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Middle East India Deepwater Pipeline (MEIDP) - Geohazard Features Assessment and Intervention at the Owen Fracture Zone and Indus Fan

Authors: Simon G. Parry, Christopher J. Burnett, Ian F. J. Nash
Peritus International Limited
Woking, Surrey, United Kingdom

1. Abstract

The Middle East to India Deepwater Pipeline (MEIDP) will provide an economical and secure source of gas for India, where the demand for energy will continue to increase over the coming decades.

The proposed pipeline will be the deepest major infrastructure pipeline laid, with water depths exceeding 3000m for significant sections of the 1300km route. In addition to its depth, the MEIDP will potentially have to contend with significant geohazards, located in the areas of the Indian and Omani continental slopes, the Owen Fracture Zone and the Indus River Abyssal Fan.

This paper uses the findings of the 2013 geophysical reconnaissance survey in the area of the Owen Fracture Zone, where the route crosses a strike slip fault between the Arabian and Indian plates, and the Indus River Abyssal Fan, where the route crosses a complex deep channel system which may be an active zone of debris and turbidity flow.

A feasible route through these geohazards is presented, together with the design process and guidelines for dealing with fault crossings, associated debris and turbidity current flow, slope stability and run-out.

2. Owen Fracture Zone

At the Owen Fracture Zone (OFZ) the MEIDP crosses the continental plate boundary between the Arabian and Indian plates, which meet forming a right lateral strike slip fault movement zone. A Digital Terrain Model (DTM) of the OFZ showing the initial pipeline route and fault crossing is presented in Figure 1.

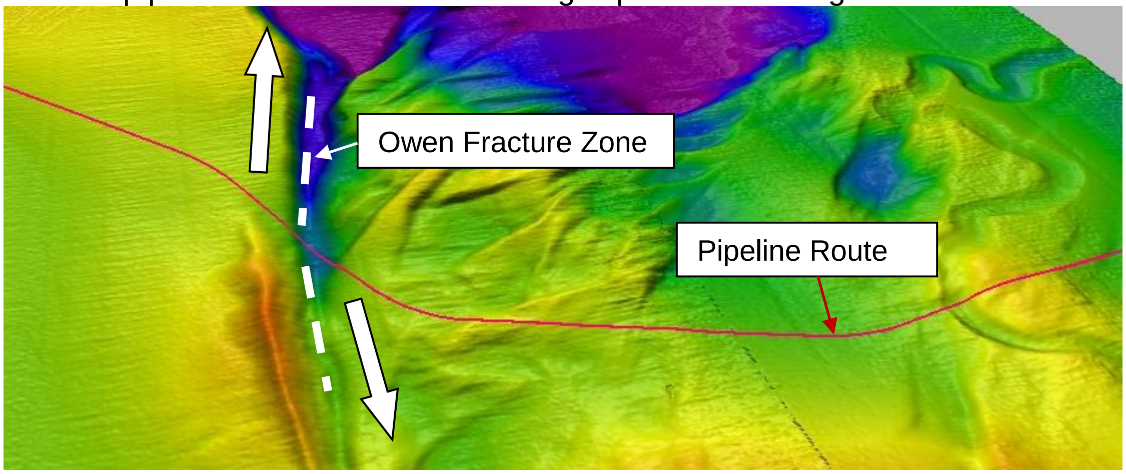

Figure 1 Owen Fracture Zone

The fault crossing poses a hazard to the pipeline as relative motions of the two plates could cause overstressing, buckling or even failure, particularly if the movements put the pipe into compression. Additionally, the general disturbance of the seabed may create freespans subject to excessive levels of fatigue damage due to vortex induced vibrations (VIV).

To assess overstressing at the fault crossing, a parametric study was performed using the general purpose Finite Element Analysis (FEA) software Abaqus 2016 and a DNV-OS-F101 Load Controlled Condition (LCC) buckling check carried out on the results.

The models, shown in Figure 2, are of an idealised pipeline resting on two independent seabed surfaces under representative pressure and temperature loading. The two surfaces are moved relative to each other to simulate fault slips. The magnitude of these slips and the angle that the pipeline crosses the fault are both varied to quickly determine a band of acceptable crossing angles which then guides the initial pipeline routing. A parametric assessment where crossing angles of between 45°, which will pull the pipeline into tension, and 135° which will push the pipeline into compression were analysed. A slip magnitude of 7m, representing a 1000 years of accumulated movement was considered sufficient as the pipeline is in a DNV-OS-F101 “low” safety class zone, which required an annual probability of failure of 10^{-3} or less. In addition to the slip, a load of 0.6 times the pipeline’s submerged weight was applied to the pipeline, based on a maximum 1000-year Peak Ground Acceleration (PGA) of 0.6g predicted at the OFZ.

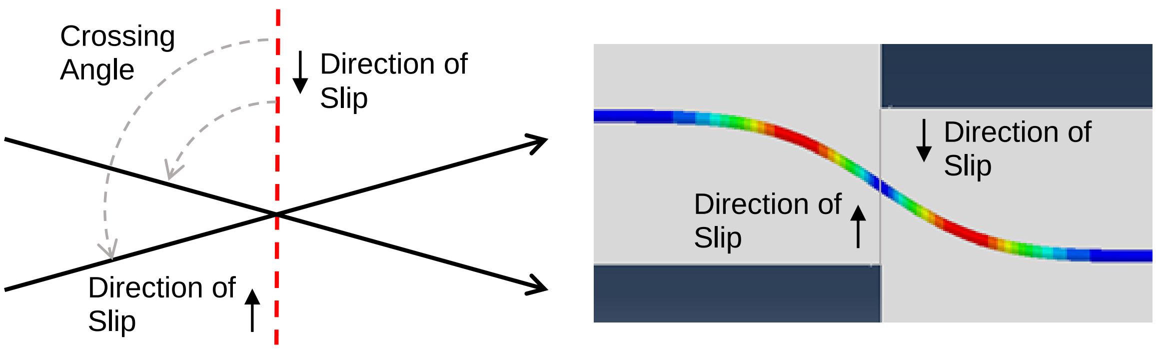

Figure 2 Fault Crossing Schematic and Abaqus Model

Figure 3 presents the results of the parametric fault crossing analysis and plots the DNV-OS-F101 LCC utilisation versus slip magnitude and fault crossing angle. It can be seen that crossing angles greater than 90°, where the pipeline is placed in compression, cause a sharp increase in LCC utilisations and that crossing angles greater than 120° would be unacceptable for a 1000-year slip. This increase is due to the relative orientation of the pipeline and fault line, which causes the pipeline to be pushed into compression by the slip. For slip magnitudes of greater than approximately 1.0m the compressive force is sufficient for snap buckling to occur, leading to a further jump in LCC utilisations.

Meanwhile, crossing angles of less than 90° are orientated such that a slip would pull the pipeline into tension, where the pipeline has a far greater capacity, leading to lower LCC utilisations. However, it should be noted that whilst tension is preferable in these idealised analyses, the additional tension may create / enlarge existing freespans on the seabed.

For MEIDP routing a fault crossing angle of 40° was chosen for the OFZ and, as an extra precaution, two route bends were included on either side of the fault on the basis that these would pull out and help relieve tension, minimising span growth, in the pipeline in the event of a slip.

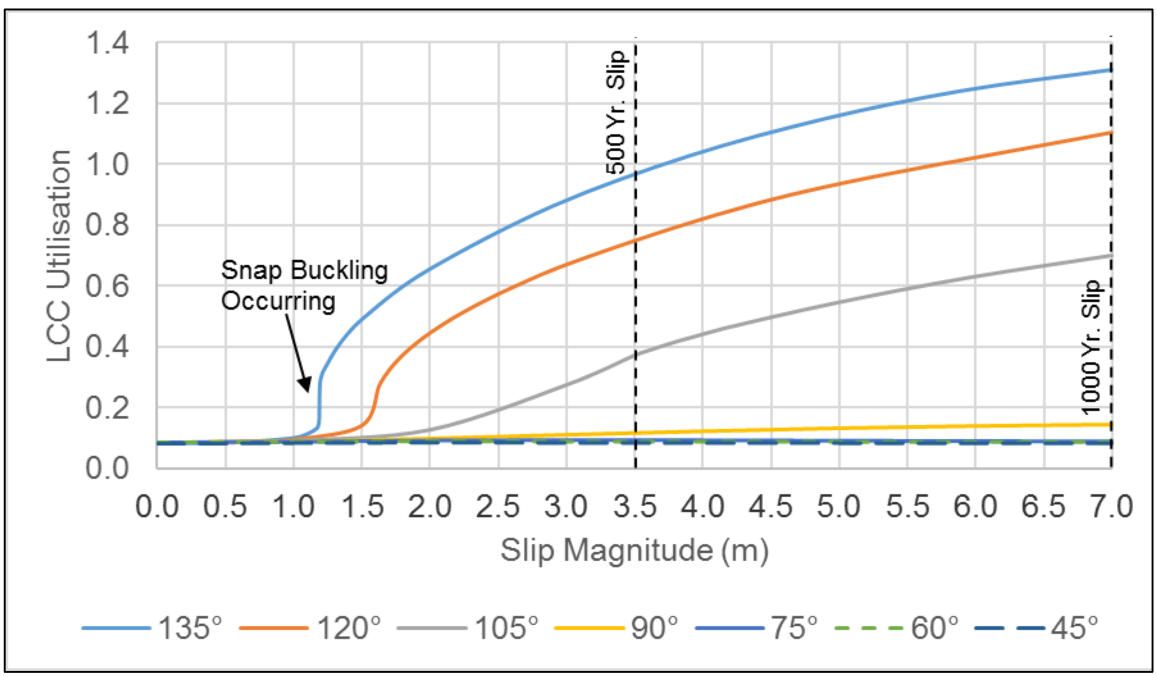

Figure 3 DNV Utilisation Versus Fault Crossing Angle

Based on this preliminary FEA work, Figure 4 presents the route through the OFZ.

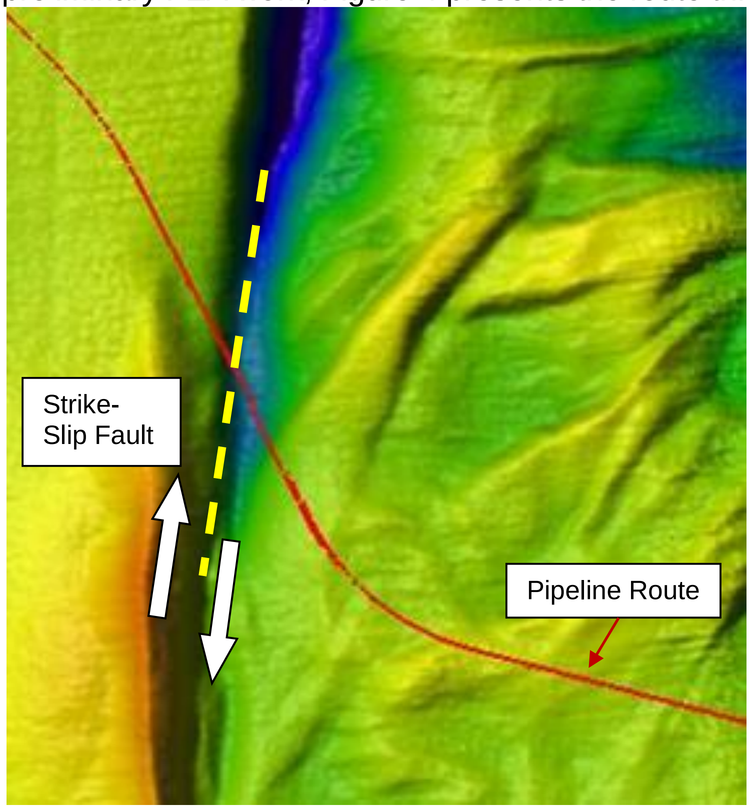

Figure 4 Fault Crossing Plan

The idealised flat seabed crossing of the OFZ is however quite far from reality. Figure 5 shows the profile of the seabed along the pipeline route as it crosses the OFZ.

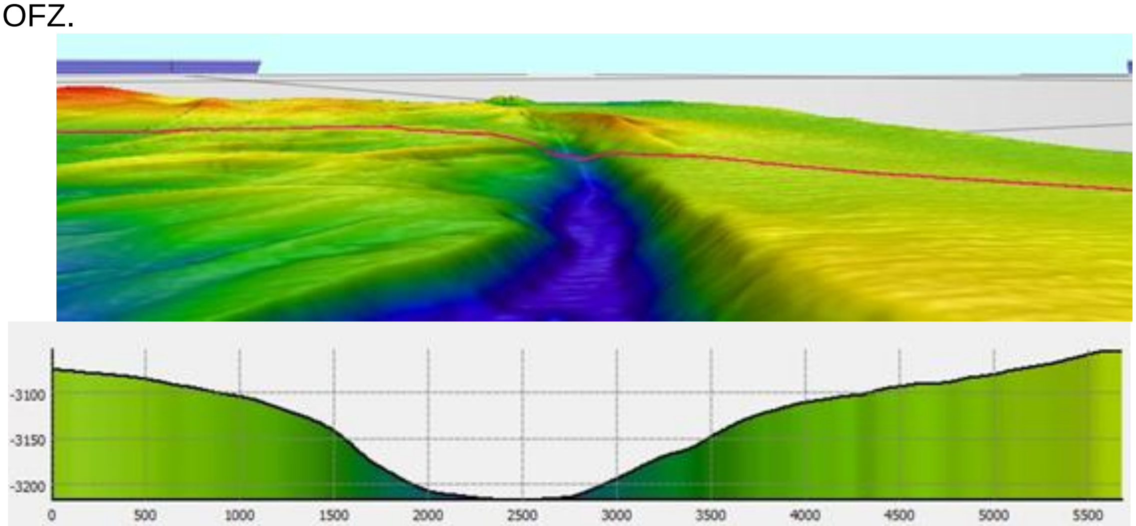

Figure 5 Fault Crossing Profile

To ensure that the selected route was acceptable a more detailed FE analysis was performed using the same Abaqus models with the addition of a full 3D seabed based off the route centreline plus 50m either side of the line. Furthermore, S-lay installation was simulated within the analysis, as this could have an effect on observed freespans and residual lay tensions.

Figures 6 and 7 present plots of the detailed Abaqus models under design conditions and including the 1000-year slip of 7.0m. The resulting LCC utilisation for a 1000-year slip was 0.151 which is within acceptable limits, and close to the result predicted by the initial idealised fault crossing analysis which was 0.121.

A single freespan of 20m can be observed at the fault, however a span of this length at 3,200m water depth does not show significant levels of VIV fatigue damage. Resonance of the span may occur during a seismic event, however, considering the freespan is short, it will have a large natural frequency and so is unlikely to be prone to resonation during seismic events.

No other freespans are predicted given the combination of the fault crossing angle and the two route bends, further complimented by the soft seabed resulting in relatively large pipeline embedments.

If large freespans were observed a detailed VIV fatigue assessment to DNV-RP-F105 or similar would have been carried out using a combination of a modal analysis in Abaqus to determine the natural frequency of the freespan and associated mode shapes. The results would then be post processed using DNV's Fatfree software or similar to calculate the predicted VIV fatigue damage. The additional stresses due to resonation of the freespan during seismic events would, as a simple first pass be assessed by adding an additional load to the pipeline based on the fault's 0.6g PGA value, multiplied by the pipeline's added mass. The fatigue damage due to this additional stress would then be calculated, with the number of stress cycles based on the span's natural frequency and duration of a seismic event. During further analysis a more detailed assessment of seismic related stress, considering the relative natural frequencies of the span and seismic event would be required, however this simplified method would be acceptable for a first pass.

If unacceptable damage is predicted, then an allowable freespan length should be determined, followed by an iterative approach of re-orienting the pipeline until both LCC utilisations and fatigue are acceptable would be required. The final orientation of the pipeline chosen must lead to a robust solution, i.e. small deviations in the route angle or corridor due to installation tolerances must not lead to unacceptable utilisations.

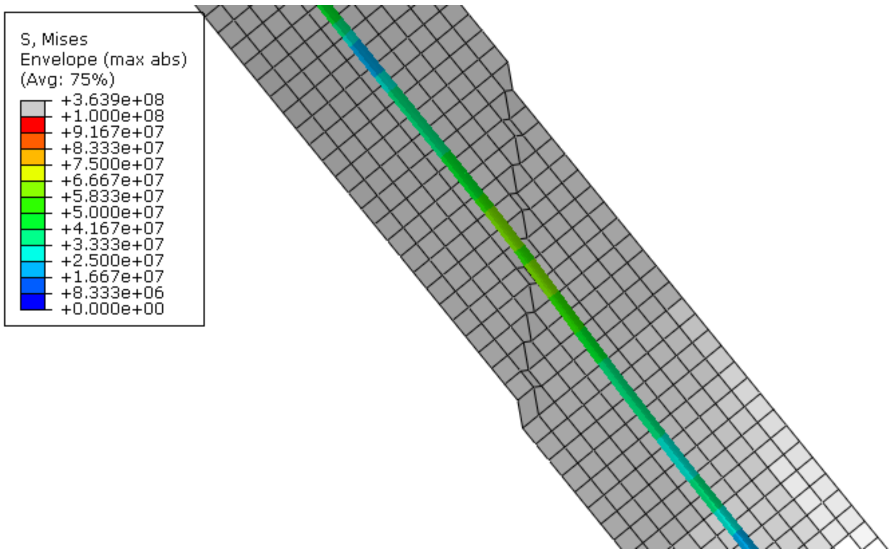

Figure 6 Fault Crossing Plan in Abaqus Showing von Mises Stresses

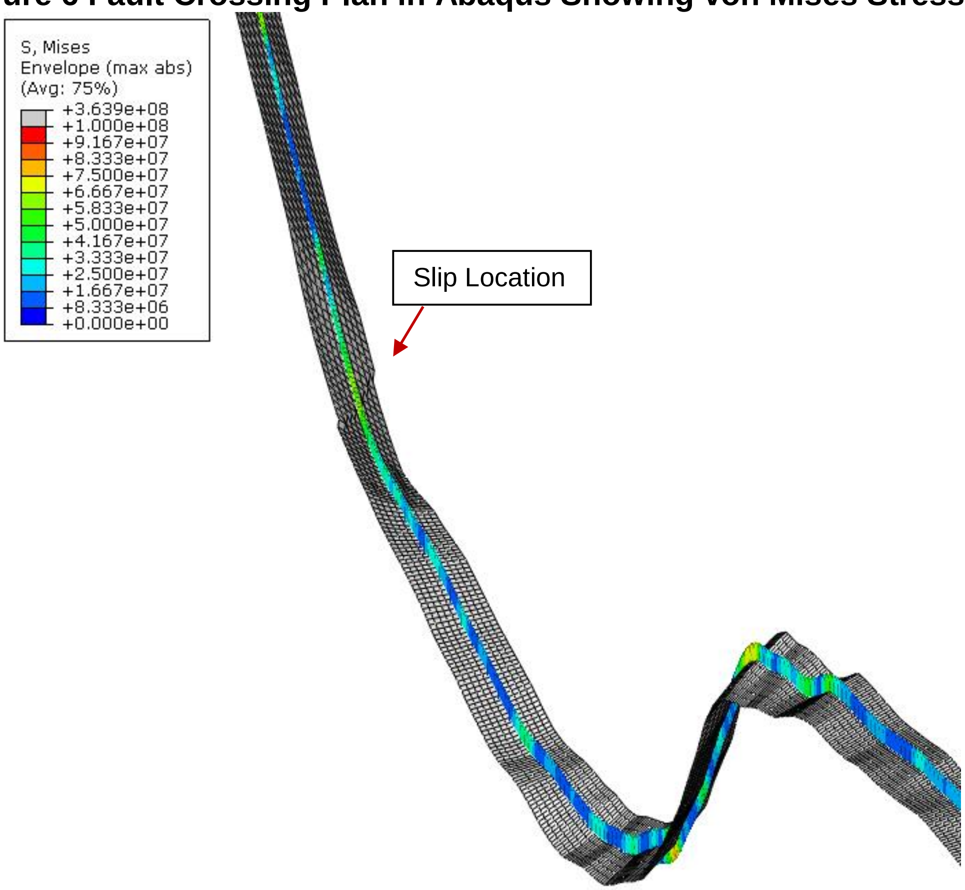

Figure 7 Fault Crossing Profile in Abaqus Showing von Mises Stresses

In summary, the assessment of the fault crossing took the following form:

- Reconnaissance survey to determine features of seabed and possible approaches.
- Characterisation of fault to be crossed including appropriate magnitudes of slips, PGA accelerations, and soil characteristics in the region.
- Parametric study using representative, idealised FEA models to determine suitable fault crossing angles considering DNV-OS-F101 LCC buckling criteria or similar utilisation criteria.
- Routing of pipeline through fault zone considering suitable fault crossing angles, attempting to orient the pipeline so that slips at the fault pull the pipeline into tension, and if possible including route bends in close proximity before and after the fault crossing to add flexibility to the pipeline.
- Detailed FEA of selected route to ensure utilisation criteria remain fulfilled and to further assess free spanning (particularly VIV and seismic resonance fatigue) and similar and to ensure the solution is relatively robust with respect to installation tolerances, etc.
- Possible iteration to refine route and confirmation by detailed FEA.

This represents the general framework which should be followed for a pipeline crossing a subsea fault, with site characterisation and detailed FEA being the most important steps and buckling and free spanning in the event of a slip being the most important considerations for an acceptable design.

Note that this assessment did not include any consideration of potential uplift of the plates at the fault because seismic studies show it is specifically a strike slip fault., however uplift may lead to an increase in the size of the freespan, therefore further characterisation of the fault will be required.

A further potential source of error which requires further work is the model chosen to simulate interaction between the pipeline and soils, which will impact the state of the pipeline. For the purposes of this paper a Mohr-Coulomb interaction, with a 0.6 axial and 0.7 lateral friction coefficient was considered sufficient. However, later phases in this and other projects should consider the effects of breakout berms, changes in embedment and the rate at which the pipeline deforms the soil. Such effects are relatively easy to include within the FEA through the use of custom made subroutines, however, the model controlling the soil's behaviour, be it empirical or analytical, should be carefully chosen to ensure it is applicable and predicts reasonable behaviour. The question of the rate at which the pipe is deforming the soil may also be important, as there is not a large amount of available information in this field. Most soil models are applicable to buckling or walking, and may not be applicable to the high rate of change expected during a fault slip.

3. Indus River Abyssal Fan

At the Indus River Abyssal Fan, the MEIDP route crosses a 300km long levee system that is characterized by five turbidity current channels with a series of adjacent terraces and numerous abandoned channel loops which are partially refilled by the overspill sediments from active canyon areas. Figure 8 shows the five channels, whilst Figure 9 presents a view of an abandoned channel loop, terraces and overspill.

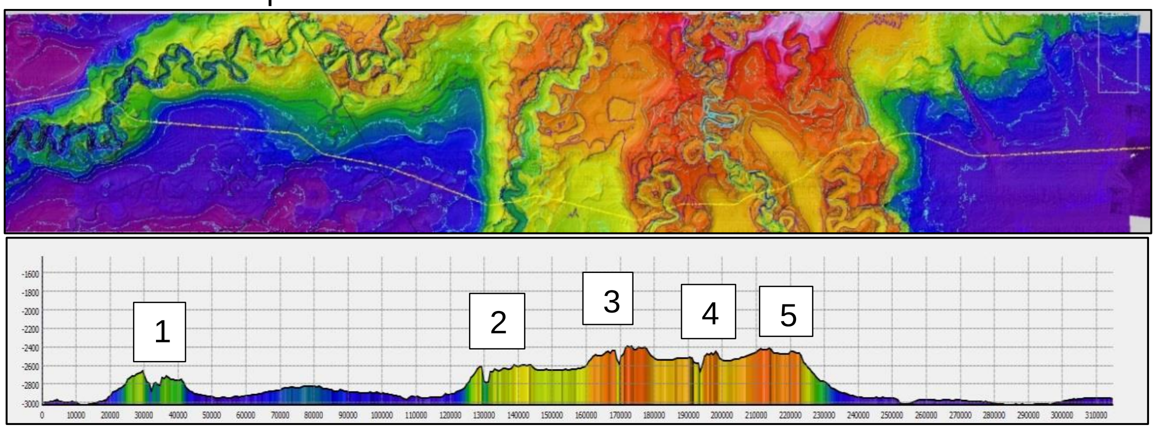

Figure 8 Indus River Abyssal Fan System

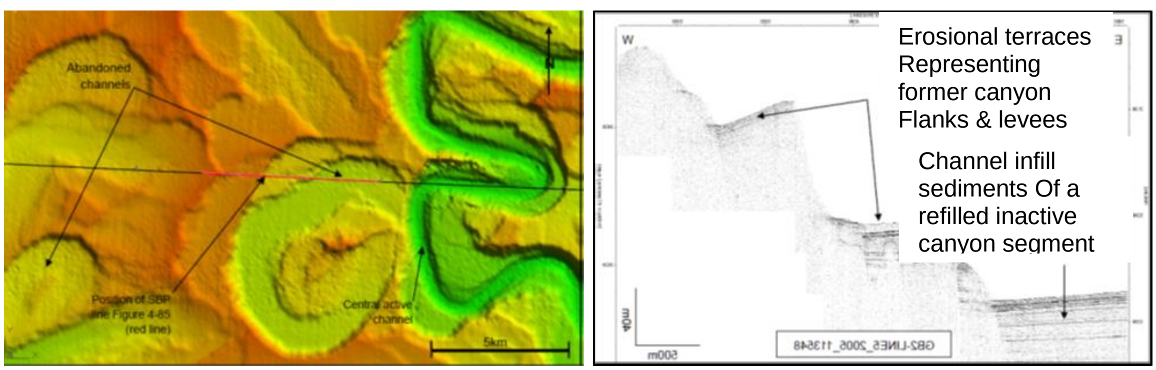

Figure 9 Abandoned Channel Loop

It was decided that a parametric analysis of the pipeline through this region would not be beneficial due to the large number of variables controlling the design, such as channel depth, width, side slopes, soil conditions and the possibility of debris and turbidity flows. Instead, an initial route through the channel system followed by detailed FEA was carried out and, if required, the route revised.

The initial routing aimed to minimise spans and areas of steep slopes and give flexibility to the pipeline in order to accommodate potential debris and turbidity flows in the channels. This generally involved crossing the channels where they were broadest, flattest, and orientating the pipe so that it was perpendicular to the channel.

Channel four, shown in Figure 10, is of particular interest, and is the focus of the Abaqus analysis, as it appears to have been active in recent geological time (last 10,000 years).

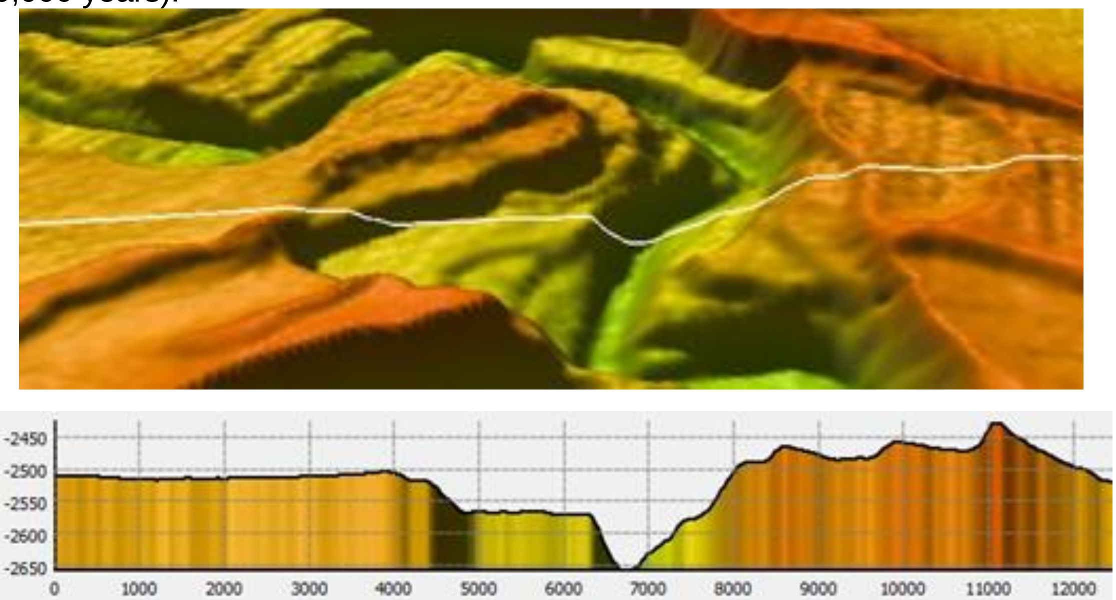

Figure 10 Channel 4 Crossing

For the detailed analysis of channel four, a 3D seabed consisting of the route centreline plus 250m either side was extracted and used within Abaqus models similar to the ones used for the detailed fault crossing analysis. An S-lay installation analysis, followed by hydrotesting and operation was then performed and the stress state and freespans were assessed for regular water based currents.

Figure 11 presents a snapshot of the freespans of the empty pipeline under post installation conditions. Freespans occur on the steep side slopes of the canyon and are approximately 80 to 100m in length. After further analysis these were found to be acceptable from both a stress and freespan VIV fatigue perspective. Because current velocities in the channels are currently unknown, the VIV analysis was carried out using increasing current velocities until either unacceptable levels of fatigue damage occurred or unrealistically high currents were reached. Currents were increased up to a velocity of 1m/s, with associated VIV fatigue damage of 0.2%, at which point it was decided the freespans were acceptable on the basis of previous project experience showing that current velocities of 1m/s could be experienced in a 2,500m deep canyon.

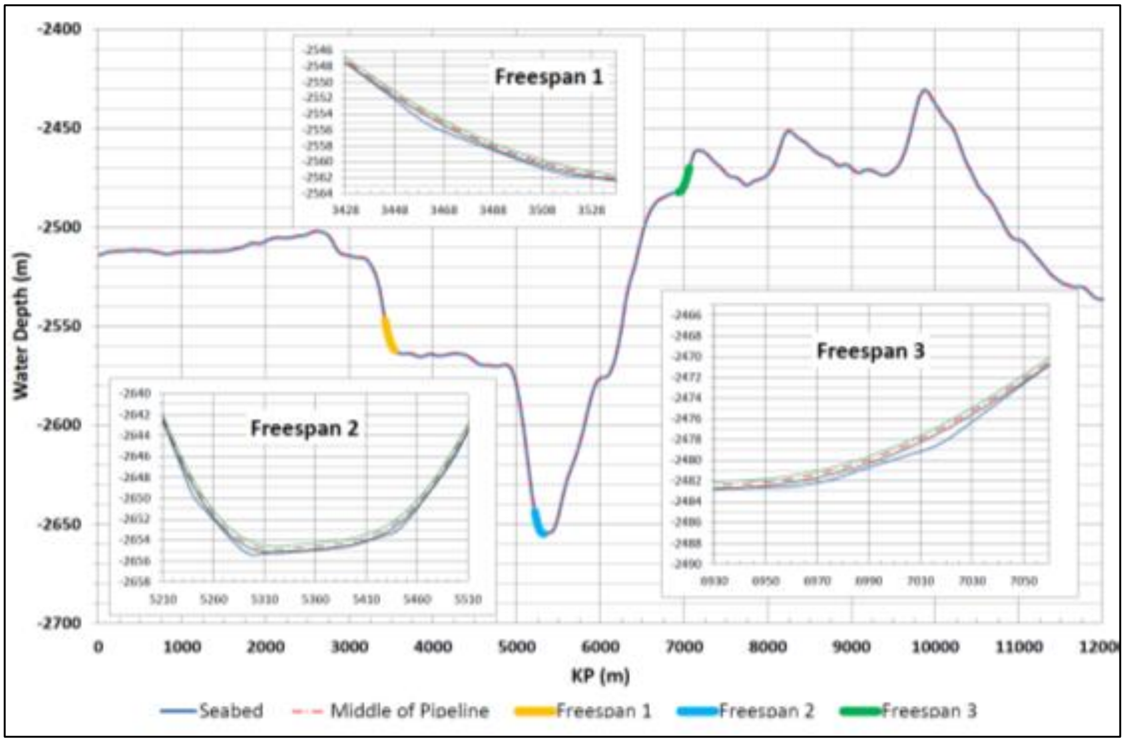

Figure 11 Freespans at Canyon Feature 4

With the basic routing of channel 4 shown to be acceptable, an assessment of debris and turbidity flows was carried out. Debris flows can occur when the side slopes of the canyons collapse, leading to forces acting in-line to the pipe which can increase freespan lengths, pull out the pipe or cause buckling. Turbidity flows are caused by slurry flows running down the canyon, impacting the pipe side on, causing large transverse displacements, potentially overstressing the pipelines and increasing freespan length.

Both debris and turbidity flows are based on the velocity and relative density of the material being transported, however, as with the steady currents controlling freespan VIV, details of the flows are currently unknown. Debris and turbidity flows were therefore applied to the pipeline using uniformly distributed loads (UDL) increasing in size until either the pipeline failed stress and freespan VIV checks, or the loads became unfeasibly large.

Figure 12 presents a plot of the base of the canyon, near Freespan 2, and highlights the length which was assumed to be subject to turbidity currents. To maximise the length over which the UDL was applied, it was assumed that the flows would reach approximately halfway up the side slopes of the lower canyon, however it is likely that in reality the flows would only occur in the flat base of the canyon, approximately halving the length over which the UDL was applied. The UDL was applied perpendicularly to the pipeline to maximise the lateral force acting on it.

Figure 13 shows the effect of turbidity currents acting on the pipeline. Current velocities were increased up to 4m/s, at which point the pipeline was lifted vertically by 8m and moved laterally by 60m. Increasing current velocities past this is possible, however it was felt that as the pipeline was already 8m above the seabed, higher current velocities would be moot as any additional flow would pass under the pipeline, leaving it unaffected. This is one of the limits of using a UDL, and in the future a user defined subroutine will be made for Abaqus which calculates the UDL based on the gap between the pipeline and seabed, with increasing gaps leading to a reduced UDL due to the majority of the flow passing under the pipe.

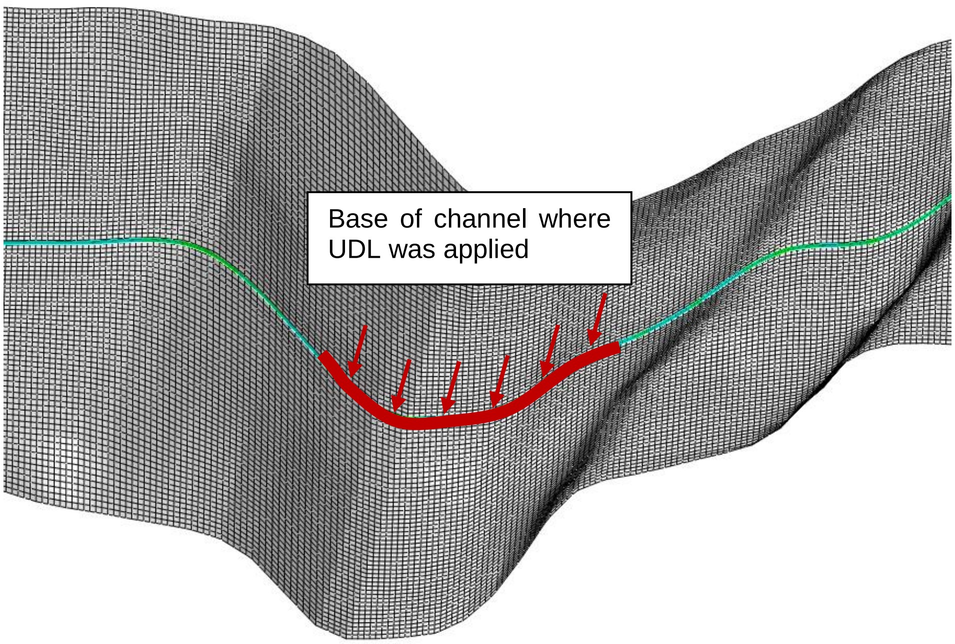

Figure 12 Canyon Feature 4 Under Operational Conditions Showing Location Turbidity Currents Were Applied

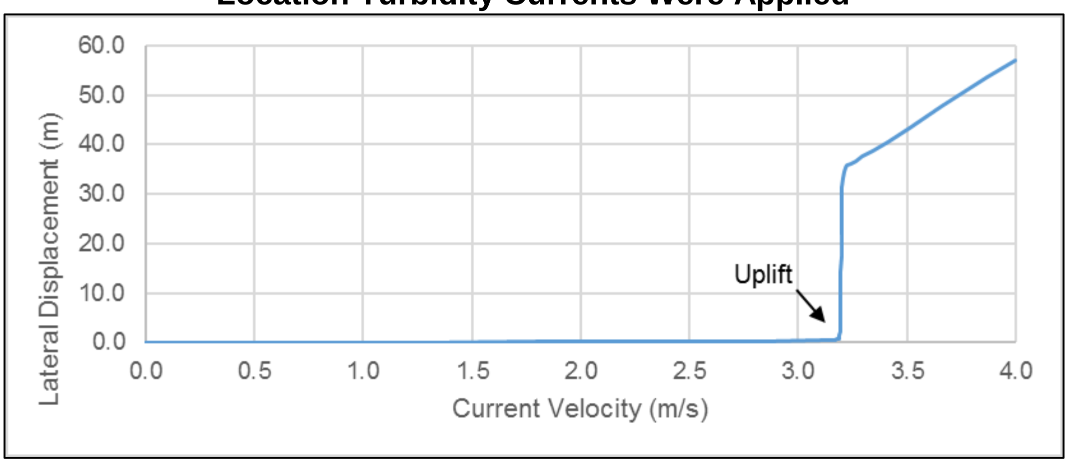

Figure 13 Canyon Feature 4 Under Operational Conditions with Turbidity Currents

Considering the large distance the pipeline was moving under turbidity loads, it was decided to cycle the UDLs to determine whether the pipeline would ratchet, with the displacements increasing with each load until the pipeline failed.

Figure 14 presents a plot of the lateral displacements of the pipeline as the turbidity loading is cycled. A step time of 0-1 represents the UDLs being applied, where it can be seen the pipeline is relatively unaffected until the point that uplift forces on the pipeline are sufficient to move it, whilst a step time of 1-2 represents the UDL being removed and the pipeline springing back. As is shown the maximum and minimum that the pipeline moved between does not change after the first loading, meaning the shoulder are stable and ratcheting is not occurring and the stresses / freespan lengths, etc. will not amplify with subsequent loading. If ratcheting were found to be occurring, an assessment of how many cycles would need to occur before the pipeline stabilised and the number of turbidity currents to be expected throughout the design life would need to be carried out, and possible intervention such as trenching to lower the pipeline into the base of the channel would be assessed.

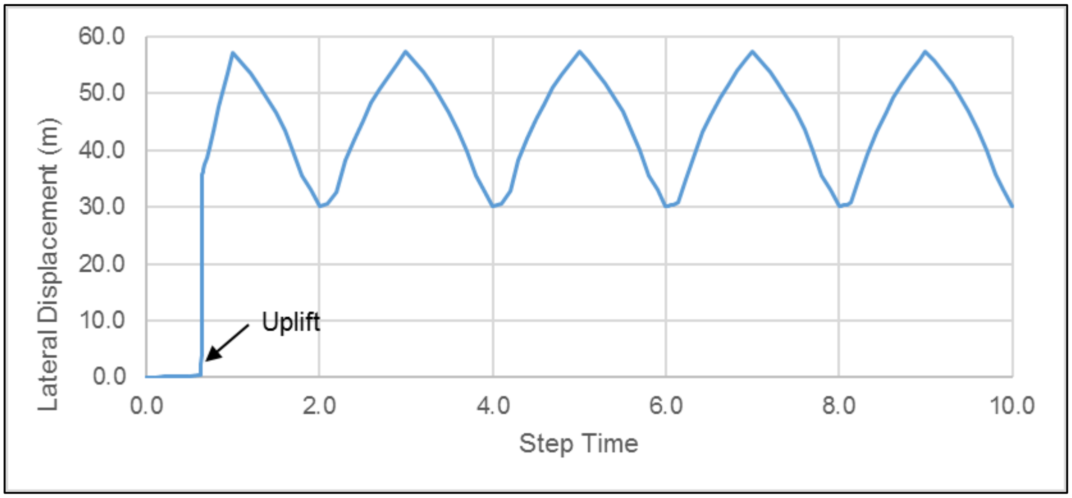

Figure 14 Lateral Displacements of Pipeline at Channel 4 Under Cyclic Turbidity Current Loading

The biggest observable effect of the turbidity currents on the pipeline was that it was being lifted up and moved horizontally. This movement increased the tension in the pipeline in a similar way to the fault slip, leading to the freespans at the canyon increasing in size.

Freespan 2, located at the base of the canyon was increased in size from 80m to 220m by the turbidity currents. A freespan VIV assessment was carried out, with a 100-year current velocity of 1m/s, and it was found that the freespan VIV fatigue damage was still within acceptable limits, with a damage of 1.0%, compared to 0.3% for an 80m span. It seems likely that due to the weight of the pipeline plus the increased shoulder embedments and tensions due to the turbidity currents that damping of the freespan has increased reducing the effects of VIV. Crossflow VIV damage is beginning to be seen on the 220m span therefore it is unlikely that the freespan lengths could be increased much further without crossflow VIV damage increasing exponentially.

A possible consideration for the turbidity currents which could not be investigated here is the duration of the currents, particularly if the currents are of a sufficient velocity to cause VIV. No analysis was carried out however as it was felt that the high density and viscosity of the flow compared to water would dampen the pipeline, preventing VIV. In the future though this should be confirmed through lab experimentation supported by full 3D, coupled CDF and FEA models of representative freespans.

Debris flow was assessed in a similar way to turbidity flow, however this time the UDLs were applied in-line with the pipeline, and along the side slope of the canyon as is shown in Figure 15. From the analysis, which again considered a current velocity of 4m/s no observable difference in the pipeline was seen, with the freespan lengths remaining unchanged and only the tension in the pipeline increasing slightly. This is due to a combination of the size and weight of the pipeline, and also because the pipeline has been routed to ensure it was at 90° to the slopes meaning the debris would only load the pipeline axially, where it has a large capacity.

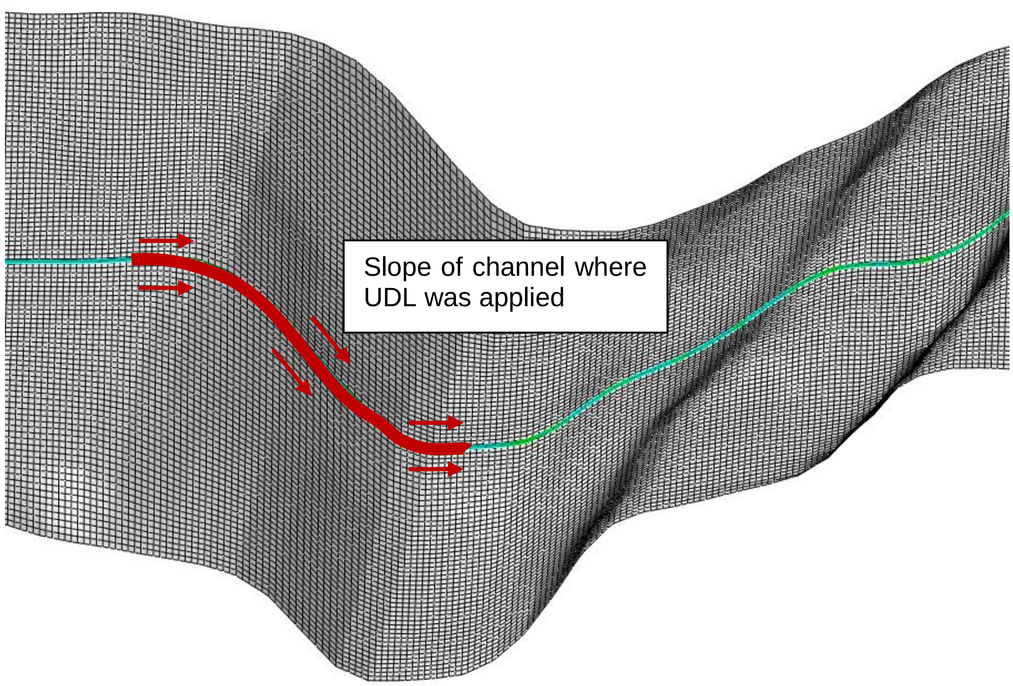

Figure 15 Canyon Feature 4 Under Operational Conditions Showing Location Debris Flows Were Applied

Based on these analyses it was therefore determined that the preliminary route through the Indus River Abyssal Fan was be acceptable but that detailed assessment of the soils, currents, debris and turbidity flows would be required to fully quantify the loading which the pipeline would be subject to.

In summary, the assessment took the following form:

- Reconnaissance survey to determine features of seabed and possible approaches.
- Characterisation of the current velocities, debris flow, turbidity currents and soil characteristics in the region.
- Create initial routing through the canyon zone, aiming to cross the smoothest seabed possible, avoid large slopes, avoid deep, narrow and upstream stretches of the canyons where turbidity currents would be more intense if they were to occur, and try to ensure the pipeline is perpendicular to the slopes in order to ensure slope collapse / debris flows act in-line with the pipeline where it has greater capacity.
- Perform detailed FEA on the pipeline route, with a focus on stresses on the pipe and freespans, and assess freespan VIV to ensure it is not an issue.
- Perform analysis of turbidity currents and debris flow to ensure the pipeline remains acceptable. Pay particular attention to flows picking up the pipe and moving it large lateral distances, and flows which increase freespan lengths. Consider multiple loadings to the pipe to ensure ratcheting is not an issue and ensure that freespans remain acceptable.

This represents the general framework which should be followed for a pipeline crossing subsea channels which show evidence of debris flow and turbidity currents, with site characterisation and detailed FEA being the most important steps and free spanning being the most important considerations for an acceptable design.

For MEIDP further information regarding the currents, debris and turbidity flows in the canyons is required, however the current methodology of increasing the loadings on the pipeline until it either fails limit states or the loads become unrealistically high are seen as a good start point, especially in lieu of more detailed data.

Furthermore, future research should be made in order to properly model pipe - turbidity flow interaction (in addition to the already stated pipe- soil interaction), in particular how the flow changes with time and height above the seabed, because as was observed here, debris flows of 4m/s caused 8m high spans, which realistically is higher than the debris flows are expected to be, meaning that it is likely that even high velocity flows >10m/s would simply lift the pipeline up a few metres and then travel under the pipeline, leaving the pipe itself untouched. Site specific investigations, followed by some sort of coordinated efforts to model the variations in flow velocity and flow density with height above the seabed in order to ensure everyone is on the same page.

Finally, if turbidity currents are found to be occurring for a sustained period of time, assessment of VIV due to these currents should be made. Considering the different densities and viscosities of the turbidity compared to water where the current VIV design codes such as DNV-RP-F105 focus on, if seems likely that full 3D coupled FEA and CDF backed up by lab testing would need to be carried out on either the freespans themselves, or a representative set of freespans to ensure that VIV induced fatigue will not compromise the pipeline.

4. Acknowledgements

I would like to thank my fellow authors and my colleagues within Peritus International UK for their help and support.

5. References and Further Reading

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