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VIV analysis of pipelines under complex span conditions

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Abstract: Spans occur when a pipeline is laid on a rough undulating seabed or when upheaval buckling occurs due to constrained thermal expansion. This not only results in static and dynamic loads on the flowline at span sections, but also generates vortex induced vibration (VIV), which can lead to fatigue issues. The phenomenon, if not predicted and controlled properly, will negatively affect pipeline integrity, leading to expensive remediation and intervention work. Span analysis can be complicated by: long span lengths, a large number of spans caused by a rough seabed, and multi-span interactions. In addition, the complexity can be more onerous and challenging when soil uncertainty, concrete degradation and unknown residual lay tension are considered in the analysis. This paper describes the latest developments and a 'state-of-the-art' finite element analysis program that has been developed to simulate the span response of a flowline under complex boundary and loading conditions. Both VIV and direct wave loading are captured in the analysis and the results are sequentially used for the ultimate limit state (ULS) check and fatigue life calculation.
Keywords: boundary condition (BC); fatigue limit state (FLS); force model (FM); kilometer post (KP); mode shape; natural frequency; response model (RM); vortex-induced vibration (VIV); ultimate limit state (ULS); unit stress
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1 Introduction

It is important to adopt an appropriate methodology to identify potential damage that could occur with the existence of a pipeline span. The integrity of the pipeline can then be evaluated with confidence in order to make a decision for the future service of the pipeline.

Free spanning pipeline analysis can be very challenging due to soil complexity, multimode vibrations and a high number of spans that can either be very long or interacting. The span evaluation is compliant with the design principles in DNV-RP-F105 0 in this study. Based on the DNV code, the study of a free spanning pipeline includes both response and force models. The response model is based on a Vortex Induced Vibration (VIV) amplitude response where the VIV is caused by vortex shedding across the pipeline. There are two types of VIV to consider: in-line and cross-flow oscillation, which occur with lateral and vertical vibration, respectively. Both in-line and cross-flow VIVs can be current induced or and wave-induced. The "combined" velocity is obtained from both current and wave velocities before it goes into the fatigue calculation, as shown in Section 4.1.5 in DNV RP-F105 0. The pipe may also experience fatigue damage and local over-utilization due to direct waves, typically in shallow water. The influencing factors in VIV and direct wave loading assessments are:

- Pipe size, weight, and geometry;
- Additional weight such as content, insulation, and concrete coating if applicable;
- Current and wave parameters;
- Static and dynamic seabed soil stiffness;
- Span shoulder geometry;
- Residual lay tension;
- Operational conditions such as temperature and internal pressure.

This paper provides details regarding the key items in the procedure of the FEA modeling, fatigue calculation and ULS assessments, which becomes a practical methodology in pipeline span analysis.

2 FEA modeling

2.1 General

The pipeline is modeled using 2-node pipe elements. The element size used in the model can be 1OD as a start based on DNV-RP-F105 0. The FE model can be single pipe with or without concrete coating, depending on project requirements. "Concrete Modeling" is discussed in the later section.

FE modeling of the span analysis is divided into two phases: static and dynamic (modal). In the static phase the sag deflection under the operating conditions, after the pipeline is laid on the seabed, is determined. In this phase,

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soil-pipe interaction is modeled using node-to-surface contact. In the dynamic phase, the natural frequencies and corresponding mode shapes are resolved and springs are used to model the interaction between soil and pipe. The dynamic phase is a linearised procedure that indicates linear effects, and any nonlinearity such as plasticity and friction are ignored in the dynamic phase even if these effects have been included in the static contact model.

2.2 Model length

Based on DNV-RP-F105 0, the boundary condition applied at the ends of the flowline section model should represent the continuity of the pipeline. Therefore, sufficient lengths of the pipeline at both sides of the span should be included, if possible, to account for the effects of the side spans. The length of the FEA model depends on the number of critical spans, span interactions, and span isolation of the pipeline region, as well as model boundary conditions, computation time and result accuracy.

There are several methods to define model length. One of them is described in the following:

- Use a separate FEA model on a smooth seabed with a maximum possible span length;
- Use the relevant pipe geometry and soil conditions
- Fix both ends;
- Identify the virtual anchor spacing – ideal model length;
- Identify the final model length using a comparison study.

2.3 Fluid mass consideration

The fluid content is not normally modelled using elements in ABAQUS. To capture the impact from the content on the natural frequency and unit stress, the options below can be used:

Option 1: Equivalent Pipe Density

$$\rho_p' = \rho_p + M_c/V,$$

where ρ_p' is equivalent pipe density; ρ_p is pipe density; M_c is content mass; V is pipe volume.

Option 2: Equivalent Pipe Weight plus Equivalent Added Mass Coefficient

$$W_p' = W_p + W_c,$$

$$C_A' = C_A + \text{Content Mass}/(0.25\cdot\pi\cdot D^2\rho_{water}),$$

where W_p' is Equivalent pipe weight; W_p is Pipe weight; W_c is Content weight; C_A' is Equivalent added mass coefficient; C_A is Added mass coefficient; D is Pipe OD including coating; ρ_{water} is Water Density.

2.4 Concrete modeling

For single pipes with concrete coating, the concrete can be modeled as an outer pipe relative to the steel pipe. The inner steel pipe and outer concrete pipe can be unbonded with a relative axial displacement slippage. The inner steel pipe and outer concrete pipe can also be bonded, sharing the same nodes. For both unbonded and bonded models, concrete degradation can be taken into account by using reduced concrete stiffness. In addition, a pure single pipe model can be used with an equivalent weight and stiffness for both pipe and concrete. The pure single pipe model does not capture the slippage phenomenon.

Modeling field joints in the FE span analysis may not be necessary, as the joints are too short to impact the overall deformed pipeline curvature. The Stress Concentration Factor (SCF), which depends on pipe and concrete geometry, and concrete degradations, and normally increases the bending stresses, can be calculated using the proposed equation below:

$$\text{SCF} = 1 + \left(\frac{EI_{\text{conc}}}{EI_{\text{steel}}}\right)^{0.75},$$

where EI_{conc} is Bending stiffness of concrete coating; EI_{steel} is Bending stiffness of steel pipe.

It should be noted that this equation is similar but different from the equation defined in Section 6.2.5 of DNV-RP-F105 0 for an analytical calculation (approximate response quantities). In the DNV equation, the full young's modulus of concrete is used, and Kc is constant accounting for the deformations/slippage in the corrosion coating and the cracking of the concrete coating, and K_c is 0.25 for PP/PE coating. In the equation defined above, either full or degraded concrete stiffness is used without K_c (i.e. K_c = 1). The SCF results using the equation above apply to both the response model and the force model when the fatigue life and ULS are calculated. The equation is easy to use and accurate once calibrated.

The calibration of the equation is performed using a separate FE model. In the model, the effect of pure bending imposed at both ends of a single 50-meter long pipe with a concrete coating is studied. The model uses pipe elements for both the pipe and concrete coating. There are two sub-models: the base model and the field joint model. The base model has a concrete coating over the entire pipe, and the field joint model has a concrete gap located in the pipe middle to represent the field joint, as shown in Fig.1 and Fig.2. The SCF can then be obtained as the ratio of bending stresses extracted from two FE models.

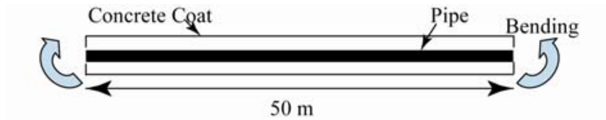

Fig.1 Base model without field joint

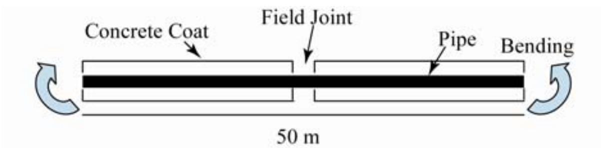

Fig.2 Model with field joint

3 Fatigue analysis and ULS check

The fatigue analysis is conducted for each span corresponding to the applicable changes in concrete coating thickness, seabed topography, water depth, span gap, and environmental data. In the fatigue analysis, static load, VIV load (In-line and Crossflow) and direct wave loads (In-line if in shallow water) are considered in the calculation. In the ULS check, static load, VIV load (In-line and Crossflow) and the direct wave loads (In-line) are considered in the calculation. The span gap is calculated as the average value over the central third of the span based on suggestions from DNV-RP-F105 0, 0. During the fatigue and ULS assessment the key items: worst condition identification, wave and current data directionality, direct wave load consideration, and result sensitivity are discussed below.

3.1 Worst conditions

The span analysis should consider the soil stiffness variation and concrete degradation. The following tolerance can be used:

- The soil static and dynamic stiffness: nominal −30%;
- Concrete condition – Young's modulus: nominal −30% and nominal −100%.

In theory, higher dynamic soil stiffness will result in a higher natural frequency thus enhancing fatigue life, and higher concrete degradation should impair the fatigue life. However, when the residual tension is unknown for an existing pipeline, it is determined when the FEA pipe profile matches the survey profile. Under this condition, a higher tension may be required to have profile match if the concrete stiffness is decreased. As a result, zero concrete stiffness may not be the worst case for an existing pipeline.

An example shown in Fig.3 for a new pipeline is presented to demonstrate the influences of soil stiffness and concrete condition, and the fatigue results are presented in Table 1.

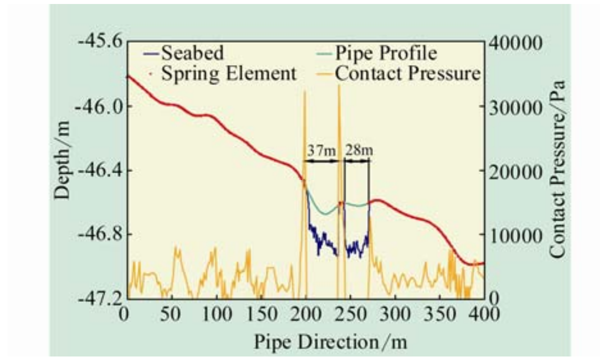

Fig.3 Seabed and pipe profiles

Table 1 Fatigue life results at concrete degradation and soil stiffness variation

Tolerance / %	Concrete stiffness	Static soil stiffness	Dynamic soil stiffness
0 (Base Case)	146	146	146
−30	110	146	127
−100	23	N/A	N/A

The static soil stiffness and dynamic soil stiffness have different impacts to the span. The results indicate that the static soil stiffness does not influence the fatigue life but the lower dynamic soil stiffness decreases the fatigue life. The soil type will also influence the fatigue life as various soil types have different soil stiffness. It can also be concluded that the concrete stiffness degradation has a huge impact to the fatigue life.

3.2 Wave and current data directionality

During the fatigue calculation, the wave and current magnitude and direction are required 0. However, the direction information may not always be available. Therefore, the conservative assumption of direction combination of wave and current is adopted.

If the directions of both currents and waves are not available, perpendicular assumption can be made in the analysis. However, if the direction of only one phenomenon is available, users must define the same directionality for both phenomena. This is due to how the current and wave statistics are intended. They are independent, but in order to depict most accurately, the probability density function should be joint, i.e. there should be a three dimensional matrix of probabilities associated with current velocity (U_C), wave period (T_P) and wave height (H_S) for each direction. Therefore, the probability density functions are interpreted as simultaneous, i.e. the wave data and current data are assumed to act in the same direction at all times, as such wave and current are assumed locked to each others direction.

3.3 Direct wave load

Direct wave loading may not be necessary in the analysis primarily depending on water depth, wave data, pipe size, etc. Normally, the direct wave is influential in shallow water.

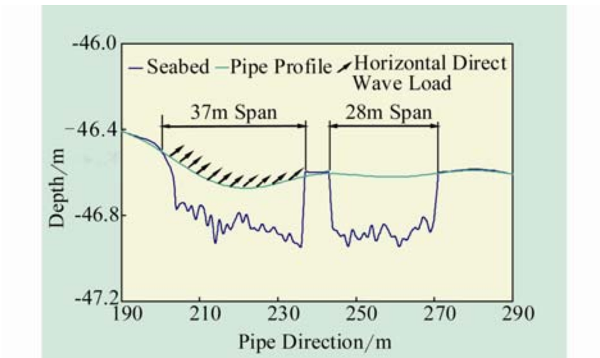

Fig.4 Wave load applied to one segment

For the ULS calculation due to direct wave loading, the loading may be considered as acting on one or two interacting span segments at a time depending on the loading direction, shown in Fig.4 and Fig.5. The ULS check for both scenarios is required and either of them can be considered a worst case depending on the shoulder length, lateral friction and direct wave load magnitude.

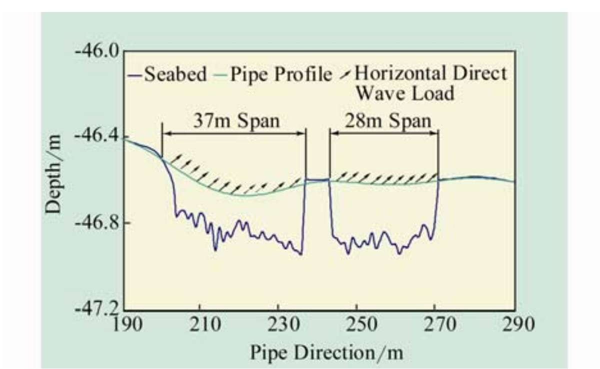

Fig.5 Wave load applied to two segments

3.4 Result sensitivity

3.4.1 Sensitivity due to metocean data

In the analysis, it is important to verify the influences from the tolerance or data range of the metocean data to identify the worst impact. An example using the following metocean data is presented and fatigue results are shown in Fig.6.

- Base case: Nominal current and nominal wave data;
- Current –0.1 m/s: Nominal current –0.1 m/s;
- Current +0.1 m/s: Nominal current +0.1 m/s;
- Wave Period +1 s: Nominal wave period +1 s;
- Wave Height +0.5 m: Nominal wave height +0.5 m.

The results show the impact of tolerance or variation of metocean data, which should be considered in the analysis.

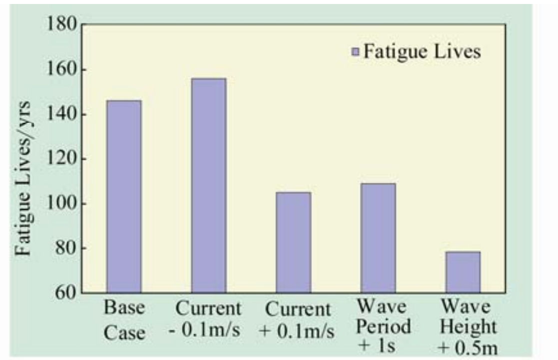

Fig.6 Fatigue life sensitivity with metocean data

3.4.2 Bending moment sensitivity

Bending moment in the ULS calculation due to direct wave loading can be very sensitive for interacting spans, especially for spans with a short shoulder in between. The sensitivity depends on the loading magnitude as well as the lateral friction factor. Refer to example shown in Fig.7. When the wave force is initially applied to two span segments, the lateral friction at the shoulder holds the pipe from moving laterally. However, the moment greatly increases with the force when the pipe at the shoulder starts to move laterally when the friction can no longer hold the pipe and the moment becomes very sensitive to the applied force.

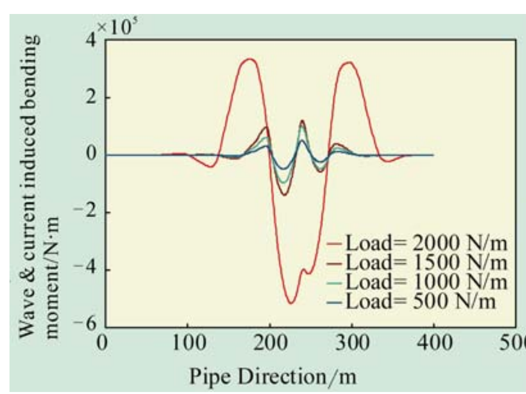

Fig.7 Bending moments with various environment loads

3.4.3 Slugging condition

The slugging condition, if occurs, should be analyzed. Under this condition, the pipe may sag deeply due to increased content weight.

4 Summary and conclusions

This paper presents a practical methodology for analyzing free span pipelines. The methodology with details and examples, highlights key factors in FE modeling and fatigue and ULS calculations during the analysis. The methodology has been used on real projects in various scenarios, yielding the following main conclusions:

- Advanced numerical FE tools can adequately simulate the span of pipelines in static and dynamic phases with a good understanding of the DNV RP-105 [5];
- Identification of worst condition is required with variation of concrete degradation, and soil stiffness
- Special care is to be exercised as well for consideration of wave/current directionality, the influence from the direct wave loading, and metocean magnitude tolerances;
- In the ULS check, it should be noted that the bending moment is very sensitive to the lateral friction, especially for the interacting span with a very narrow shoulder in between;
- The assessment of the slugging condition is needed - slugging may increase or decrease the ULS results.

It is believed that this methodology can be used as a starting point for projects with complicated spans.

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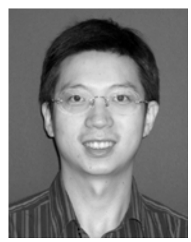

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