scaling issues, particularly in view of the inability to use a similarly scaled soil for the tests (the tests were performed using prototype soil). This problem was addressed during the preparation phase of the physical model testing campaign. An assessment was therefore performed, in particular to quantify the level of error associated with the onset and extent of scour development in the physical model relative to what was expected in the prototype.

Despite the inevitable scale of 1:5.8 used during the testing campaign in the O-tube, it is noted that this is closer to full scale compared to previous (similar) physical model testing. To date, physical model tests involving subsea pipelines have typically been performed at scales of 1:20 or smaller, and this leads to scour-scaling distortions in the order of 100 to 200%. In comparison, the time required to reach equilibrium scour in the O-tube has been assessed to be approximately 35% relative to prototype scale. The soil-particle size will not affect the equilibrium scour depth or the initiation of local scour.

An example of the results of one test is provided in Figs 7 and 8. This particular test was intended to simulate a 2D pipeline slice embedded symmetrically to a level of 50% of its external diameter subjected to a 100-year return period hydrodynamic load in the form of a storm time-history with 3 hrs ramp-up, 3 hrs peak storm duration, and 3 hrs ramp-down (prototype timescale), and with a scaled-down combination of irregular wave-induced and steady-state currents.

It was noticed that seabed instability (local scour), for this particular test, occurred before the peak of the storm, and well before the model pipe became unstable. The model pipe was displaced laterally after approximately 4 hrs (prototype) from the start of the storm, upon which the model pipe was restrained laterally (but not vertically – i.e. constant SG) to monitor the seabed response to hydrodynamic loading in the event that adjacent sections of the pipeline would be stable (due to more embedment and/or reduced hydrodynamic loading).

The measured forces and seabed data of all testing performed were subsequently analysed and captured in a numerical model for input into the 3D finite-element analyses.

Soil lateral-resistance model

The development of a reliable and realistic pipe-soil resistance model for the carbonate soil used here was a key element of the trunkline stability assessment. Pipe pull-out tests were performed in the O-tube using the model pipe embedded into the seabed soils, for a range of embedment levels, to define a pipe-soil resistance model specific for this pipeline and soil combination.

DNV RP-F109 [2] recommends modelling soil resistance using the Verley and Sotberg soil passive-resistance model [9] in combination with a Coulomb friction factor of 0.6. According to this model, the Coulomb friction factor is

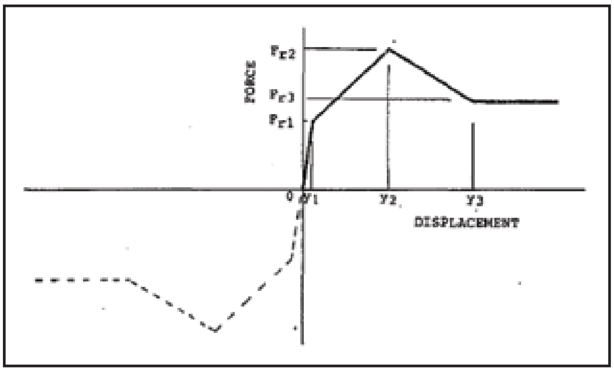

Fig.9. Verley pipe-soil passive-resistance model [9].

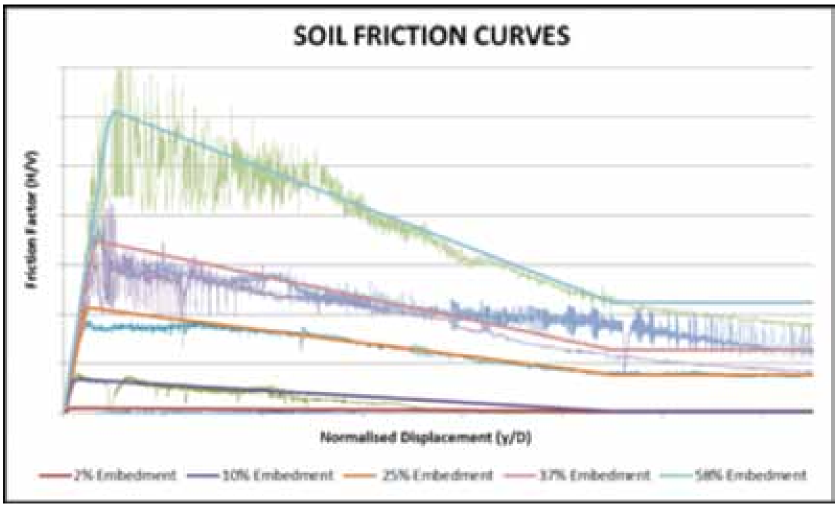

Fig.10. Modified Verley pipe-soil passive-resistance model.

assumed to be constant, while the passive resistance is dependent on both the pipe-soil vertical contact force and pipeline embedment.

The Verley model has been obtained from physical model tests performed on silica soils, while the NRA trunkline is located in carbonate soils. In addition to this, the method used to achieve pipeline embedment with the Verley model is different from the method used for the O-tube pull-out tests. The physical model tests used to develop the Verley model achieved pipeline embedment by running a predefined number of small, constant-amplitude, oscillations. In the O-tube, the specified embedment was achieved by positioning the model pipe in a prepared trench with a flat seabed either side, prior to a test commencement. In all the O-tube tests performed, there was no evidence of pipeline embedment generated through a process of small pipeline oscillations. In all cases, the test pipe remained essentially static until a large wave-induced current caused displacement leading directly to break out, or loosening the soil around the model pipe through local scour, allowing subsequent wave-induced current oscillations to complete the break-out process. This suggests that the preparation method used for the O-tube pull-out test is the more suitable for the development of a soil-resistance model capable of analysing the stability of the NRA trunkline. The trunkline did not achieve the current embedment through cyclic movements from the surface: the pipeline was post-trenched by ploughing following installation, and it is suspected that reduction of its embedment has subsequently occurred during cyclonic activity. The O-tube method of placing sand around the pipe to achieve embedment is considered more representative of this situation, compared to the cyclic-oscillation process used to achieve embedment in the database of earlier pipe-soil model tests from which the Verley model was calibrated.

The Verley model is based on a force-displacement curve, as shown in Fig.9, where F_{r1}, F_{r2}, and F_{r3} represent the peak elastic, peak break-out resistance, and residual passive forces respectively, and y represents the corresponding lateral mobilization distances.

Relative to the O-tube (and other similar soil models developed for pipelines in the Northwest Shelf of Western Australia), the Verley and Sotberg passive-resistance model significantly overestimates both peak breakout resistance (F_{r2}) and peak break-out distance (y_2). This is consistent with findings recorded in the SAFEBUCK JIP [10].

For the purpose of this project, the Verley model has been modified in order to alter the magnitude and shape of the passive-resistance curve to be in line with the O-tube pull-out

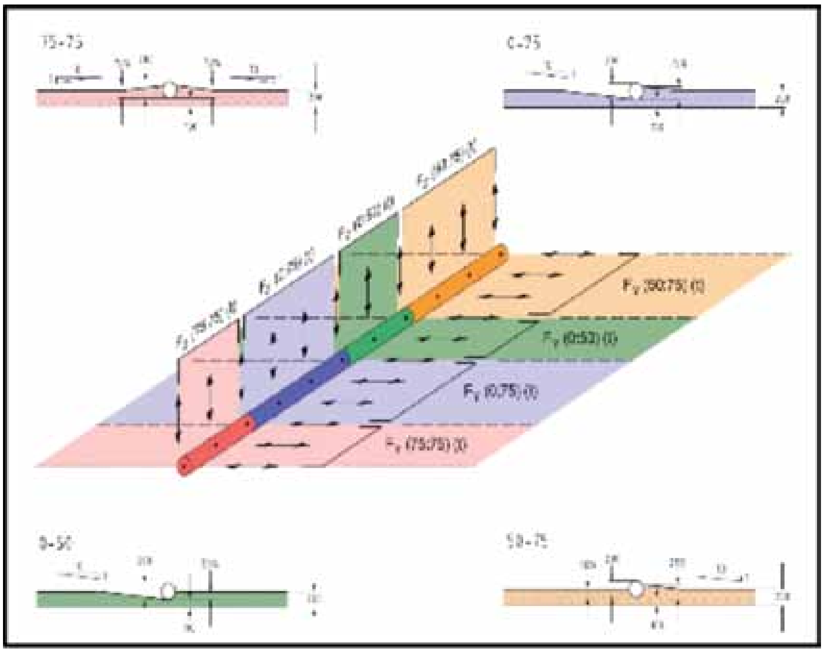

Fig.11. Schematic of the loads applied during an analysis increment.

test data, and comparisons between the modified model and the O-tube pull-out tests are shown in Fig10. This allows the un-conservatism inherent in the Verley model when applied to this particular carbonate soil type to be removed, while maintaining the generic form of loading-unloading-break-out behaviour described within the Verley model in the 3D dynamic FEA modelling of the NRA trunkline.

3D finite-element analyses

A 3D finite-element pipeline stability analysis was performed to translate the results from the 2D scaled physical model testing to the 3D prototype 40-in diameter pipeline. This dynamic on-bottom stability analysis was performed using the *CORUS-3D* analysis software [11]. The 11-km section of trunkline route (KP 52 - KP 63) was partitioned into ten sub-sections, varying in length from 220 m up to 1,830 m, with each sub-section analysed independently. The assessment was performed by subjecting the trunkline, in its current condition, to a 100-year return period hydrodynamic loading condition.

The objective of using the *CORUS-3D* analysis software over and above the 2D physical model testing was to account for the stabilizing effects of adjacent pipeline sections with higher initial embedment levels on sections of pipeline which would otherwise be considered unstable in 2D. *CORUS-3D* is also able to reduce the conservatism present in the 2D modelling by simulating 3D wave loading.

This FEA model incorporated the interactions that exist between a pipeline and the surrounding fluid (hydrodynamic effects), a pipeline and the seabed (passive resistance) and, to a limited extent, the dynamic interaction between the seabed and the fluid.

The analysis software was validated against the O-tube initial embedment test results, which included scaling the test results from the model scale to prototype scale. The following steps were undertaken to define the sub-sections to be analysed:

- A three-point moving average was applied to the pipeline embedment data to define the initial embedment profiles at 5-m intervals along the pipeline.
- The initial embedment level along the trunkline varies, and eight such embedment cases were modelled in the O-Tube (i.e. in terms of left:right embedment level as a percentage of pipeline diameter (D): 0D:0D, 0D:50D, 0D:75D, 50D:0D, 50D:50D, 50D:75D, 75D:75D, and 90D:90D). The initial embedment profile (at 5-m intervals) was rounded down to the nearest test profile. For instance, where the survey data shows a section of the trunkline route with an initial embedment of 0D:25D, the initial embedment has been rounded down to the nearest available test data, which is the 0D:0D initial embedment test data. This is considered to be a conservative approach.
- The extent of each analysis model has been determined by identifying regions that will provide highly stable, effectively fixed-end, conditions such as long regions (50-100 m) of fully buried or rock dumped pipeline.

The schematic presented in Fig.11 is a representation of the loads applied to the beam in an analysis time increment.

Based on the 3D dynamic stability analysis results, it was concluded that the most critical region of trunkline (between KP 52 to KP 63) is not expected to break out of its embedment during 100 year return period conditions due to hydrodynamic loads alone. Furthermore the analysis was shown to have a significant margin of safety, as demonstrated by the fact that the pipeline remains essentially stable even considering reduced soil passive resistance of up to 70%. The effects of seabed mobility were incorporated in the 3D FEA model by applying at each pipe element the changing embedment experienced in the relevant 2D physical model tests, which captured the scour during the life of the storm.

It was demonstrated, however, that the potential exists for lateral buckling driving loads, acting in combination with the hydrodynamic loads, to cause sections of the pipeline to break out. However, although the pipeline may break out of its embedment at discrete locations, this will not result in overstressing, and is not considered likely to lead to global instability of the pipeline. Consequently it is considered that this risk can be adequately addressed through monitoring of the pipeline following significant tropical storms, and intervention to restabilize the pipeline as necessary.

Conclusions

The need for the application of a new pipeline stability analysis method became apparent during the early stages of the NRA trunkline stability assessment. It was decided to perform physical model testing to identify seabed mobility effects, and apply these observations to a 3D FEA program to simulate the prototype pipeline. Existing 3D FEA software packages, which are commonly used in the industry, were viewed to be inadequate due to their inability to model seabed material instability. The significant effect of seabed material instability on pipeline stability is a proven phenomenon and has been addressed in the past by Professor Andrew Palmer [3]; the physical model testing performed as part of this project confirms this.

The application of the 3D dynamic FEA software package described in this paper, and which simulates pipeline response to hydrodynamic loading while accounting for the effects of seabed instability during ramp-up, peak, and ramp down of a severe storm, has proven to be effective in assessing the stability of a pipeline in a mobile seabed environment.

The decision taken to develop a custom-built physical model testing facility and to run a series of large-scale tests to provide input into and validate the 3D FEA software was strategic and effective.

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