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Free span Analysis for Subsea Pipeline Integrity Management Strategy

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Abstract. Over a rough seabed or on a seabed subject to scour, free spans can occur when contact between a subsea pipeline and the seabed is lost over an acceptable distance. When this exceeds the allowable free span length, design stresses can be exceeded, and a vortex-induced vibration (VIV) response can be initiated, resulting in the risk of fatigue failure. If this is not predicted and controlled properly, it will affect pipeline integrity, leading to expensive rectification and intervention work. Free span analysis consisted primarily of a screening check in which the as-found free spans from Remotely Operated Vehicle (ROV) or multibeam Side Scan Sonar (SSS) inspection survey were compared against the allowable design lengths and determine the expected fatigue life of a free span that may be experiencing Vortex Induced Vibration (VIV). Free spans are acceptable if the calculated fatigue life exceeds the design life criteria. This paper describes the free span analysis developed to perform detailed free span engineering assessments, incorporating the latest survey and as-laid conditions. This analysis follows a methodology in standard code DNVGL RP F105 that has been accepted and used by operators to produce more accurate and less conservative free span analysis results, leading to a subsea pipeline integrity management strategy with fewer unnecessary interventions and greater cost benefits.

Keywords: *Seabed, Free span, Allowable, VIV, Fatigue, ROV, SSS, Integrity, Rectification, Pipeline Integrity*

INTRODUCTION

Subsea pipelines are some of the most reliable and efficient infrastructure for transporting liquid and gaseous products, such as petroleum and natural gas, across extensive distances. During installation or operation, seabed irregularities following scouring or horizontal pipeline movement create pipeline spanning [1]. Free span is one example of failure in the pipeline system caused by interactions between the environment and the metal pipe [2]. These pipelines are surrounded by extreme environmental events such as wave and current loading and unevenness of the seabed that may cause stress on the pipeline, which in this case would encounter loading due to vibration. The pipeline begins to vibrate after the natural frequency of the span is reached by the shedding frequency produced by the initiating flow. This causes the Vortex Induced Vibration (VIV) reaction, which increases the likelihood of fatigue failure [3].

The topography of the seabed and the pipeline construction as imposed by the laying vessel will determine the length of the free span. The unevenness seabed may be uncertain due to the bathymetric measurement survey. The shorter free span will be acceptable, whereas longer spans will be avoided due to the potential likelihood of fatigue failure.

FREE SPAN DESCRIPTION

Free Span

Free spanning pipeline refers to an unsupported length that formed between subsea pipelines and the seabed surface due to the seabed unevenness, erosion caused by the current, etc. [4]. Free spans represent critical sections in the pipeline system where high bending stress may develop, and in combination with the hoop stress from the internal pressure, and temperature-induced stresses, an increased risk for yielding or local buckling of the pipeline wall exists. Furthermore, the free span is an elastic structure which may undergo large amplitude oscillations if exposed to dynamic cyclic loads having a frequency near the natural frequency of the span. The pipeline system and span configuration are illustrated in Fig. 1.

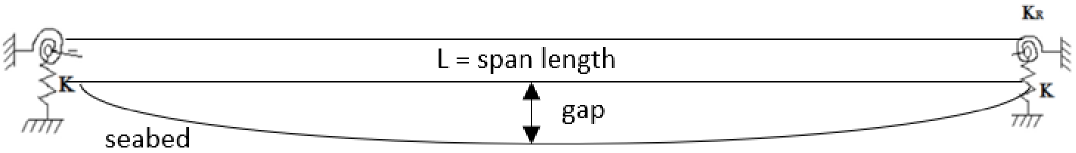

FIGURE 1. Schematic of free span configuration [5]

Free Span Morphology

The free span formed form seabed irregularity has various morphology. The objective of the free span morphological classification is to determine whether two or more adjacent free spans may potentially interact when the pipeline undergoes VIV. Free span morphology is also used to define between isolated single spans and interacting multi-spans [6]. In Fig. 2 and Fig. 3, a typical isolated single and an interacting multispan are shown, respectively.

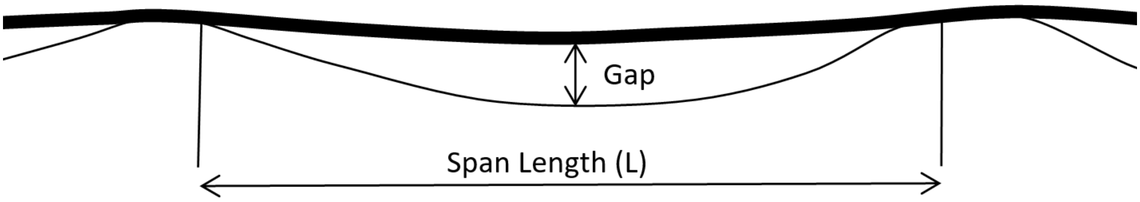

FIGURE 2. Isolated single span configuration [6]

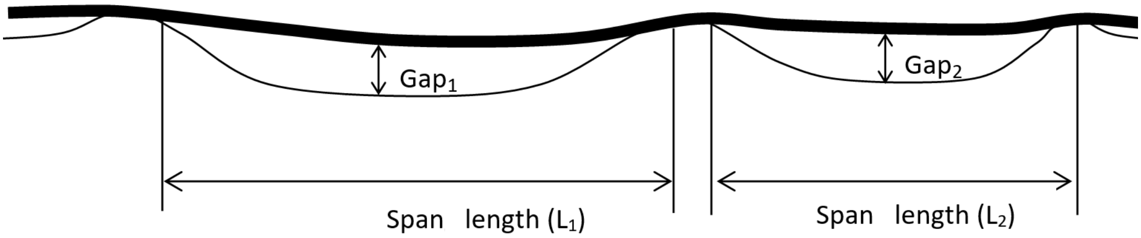

FIGURE 3. Interacting multispan configuration [6]

It is necessary to determine an equivalent free span length for free spans considered to be interacting. The equivalent free span length (L_{eq}) for multispan is calculated based on formulae to identify any spans that may potentially be interacting.

For two interacting free spans, the equivalent free span length (L_{eq}) is described in the equation below [7].

$$L_{eq} = \frac{1.1L_1 + 0.2L_2}{1.1} \quad (1)$$

For more than two interacting free spans, the length of the center span (L_2) is repeated depending on the number of center spans.

Vortex Induced Vibration (VIV)

Vortex induced vibration (VIV) is frequently present when an external current crosses a subsea pipeline of unsupported length (free span).When the vortex shedding frequency approaches the pipeline natural frequency, synchronization or locking may take place, increasing the pipeline's response amplitude and creating cyclic load that could damage the pipe's wall and lead to failure. [8].

VIV can occur in two directions:

1) Oscillation In-line with velocity vector (in line motion)
2) Oscillation perpendicular to velocity vector (cross flow-motion)

The maximum allowable span length for VIV is determined based on the following criteria:

- Onset criteria, in accordance with DNV-RP-F105 [6]. The onset criteria require that no vibrations occur at the span. To fulfill this criterion, the critical span length is determined when the natural frequency of the span is equal to the onset frequency.
- Screening Criteria, in accordance with DNV-RP-F105 [6]. The VIV spans calculated based on screening criteria are expected to provide a minimum design life of 50 years, therefore, the allowable span length based on screening criteria is less conservative than those obtained from onset criteria.

Fatigue Screening Criteria

The procedures to calculate the free span fatigue damage based on the fatigue screening criteria are as follows [9]:

1. Calculate the stress ranges and verify that the magnitude of the maximum stress is below the yield stress of the steel pipe.
2. Calculate the number of stress cycles.
3. Determine the allowable number of stress cycles to failure from S-N curves.
4. Calculate the damage using Palmgren-Miner’s rule.
5. Verify that the damage criterion is satisfied.

The fatigue screening criterion proposed here applies to fatigue caused by vortex induced vibration (VIV) and direct environmental loads (current and wave), including pipeline self-weight. The VIV itself divided into two categories based on oscillation direction for in-line and cross flow. A pipeline exposed to an external flow will shed vortices in its wake. These vortices cause local pressure variations on the surface of the cylinder.

The frequency at which these vortices are shed depends on the velocity of the flow and the pipe diameter. If the shedding frequency approaches the natural frequency of the pipeline, a condition called “lock-in” occurs. This is where the shedding frequency rapidly collapses to the natural frequency of the pipe span. This resonant condition causes oscillation, which can rapidly accumulate fatigue damage in the pipeline.

Ultimate Limit State (ULS) Criteria

The ULS criteria must be met when designing pipe spans that are subject to bending moments, effective axial forces, and external (or internal) overpressure [6]. The analysis of the allowed span length due to ULS criteria is evaluated with load controlled criteria after bending moments have been determined [10]. Pipe members subjected to bending moment, effective axial force and internal overpressure shall be determined to satisfy the following condition at all cross sections. Then the pipeline section is checked for local buckling due to the resultant bending moments. The ULS check is obtained from a separate load step in the FEA model. It is not used for the fatigue calculations, which are based on resultant of moment from the effect of the significant wave.

In the ULS check, it is important to select the environmental data for the calculation. The maximum wave height is used in the wave loading calculation for ULS analysis. The significant wave height is used in the VIV induced moment calculation.

For the ULS check, two combinations of waves and currents are used as follows [10]:

- 100-year Wave + 10-year Current.
- 10-year Wave + 100-year Current.

METHODOLOGY

Level 1 Screening

Free span interaction or Level 1 screening is checked using the free span interaction methodology [6]. Level 1 free span screening analysis involves assessing the interactivity of all reported free spans from Remotely Operated Vehicle (ROV) or multibeam Side Scan Sonar (SSS) inspection survey inspection data as follows:

- Single free spans that are isolated on the seabed are screened by comparing free span lengths with the allowable free span length derived for single free spans (whichever is the governing length, in-line or cross-flow);
- Interacting free spans are screened by comparing the effective lengths of an interacting free span pair (or multiples) with the derived allowable free span lengths.

The free span interaction screening is to determine whether two or more adjacent free spans may interact when the pipeline undergoes VIV. If a comparison between the actual and allowable free span lengths reveals that the free span is anomalous (exceed the allowable), a Level 2 fatigue analysis will be performed.

Multispan classification methods and interaction mechanisms of submarine pipelines undergoing vortex-induced vibration (VIV) are shown in Fig. 4.

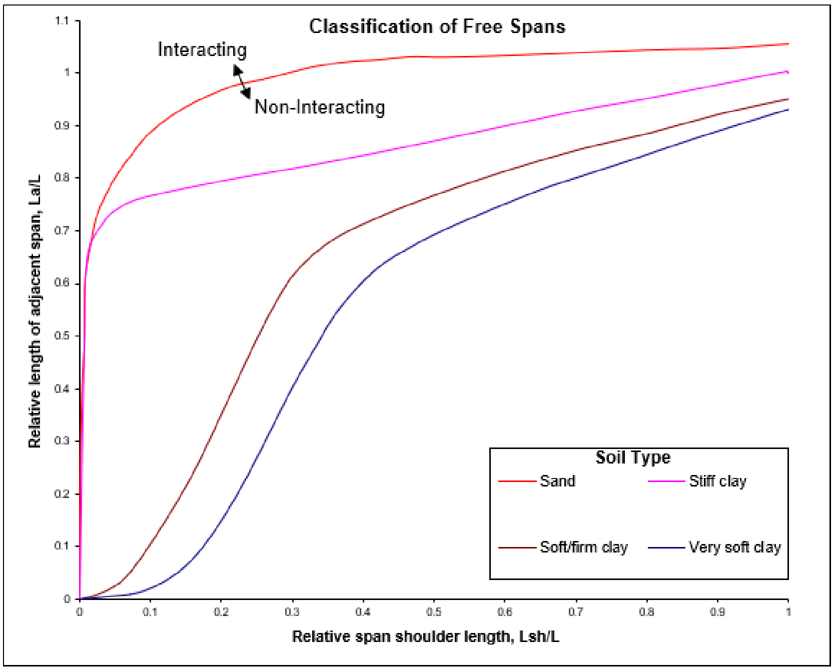

FIGURE 4. Free spans Interactivity Classification [4]

Level 2 Fatigue Analysis

A Level 2 fatigue analysis performed to free spans exceed the allowable lengths (Level 1). The Level 2 assessment considers each anomalous free span on an individual basis by assessing the free span length, its end conditions (whether it is interacting or isolated span), and the free span gap (height). This approach is generally based on the assumption that free spans can be idealized with simple end conditions, resting on a flat seabed, and with a given pipe/seabed gap. Interacting free spans are also modeled as resting on a flat seabed. However, the pinned-pinned end condition for interacting span is used to model the behavior of the free spans as they interact with one another [11]. The Level 2 fatigue analysis was performed using DNV's FatFree software, which allows VIV to occur, and calculates the expected fatigue life caused by in-line (IL) and cross-flow (CF) VIV [6].

Level 2 Acceptance Criteria

Free spans are considered acceptable following Level 2 analysis provided:

- The calculated fatigue life exceeds the design life of the pipeline plus an additional 10% for temporary phases.
- No approximate response quantity limitations are exceeded as stated in DNV RP-F105 Sect. 6.7.1 [6].

Limitation of Level 2 Fatigue Analysis

The Level 2 analysis is based on linear beam theory and the pipeline being totally restrained to calculate the effective axial force. The effective axial force (S_{eff}) is used to adjust the natural frequencies of free spans due to the change in geometrical stiffness caused by the axial force and pressure effects and is given by the following equation:

$$S_{eff} = H_{eff} - \Delta p_i(1 - 2v) - A_s E \Delta T \alpha_e \qquad (2)$$

Where:
H_{eff} = Effective lay tension
Δp_i = Internal pressure difference relative to laying
A_s = Pipe steel cross section area
ΔT = Temperature difference relative to laying
α_e = Temperature expansion coefficient, may be temperature dependent

The free span deflection will gradually increase as the axial force tends towards the critical buckling value. As the effective force increases in compression and approaches the theoretical buckling limit, the pipeline response becomes complicated and highly non-linear. Therefore, the linear beam theory cannot be applied.

Limitations on linear beam theory for approximating response quantities are mentioned as follows:

1) $L / Ds < 140$
2) $\delta / D < 2.5$
3) $S_{eff} / P_{cr} > -0.5$

Where:
L = actual free span length
Ds = outer steel diameter
δ = pipe deflection or statistical skewness
S_{eff} = effective axial force
P_{cr} = critical buckling load

Level 2 analysis cannot accurately compute fatigue life if one of these limitation is exceeded; instead, a thorough Level 3 employing the Finite Element Analysis (FEA) method is needed. [6, 12].

Level 3 Analysis

Level 3 free span analysis individually assesses those free spans that do not meet the requirements of Level 2 analysis using detailed three-dimensional Finite Element Analysis (FEA). This methodology is used to calculate the predicted natural frequencies of the free span (or interacting free spans) and deflected shape of various vibration modes, based actual seabed profile response model [6].

Note that the fatigue life assessed in Level 2 are typically more conservative (shorter) due to idealization and simplification response model, than those derived using Level 3 analysis.

Level 3 Finite Element Analysis (FEA)

The behavior of a pipeline installed on an uneven seabed can only be fully captured by a non-linear FEA in-place pipeline model. The pipe is modelled on the uneven seabed and then subjected to loads while taking span interaction into consideration. To perform a detailed in-place FEA of each critical span, sufficiently high-quality survey data from ROV is required, in order to match the simulated pipe/seabed configuration with the survey data (thus verifying the FEA model by comparing the model output with the survey data). Even with accurate input data describing the seabed profile and operating conditions, some trial and error (through varying the model input parameters) is involved to match simulated and observed pipe/seabed configuration (e.g., local variations in seabed/soil stiffness, or compaction of seabed beneath span shoulders).

Finite Element Analysis (FEA) Analysis Steps

The Level 3 free span analysis is divided into 2 steps, namely static and dynamic modal analysis. The static step is initially performed to match the pipeline profile derived from the FEA iteration with the surveyed pipeline profile. The FEA iteration is conducted by varying the residual lay tension, marine growth, temperature, etc. The iteration or matching profile is complete when the absolute difference between the survey and FEA profiles are less than 30 cm. Figure 5 below shows the profile FEA free span modelling.

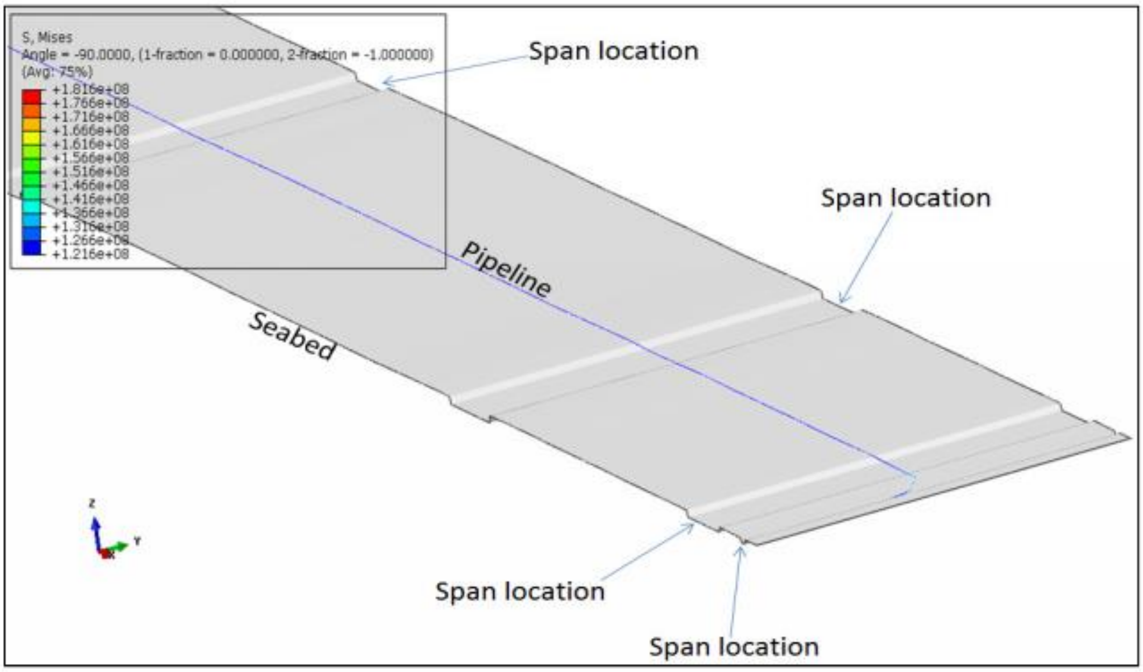

FIGURE 5. FEA free span static modelling

The second step or modal (dynamic) analysis was performed based on the FEA results of the first step. Other information such as added mass coefficient and gap between the FEA bottom of pipe and seabed at the investigated free span are required. There are two types of FEA dynamic vibration analysis at the second step: namely cross flow (CF) and inline (IL) analysis. Figure 6 and Fig. 7 shows the FEA dynamic modelling and vibration mode shapes under IL and CF load conditions, respectively.

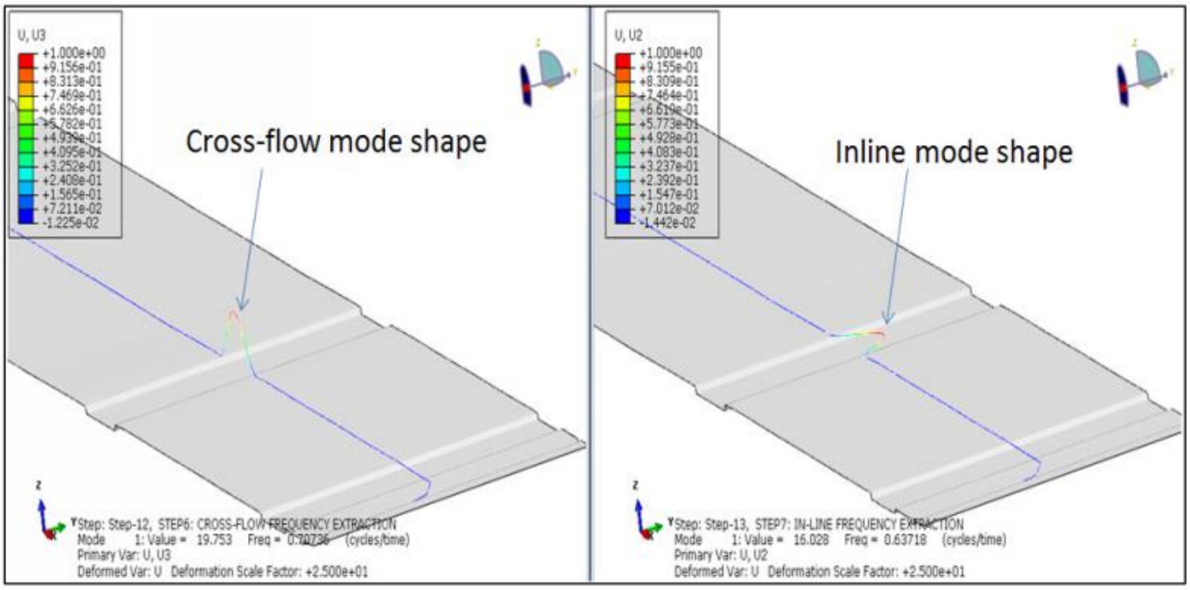

FIGURE 6. FEA free span dynamic modelling

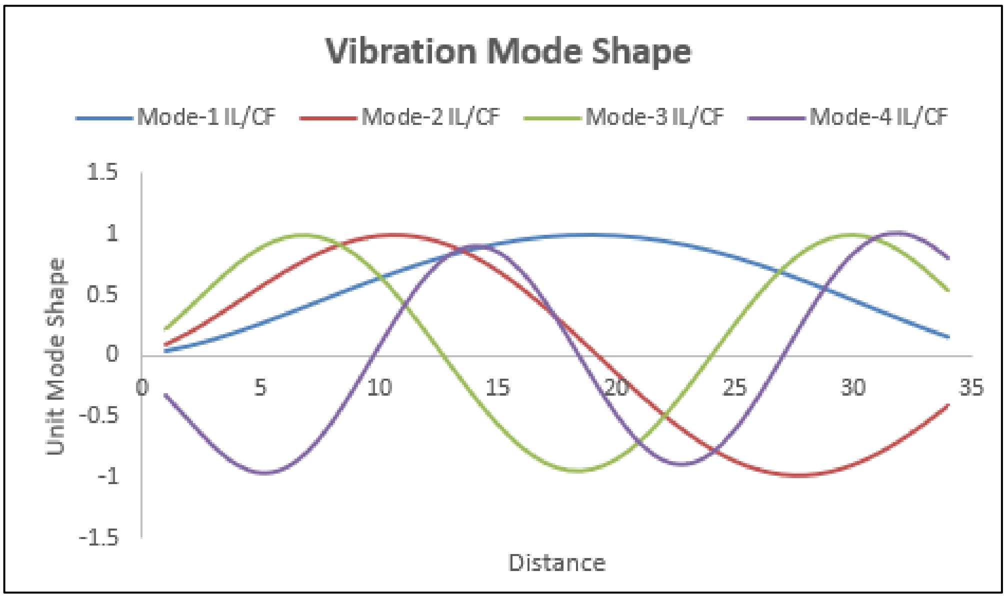

FIGURE 7. Vibration mode shapes under IL and CF load conditions

Finite Element Analysis (FEA) Post-processing

After two FEA step analysis have been completed, the post-processed conduct to obtain the natural frequencies and the mode shapes at the CF and IL flow load responce to determine fatigue life using DNV FatFree software. Free spans are considered acceptable following Level 3 analysis provided the calculated fatigue life exceeds the design life criteria. The flowchart of Level 3 FEA fatigue analysis is shown in Fig. 8.

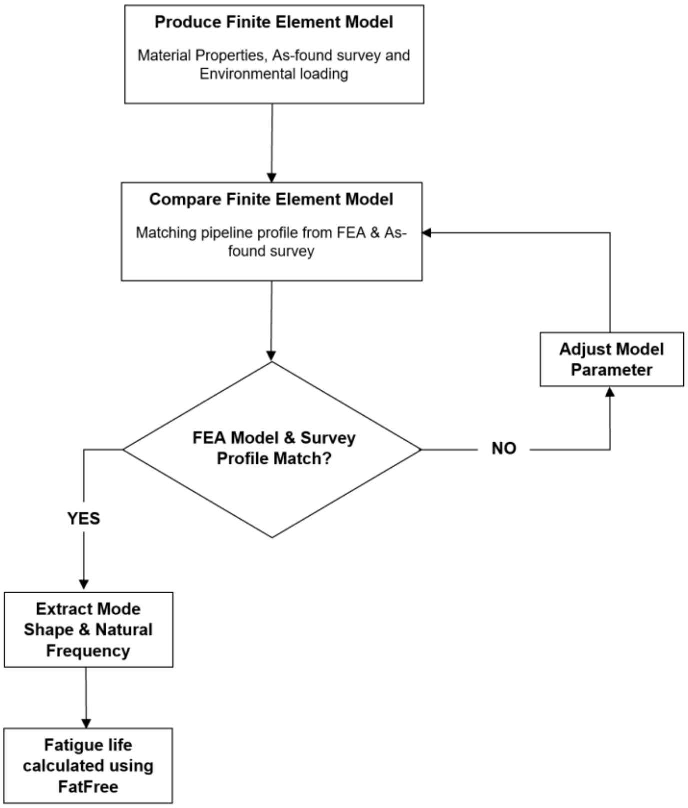

FIGURE 8. Flowchart of Level 3 FEA fatigue analysis

DISCUSSIONS

Three (3) level of free span analysis has been performed to determine fatigue failure due to VIV. Free spans are considered acceptable following 3 level of analysis provided the calculated fatigue life exceeds the design life criteria. If fatigue life found shorter than design life criteria, free span tend to fatigue failure due to Vortex Induced Vibration (VIV) and recommended to rectification.

Pipeline Integrity Management (PIM) is approach of understanding and operating pipelines in a safe, reliable manner. PIM programs are systems managed by pipeline owner-operators that consider all stages of the pipeline life cycle, from conception, to engineering and design, construction, operation, inspection, and finally to repair/replacement when necessary. Free span, for example, can compromise the integrity of pipelines and reduce their lifespan. PIM strategy allows operators to assess locations on a pipeline that are most vulnerable to free span exceed the allowable and fatigue life criteria. Thus, preventing it from occurring is critical. Pipeline integrity management (PIM) strategy plays an important role for free span over a rough seabed or on seabed subject to scour when this exceeds the allowable free span length can lead fatigue damage due to Vortex Induced Vibration (VIV). If this not predicted and controlled properly by calculates the accumulated fatigue damage compared to design criteria, it will affect pipeline integrity, leading to expensive rectification and intervention works. By conducting a detailed analysis of the free span findings, PIM strategy has been carryout. The modern PIM are performance-based while earlier using prescriptive [13].

Free span intervention with rectification is required for all spans exceeding the specified acceptable length or height (gap) for specific location. The specific methods of free span rectification and protection regarding execution, monitoring and acceptable criteria shall be documented. This installation location was recorded during the rectification to make sure the position below the allowable span length [14]. Requirement for vessels, survey equipment, as-laid survey etc. shall be addressed in the installation and leads to expensive rectification cost. Without detailed level of free span analysis, the more free span will failed fatigue damage and required remedial action.

The rectification and protection type of free span subjected to exceed the allowable length e.g., by trenching and backfilling, gravel dumping, concrete mattresses and grout bag installation. Figure 9 present one of the type of grout bag (GB) rectification method.

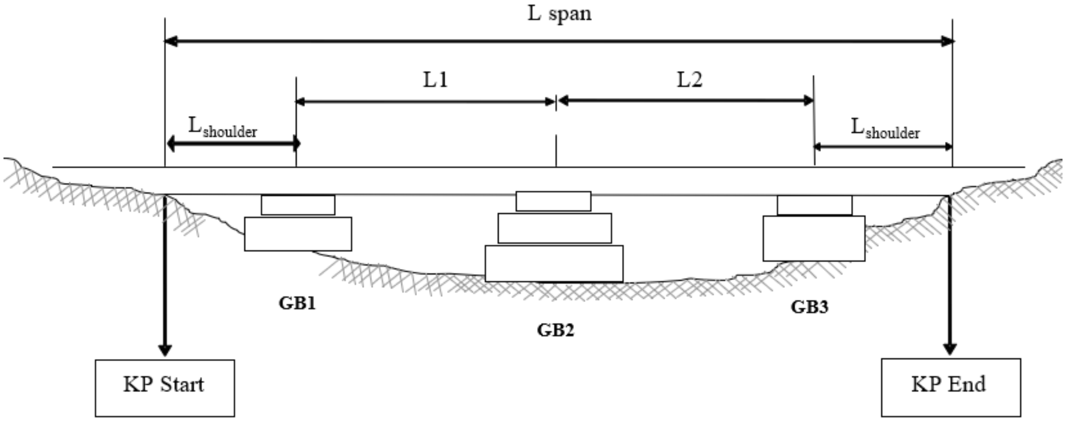

FIGURE 9. Schematic of free span grout bags rectification

Detailed of level free span analysis is performed to minimize the requirements for free span interventions, including:

- Reducing the number of rectifications required.
- Extending the time period before rectification is required.
- Allowing for repair planning – proactive vs reactive

CONCLUSIONS

As a summary, the results of free span analysis can be concluded as follows:

- Free spans can occur when contact between a subsea pipeline and the seabed is exceeds the allowable length that lead to fatigue failure due to vortex induced vibration (VIV).
- Free span analysis has been performed use a methodology from standard code DNVGL RP F105 to determine fatigue life of a free span due to vortex induced vibration (VIV).
- Pipeline integrity management (PIM) strategy plays an important role for free span subjected to Vortex Induced Vibration (VIV). If this not predicted and controlled properly, it will affect pipeline integrity, leading to expensive rectification and intervention works.
- An effective free span management strategy will ensure long term pipeline stability and reduce risks of failure due to free spanning.

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REFERENCES

1. M. M. Shabani, H. Shabani, N. Goudarzi, and R. Taravati, “Probabilistic modelling of free spanning pipelines considering multiple failure modes,” Eng. Fail. Anal., vol. 106, no. April 2018, p. 104169, 2019, doi: 10.1016/j.engfailanal.2019.104169.
2. F. Hartoyo and H. Ovelia, “The Optimization Of Failure Risk Estimation On The Uniform Corrosion Rate With A Non-Linear Function,” J. Mater. Explor. Find., vol. 1, no. 1, 2022, doi: 10.7454/jmef.v1i1.1001.
3. K. Rezazadeh, L. Zhu, Y. Bai, and L. Zhang, “Fatigue Analysis of Multi-Spanning Subsea Pipeline.” pp. 805–812, Jun. 06, 2010. doi: 10.1115/OMAE2010-20847.

4. X. Li, Y. Zhang, R. Abbassi, F. Khan, and G. Chen, “Probabilistic fatigue failure assessment of free spanning subsea pipeline using dynamic Bayesian network,” Ocean Eng., vol. 234, no. May, p. 109323, 2021, doi: 10.1016/j.oceaneng.2021.109323.
5. G. Sarkar and P. Roy, “Generalised analytical solution for determining natural frequency of free span offshore pipelines considering non-homogeneity of seabed soil,” Ocean Eng., vol. 266, no. P5, p. 113171, 2022, doi: 10.1016/j.oceaneng.2022.113171.
6. DNVGL-RP-F105, “DNVGL RP F105 Edition June 2017 Free spanning pipelines,” Dnvgl Rp F105, no. Desember, 2017.
7. H. A. Sollund, K. Vedeld, O. Fyrileiv, and J. Hellesland, “Improved assessments of wave-induced fatigue for free spanning pipelines,” Appl. Ocean Res., vol. 61, pp. 130–147, 2016, doi: 10.1016/j.apor.2016.10.004.
8. T. Zhang, S. Zhang, D. Yang, and G. Huang, “Numerical investigation on competitive mechanism between internal and external effects of submarine pipeline undergoing vortex-induced vibration,” Ocean Eng., vol. 266, no. P1, p. 112744, 2022, doi: 10.1016/j.oceaneng.2022.112744.
9. M. M. Shabani, A. Taheri, and M. Daghigh, “Reliability assessment of free spanning subsea pipeline,” Thin-Walled Struct., vol. 120, no. June, pp. 116–123, 2017, doi: 10.1016/j.tws.2017.08.026.
10. DNV GL, “DNVGL-ST-F101 Submarine pipeline systems,” Dnvgl-St-F101, no. October, p. 521, 2017.
11. E. V. M. do. Reis, L. A. Sphaier, L. C. S. Nunes, and L. S. d. B. Alves, “Dynamic response of free span pipelines via linear and nonlinear stability analyses,” Ocean Eng., vol. 163, no. January 2017, pp. 533–543, 2018, doi: 10.1016/j.oceaneng.2018.06.002.
12. Fatmi, S. E., Dhaneswara, D., Anis, M., & Ashari, A "Investigation of The Effect of Corundum Layer on The Heat Transfer of SiC Slab." *Journal of Materials Exploration and Findings (JMEF)* 1.2 (2022): 1.
13. F. Khan, R. Yarveisy, and R. Abbassi, “Risk-based pipeline integrity management: A road map for the resilient pipelines,” J. Pipeline Sci. Eng., vol. 1, no. 1, pp. 74–87, 2021, doi: 10.1016/j.jpse.2021.02.001.
14. A. Reda, A. Rawlinson, I. A. Sultan, M. A. Elgazzar, and I. M. Howard, “Guidelines for safe cable crossing over a pipeline,” Appl. Ocean Res., vol. 102, no. June, p. 102284, 2020, doi: 10.1016/j.apor.2020.102284.