Technical Note:

Analysis of Offshore Pipeline Allowable Free Span Length

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Abstract: *Determination of allowable free span length plays a crucial role in design of offshore pipelines. The seabed intervention cost and safety of an offshore pipelines project are largely influenced by pipelines free spanning during the project life time. Different criteria are proposed by both the current designing guidelines and researchers; there is however lack of comprehensive assessment of independent parameters affects the design length of free span. In this note, it is intended to investigate the effects of seabed formation along with axial force on Natural Frequency of offshore pipelines. Based on this assessment a new simple formula is proposed. Finally, to evaluate the result of this study, the allowable free span length of Qeshem Island pipelines is calculated as a case study and compared with those of the DNV (1998) and ABS (2001) guidelines and the modal analysis.*

Keywords: *Offshore pipelines, free spanning, allowable length, modal analysis and pipe resonance*

Introduction

Nowadays, offshore pipelines have a significant role in development of oil and gas industry in different parts of the world. This crucial industry is laid on seabed by various methods either embedded in a trench (buried method) or laid on uneven seabed (unburied method). Construction of unburied pipeline is the most common method for its rapid and economic performance. In this method, however, the pipelines are subjected to various lengths of free spanning throughout the route during its life time, which may threaten the pipelines safety. Free spanning in offshore pipelines mainly occurs as a consequence of uneven seabed and local scouring due to flow turbulence and instability; hence, with no doubt, free spanning occurrences for unburied pipelines are completely inevitable.

Fredsoe and Sumer (1997) assessed the role of free spans in unburied offshore pipelines. They acknowledged the previous studies and mentioned that resonance is the main problem for offshore pipelines laid on the free spanning. Pipelines resonance happens when the external load frequency as a result of vortex shedding becomes equal to the pipe Natural Frequency. This phenomenon may burst the pipe coating and may lead to develop more fatigue on the pipelines. Different design guidelines, e.g. DNV (1998) and ABS (2001), have accepted a less stringent approach and recommend the free spanning to be reduced to the allowable length to avoid fatigue damage. These guidelines proposed a simple formulation to calculate the first Natural Frequency based on the pipelines specifications and seabed conditions; however, all of the guidelines encourages using modal analysis at the final phase of design.

Choi (2000) studied the effect of axial forces on free spanning of offshore pipelines. The results indicated that the axial force has a significant influence on the first Natural Frequency of the pipe. In this research, the different seabed condition has been broken down into three main types and the general beam equation for the boundary conditions was analytically solved. He also compared his result with Lloyd's approximate formula, which estimates the first Natural Frequency of the beam considering axial load effect. Xu et al. (1999) applied the modal analysis to incorporate the real seabed condition to assess pipelines fatigue and Natural Frequency (NF). Later, Bai (2001) approved Xu et al. (1999) approach and emphasis on applying the modal analysis to determine the allowable length of free span for offshore pipelines.

In practice, a considerable amount of works have been applied to determine the allowable free span length, however, there is still lack of knowledge in assessing the role of all effective parameters in determination of allowable free span length. The objective of this paper is two folds: (i) to assess the role of main effective parameters on Natural Frequency; and (ii) to present a simple formula for allowable free span length with accounting for the seabed condition. To do so, first the approaches of DNV (1998) and ABS guidelines are discussed and then the modal analysis is outlined to have a useful tool to assess the role of all involved parameters. Finally, a case study on the Qeshem pipelines is performed to evaluate the free span allowable length.

DNV and ABS ApporximationFormula

DNV (1998) and ABS (2001) guidelines determine the allowable length of free span with the following equations:

$$L = \left(\frac{EI}{m_e}\right)^{0.25}\left(\frac{CV_R D}{2\pi U}\right)^{0.5} \tag{1}$$

in which E = modulus of elasticity; I = bending moment of inertia of pipeline; C= coefficient of seabed condition; and V_R= reduced velocity defined according to Fredso and Sumer (1997) by

$$V_R = \frac{U}{f_n D} \tag{2}$$

in which U = streamwise flow velocity (normal to the pipe); D = outer diameter of pipe; m_e = effective mass (including structural mass, mass of content and added mass); and f_n = Natural Frequency of the pipe free span. In order to solve Eq. (1), f_n should be replaced by vortex shedding frequency to avoid resonance. In other words, the pipe Natural Frequency based on these codes is expressed as:

$$f_n = C\sqrt{\frac{EI}{m_e L^4}} \tag{3}$$

In practice, employing the above-mentioned formula for estimation of pipelines free span length is not very applicable due to the difficulties in determination of the exact seabed conditions: therefore, alternative approaches including modal analysis usually will be adopted.

Modal Analysis

Natural Frequency of pipelines can be obtained accurately based on the Euler-Bernoulli beam equation which is defined according to Xu et al. (1999) and Bai (2001) as follows:

$$m_e \frac{\partial^2 y}{\partial t^2} + C\frac{\partial y}{\partial t} + EI\frac{\partial^4 y}{\partial x^4} - T\frac{\partial^2 y}{\partial x^2} = F(t,u,y) \tag{4}$$

in which y = in-line displacement of pipe; x = position along the pipe span; t = time; C = total damping ratio; T= axial force of pipe (positive under tension); and

$F(t,u,y)$= total external forces. The boundary conditions can be expressed as follows:

$$\begin{cases} EI\,\dfrac{\partial^2 y(0,t)}{\partial x^2} = k_{r,1}\dfrac{\partial y(0,t)}{\partial x} \\ EI\,\dfrac{\partial^2 y(l,t)}{\partial x^2} = -k_{r,2}\dfrac{\partial y(l,t)}{\partial x} \\ T\,\dfrac{\partial y(0,t)}{\partial x} - \dfrac{\partial\left(EI\left(\dfrac{\partial^2 y(0,t)}{\partial^2 x}\right)\right)}{\partial x} = k_{t,1}\,y(0,t) \\ T\,\dfrac{\partial y(l,t)}{\partial x} - \dfrac{\partial\left(EI\left(\dfrac{\partial^2 y(l,t)}{\partial^2 x}\right)\right)}{\partial x} = -k_{t,2}\,y(l,t) \end{cases} \tag{5}$$

in which $k_{r,1}$, $k_{r,2}$ = rotatory spring constants for left and right end of the pipe span respectively; $k_{t,1}$, $k_{t,2}$ = respectively translator spring constant for left and right end of the pipe span; and l = length of the free span.

On the other hand, Xu et al. (2001) and Chopra (2001) discussed that Natural Frequency of a pipelines is a function of its free vibration mode that neglects both the external force and damping ratio. External force and damping ratio only influence the resonance amplitude; hence, it can be eliminated and the pipe free vibration equation can be expressed in the following form:

$$m_e\frac{\partial^2 y}{\partial t^2} + EI\frac{\partial^4 y}{\partial x^4} - T\frac{\partial^2 y}{\partial x^2} = 0 \tag{6}$$

Modal analysis has been suggested by Xu et al. (1999) and Bai (2001) to solve the free vibration equation. In the modal analysis the partial differential equation reduces to an ordinary differential equation. For different modes different equations are obtained; while, in all of the modes, the equations are completely independent. Solution to Eq.(6) can be expressed as:

$$y(x,t) = F(t)\times G(x) \tag{7}$$

in which $F(t)$= harmonic term of the equation; and $G(x)$ = shape of each independent mode. These terms can be defined as follows:

$$F(t) = \cos(\omega t + \phi) \tag{8}$$

$$G(x) = c_1\cosh(S_1 x) + c_2\sinh(S_1 x) + c_3\cos(S_2 x) + c_4\sin(S_2 x) \tag{9}$$

in which, ω = Natural Frequency of beam in the n_{th} mode; ϕ = phase angle between loading and damping motion; c_1, c_2, c_3 and c_4 = constants; and S_1, S_2 = bending stiffness parameters and will be obtained by following formula:

$$\begin{aligned} S_1 &= \sqrt{\left(\frac{T^2}{4E^2I^2} + \frac{\rho A\omega^2}{EI}\right)^{\frac{1}{2}} + \frac{T}{2EI}} \\ S_2 &= \sqrt{\left(\frac{T^2}{4E^2I^2} + \frac{\rho A\omega^2}{EI}\right)^{\frac{1}{2}} - \frac{T}{2EI}} \end{aligned} \tag{10}$$

According to Bai (2001) the pipe natural frequencies can be expressed by following equation:

$$\begin{vmatrix} S_1^2 & -\dfrac{K_{r1}}{EI}S & -S_2^2 & -\dfrac{K_{r1}}{EI}S_2 \\ S_1^2\cosh(S_1 l) + \dfrac{K_{r2}}{EI}S_1\sinh(S_1 l) & S_1^2\sinh(S_1 l) + \dfrac{K_{r2}}{EI}S_1\cosh(S_1 l) & -S_2^2\cos(S_2 l) - \dfrac{K_{r2}}{EI}S_2\sin(S_2 l) & -S_2^2\sin(S_2 l) + \dfrac{K_{r2}}{EI}S_2\cos(S_2 l) \\ \dfrac{K_{t1}}{EI} & S_1^3 + \dfrac{T}{EI}S_1 & \dfrac{K_{t1}}{EI} & \dfrac{T}{EI}S_2 - S_2^3 \\ (S_1^3 + \dfrac{T}{EI}S_1)\sinh(S_1 l) - (\dfrac{K_{t1}}{EI})\cosh(S_1 l) & (S_1^3 + \dfrac{T}{EI}S_1)\cosh(S_1 l) - (\dfrac{K_{t1}}{EI})\sinh(S_1 l) & (S_2^3 - \dfrac{T}{EI}S_1)\sin(S_2 l) - (\dfrac{K_{t2}}{EI})\cos(S_2 l) & (-S_2^3 + \dfrac{T}{EI}S_1)\cos(S_2 l) - (\dfrac{K_{t2}}{EI})\sin(S_2 l) \end{vmatrix} = 0 \tag{11}$$

The result obtained from Eq.(11) is rather different from the Natural Frequencies of offshore pipelines. Chopra (2001) discussed that the smallest positive result is called the first Natural Frequency, which is significantly important as the pipelines resonance take places most probably at this frequency. Moreover, the effects of different parameters on Natural Frequency of the offshore pipelines should be debated by using this equation.

Effect of Soil Condition

To assess the importance of different parameters, it is intend to plot each independent parameter versus the first Natural Frequency of offshore pipelines. Fig.s 1 to 4 show these influences for different seabed soil conditions. Table 1 presents the subgrade soil reaction modulus employed in this study according to Bai (2001).

Fig.s 1 and 2 are plotted based on *l*, K_t, *I* and m_ε constants of subgrade soil condition. According to these figures, it can be observed that there are two general types of rotational boundary conditions: (i) fixed boundary condition; and (ii) pinned boundary condition.This is because; there is no significant difference between zero values of the rotational spring with its extreme. Therefore, when K_r is equal to the extreme value, the boundary condition is coincided with the fixed boundary condition and while K_r is equal to zero, the pinned boundary condition is expected.

It is also evident from Fig.3 that the influence of seabed soil types on Natural Frequency is very significant. The Natural Frequency of

Table 1 Translatory spring value for different soil types

Soil Type	Subgrade reaction K_r (MPa)
Very soft Clay	1-10
Soft Clay	3-33
Medium Clay	9-33
Hard Clay	30-67
Sandy Clay/Moraine Clay	13-140
Loose Clay	5-13
Dense Clay	25-48
Silt	1-11
Rock	550-52000
Rock with marine growth	550-52000

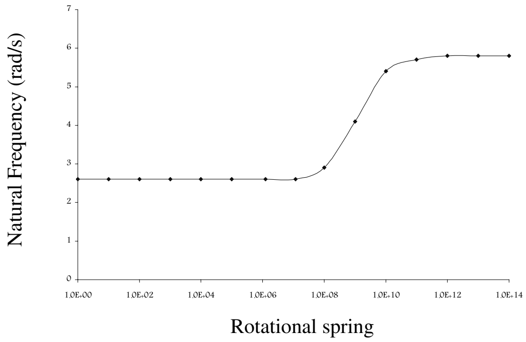

Fig.1 Effects of rotational spring for various boundary conditions for rock beds.

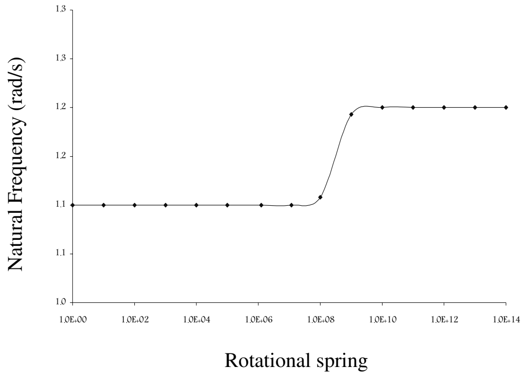

Fig.2 Effects of Rotational Spring for various boundary conditions for clay beds.

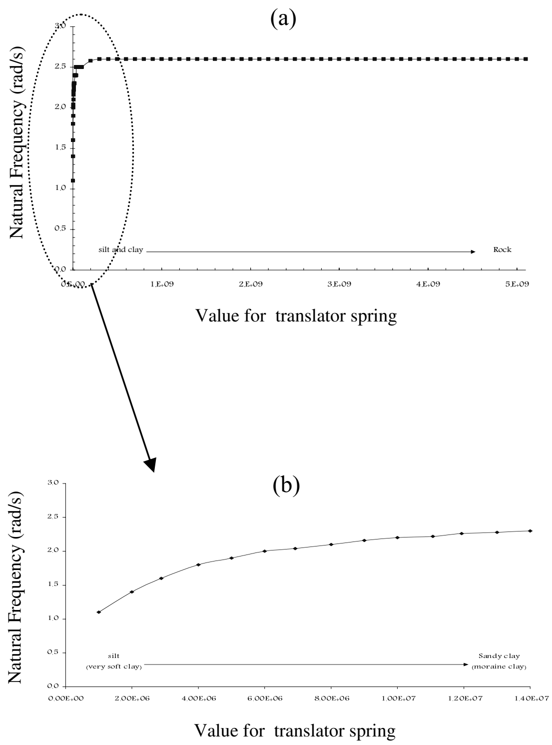

Fig.3 Effects of soil on Natural Frequency

offshore pipelines in rock beds is much greater than that of the clay beds. According to Fig.3b, it is much clear that the soil type can remarkably influences the intensity of Natural Frequency of offshore pipelines.

As the figures illustrate the intensity of Natural Frequency in the same conditions for clay formations is considerably smaller than rock formation. In other words, the soil type on this point of view can be classified into two nominal categories: namely clay formations and rock formations. As a result, based on the intensity of K_r and K_t, there are three main categories: (i) fixed-fixed; (ii) fixed-pined; and (iii) pined-pined in two nominal soil formations of rock and clay.

Effects of Axial Force

DNV (1998) and ABS (2001) guidelines recommended that the effect of axial force for unburied pipelines should be taken into account. Bai (2001) demonstrated that the internal pressure, temperature gradient and pipe deflection will result in increase of the axial forces in pipelines at free spanning sections. Hence, it is intended herewith, to assess the influence of axial force on Natural Frequency of pipelines.

According to Choi (2000), Lloyd's formula is one of the well-known approaches in determination of Natural Frequency including the effect of axial forces which is defined as follows:

$$\omega_n = \alpha\sqrt{\frac{EI}{m_e}}(1-\frac{T}{P_E})^{0.5} \quad (12)$$

in which, T=axial force in the pipe (it is positive when pipe is under tension); and P_E=Euler buckling load that can be written as:

$$P_E = \frac{\pi^2 EI}{L_{eff}^2} \quad (13)$$

in which L_{eff}= effective length of free span which is determined by DNV codes as follows:

$$\frac{L_{eff}}{L} = \begin{cases} 1.12 & \frac{L}{D} \le 40 \\ 1.12-0.001(\frac{L}{D}-40) & 40 \le \frac{L}{D} < 160 \\ 1.00 & \frac{L}{D} > 160 \end{cases} \quad (14)$$

The role of axial force in Natural Frequency based on Lloyd's approximate formula, DNV (1998) and ABS (2001) simple formulation, and modal analysis result can be expressed with the following equation:

$$f_n = S(l)\times\sqrt{\frac{EI}{m_e}}\times(1-\beta\frac{T}{P_E})^{0.5} \quad (15)$$

in which $S(l)$= function of bending stiffness; and l and β = equations constants. Thus if the first Natural Frequency of pipeline is plotted versus these parameters, $S(l)$ and β will be determined by plotting free span length versus the pipe first Natural Frequency for different axial force, (please refre to Fig.s 4 to9)

As the Fig.s 4 to 9 indicate both axial load and length of free span of pipelines are able to change noticeably the intensity of Natural Frequency; however, the change in Natural Frequency varies in the different seabed soil formations. The importance of the effective parameters is incorporated in a new formula for estimating Natural Frequency in this study presented in Tables 2 and 3.

As the results indicate, the offshore pipelines laid on seabed soil with the rock formations is less threatened by resonance effects than the ones laid on the clay formations. This is because, the Natural Frequency of the free spanning pipelines increases more in the rock seabed than that of the clay formations. It can also be debated that the axial force has less influence on the pipeline lays on rock

Table2 Natural Frequency formula (without axial force)

	Soil Type	Rock	Clay
$S(l) = \alpha \times \frac{1}{l^n}$		$\alpha . \frac{1}{l^2}\sqrt{\frac{EI}{m_e}}$	$\alpha \frac{1}{l^{0.5}}\sqrt{\frac{EI}{m_e}}$
α	fixed-fixed	21	0.017
	pinned-pinned	9.1	0.022
	fixed-pinned	14.6	0.02

Table3 Natural Frequency formula (with axial force)

$f_n = S(l)\sqrt{\frac{EI}{m_e}} \times (1-\beta\frac{T}{P_E})^{0.5}$			
β	Rock	fixed-fixed	0.00
		pinned-pinned	0.84
		fixed-pinned	0.84
	Clay	fixed-fixed	0.00
		pinned-pinned	2.10
		fixed-pinned	2.10

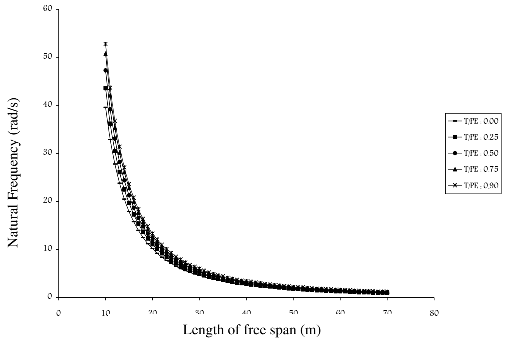

Fig.6 Effect of the axial force on NF fixed-pinned boundary condition in rock

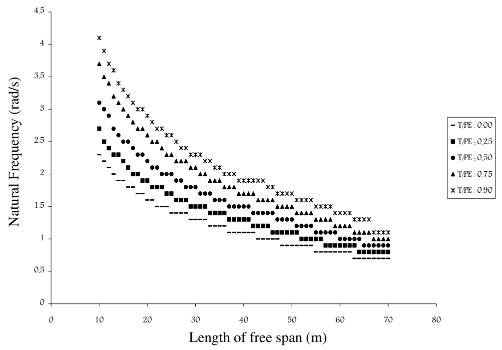

Fig.7 Effect of the axial force on NF fixed-pinned boundary condition in clay

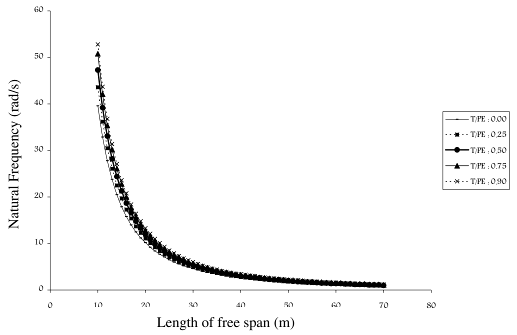

Fig.4 Effect of axial force on NF pinned-pinned boundary condition in rock

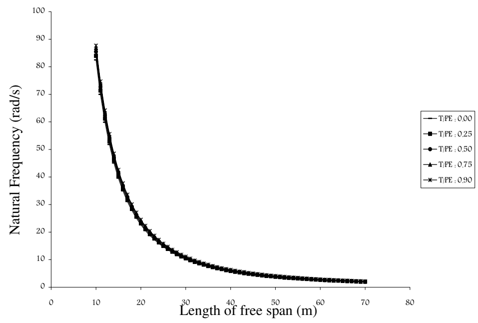

Fig.8 Effect of the axial force on NF fixed- fixed boundary condition in rock

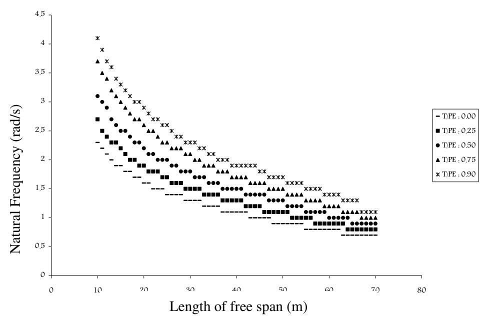

Fig.5 Effect of axial force on NF pinned-pinned boundary condition in clay

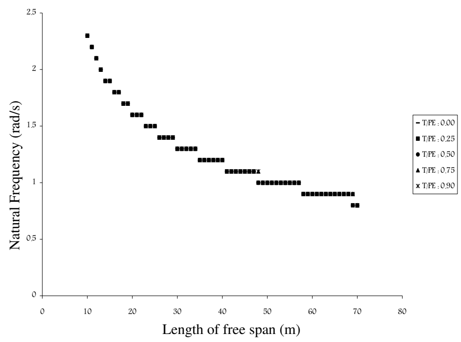

Fig.9 Effect of the axial force on NF fixed- fixed boundary condition in clay

formation than that lays on clay formation. Nevertheless the axial force has no influence provided that the pipeline boundary conditions in both sides of free spanning are fixed-fixed boundary condition. To compare the results of the new formula with the previous ones, the following case study is presented.

Case Study

To determine the allowable free span length of offshore pipelines the various methods of calculation have been employed to the Qeshem pipelines project at Persian Gulf. The Qeshem offshore pipeline specification is as follows: the outside diameter of pipelines is 28*inches* with a wall thickness of 14*mm*, and the pipelines is laid on seabed with the clay formations. The effective mass is approximated 1507 *Kg/m* and the pipe's Young Modulus is 207 *Gpa*. The intensity of tension force is 407*KN*. Table 4 presents the different result of approaches employed to determine the allowable length of free span for the pinned-pinned seabed soil condition with ambient frequency around 1.1 Hz.

According to Table 4 results, new approach reaches more accurate length compare to those of the DNV and ABS simple formula. This is because the effect of axial force has been taken into account more preciously in the new proposed formula. It should also be pointed out that the results of the modal analysis are both completely reliable and give much better estimation than the approximated formulas.

Table 4 Comparison between the different approaches

Approach	Allowable Free Span Length(m)	Error
DNV and ABS	38.3	45%
New Approach	45.3	32%
Modal Analysis	70.2	-

Concluding Remarks

Following conclusion can be drawn:

- In DNV(2002) and ABS(2001) guidelines, the recommended approach to determine the first Natural Frequency of offshore pipelines, the influence of soil translatory parameter is not fully taken into account. But as this paper present, this parameter plays a significant role in estimation of Natural Frequency of free spanning sections of offshore pipelines. Therefore, it is highly recommended that the modal analysis or new approximation formula should be applied for estimating of allowable length of free span even at the primary phase of offshore pipelines design.

- Soil type has a significant influence on the determination of allowable length of free spanning. The clay formation reduces remarkably the intensity of NF of pipelines, whereas the rock formation (at the same condition) increases the intensity of Natural Frequency noticeably.

- Axial force is extremely important to determine allowable length of free spanning of offshore pipelines. The intensity of this term is crucially dominant in the seabed with clay formations because it increases the Natural Frequency of the pipelines.

- Axial force can be neglected only when the free spanning support are the fixed-fixed boundary condition in the different seabed formations. But the axial force plays an important role in all other types of supports of offshore pipelines.

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