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Determining Natural Frequency of Free Spanning Offshore Pipelines by Considering the Seabed Soil Characteristics

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Abstract

Free spans or suspended spans normally occur in subsea pipelines due to the irregularity of seabed and by scouring phenomena around the installed non-buried pipeline. The hydrodynamic around the pipeline can lead to a vibration of the pipeline.This kind of vibration may cause fatigue damage to the pipeline. In order to study the hydrodynamic around the pipeline, calculating the natural frequency of the marine pipeline in free spans accurately is very important. Resonance phenomenon may occur when the frequency of the hydrodynamic forces induced by a vortex shedding approach the natural frequency of pipelines. A resonating span can experience significant deflections and associated stresses. Several parameters such as pipeline profile, axial forces, seabed soil and boundary conditions influence the natural frequency of the pipeline. The soil characteristic is an important factor which should be considered in determining the natural frequency of pipeline in free span. In this paper, attempts have been made to investigate the natural frequency of free spanning pipelines and influence of soil characteristic in support of pipeline in free span. In this regard, various boundary conditions were considered and the results were analyzed.

Keywords: *Offshore pipeline, Free span, Natural frequency, Finite element method*

1. Introduction

Considerable amount of energy resources are located below the seabed and ocean. Pipelines need to transfer the resources of the continental shelf offshore to other regions. The main reason for this is that pipelines consume less energy than other ways of transportation, e.g. tankers (Palmer and King, 2004). Pipelines are used for a number of purposes in the development of offshore hydrocarbon resources (Fig. 1). These include e.g. (Bai, 2001)

- Export (transportation) pipelines;
- Flow lines to transfer product from a platform to export lines;
- Water injection or chemical injection flow lines;
- Flow lines to transfer product between platforms, subsea manifolds and satellite wells;
- Pipeline bundles;

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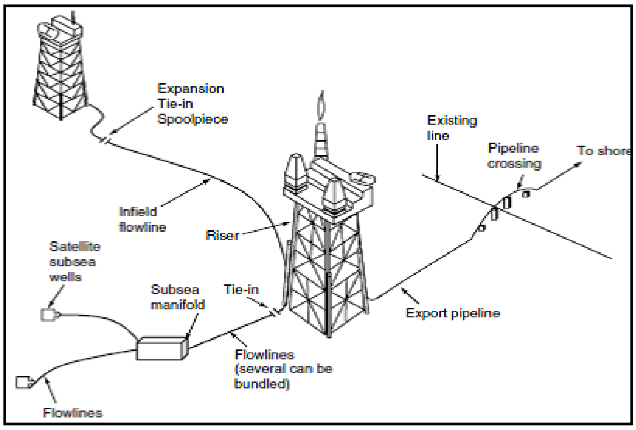

Fig. 1: Use of flow lines offshore pipeline (from Bai 2001)

Due to budget constraints or harsh seabed conditions, most pipelines are just lowered from the lay barge to sea bottom without being buried. In such cases, free spans or suspended spans, i.e. the sections of pipeline that are not in contact with the seabed, may form due to the irregularities of seabed or the scouring of underlying soil. Currents flowing across free spans of pipeline cause the formation and shedding of vortices. Vortices are shed in two ways. At lower flow velocities, vortex shedding is symmetrical, i.e. vortices are shed simultaneously from both sides of the pipe (Fig. 2a). At higher velocities, vortex shedding is asymmetrical, i.e. a vortex is shed from one side of the pipeline followed by a vortex shed from the other side in an alternating pattern (Fig. 2b).

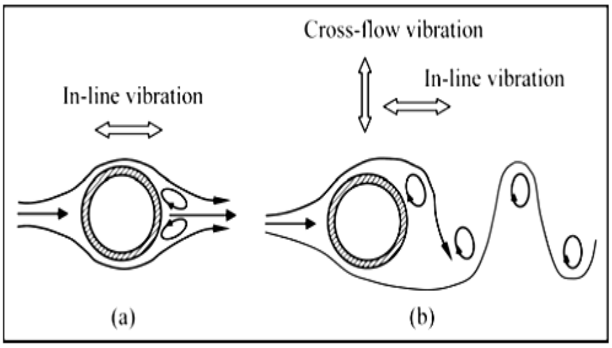

Fig. 2: Vortices and vibrations of free span section: (a) symmetrical vortices and in-line vibration; (b) asymmetrical vortices and in-line and cross-flow vibrations (Zhi-Gang Xiao et al., 2010)

Symmetrical shedding causes the pipeline to vibrate in line with the flow direction (Fig. 2a). Asymmetrical shedding, however, causes two components of vibration, i.e. in-line motion (in the direction of the flow) and cross flow motion (at right angles to the flow) (Fig. 2b). The inline impulse occurs in the same direction with every vortex. The cross-flow impulse alternates direction. Inline excitation is thus at a frequency twice that of cross flow excitation and has a smaller motion amplitude and stress (Beckmann et al., 1991).

Resonance phenomenon may occur when the frequency of the hydrodynamic forces induced by a vortex shedding approach the natural frequency of the pipelines. A resonating span can experience significant deflections and associated stresses. Therefore, studying the hydrodynamic around the of pipeline and calculating the natural frequency of the marine pipeline in free spans accurately are very important. Several parameters such as pipeline profile, axial forces, seabed soil ،boundary conditions and others can influence the natural frequency of the pipeline. Different design guidelines, e.g. (DNV, 1998; ABS, 2001), proposed a simple formulation to calculate the first natural frequency based on the pipelines specifications. Xu et al., 1999 applied the modal analysis to incorporate the real seabed condition to assess pipelines fatigue and natural frequency.

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. He also compared his result with Lloyd's approximate formula, which estimates the first natural frequency of the beam considering axial load effect. DNV, (2006) guidelines proposed a formulation to calculate the first natural frequency based on the pipelines specifications, axial forces and static deflection. Zhi-Gang and Xiao- Ling (2010) investigated the influence of boundary conditions, mass of hydrocarbon product, axial force, and multiple spans on the natural frequency by finite element method in ABAQUS software. Review of previous studies showed that the influence of soil characteristic was not considered in determining the natural frequency of free span. Therefore, the purpose of this study was calculating the natural frequency of free subsea pipeline due to soil characteristic of supports of pipeline in free span. In this regard, first, a formula for determining the natural frequency of pipeline in free span which can take into account the soil characteristic of pipeline supports was presented. This formula could be soil bed by applying the analytical Rayleigh method. Second, a pipeline including its seabed characteristics around the supports has been modeled in ABAQUS.

2. Material and Methods

2.1. Calculation of the Natural Frequency of the Pipeline with Equation

To obtain the natural frequency of a subsea pipeline, the Rayleigh method was applied. This method assumes that the maximum potential energy of the system is equal to its maximum kinetic energy. The natural frequency equation for such a beam usually takes the following form (Chopra, 1995).

$$\omega^2 = \frac{k}{m} \tag{1}$$

Where, *m* is the total mass; and *k* is the total stiffness. Total stiffness includes pipe flexural stiffness (Stiffness of the pipelines specifications) dependent cross section and pipe type, spring stiffness for pipe soil interaction, geometric stiffness caused by axial force. The total mass is defined by pipeline mass, mass of concrete coating, mass of hydrocarbon product and added mass (Chopra, 1995). Therefore:

$$m = \int_0^{L_{eff}} \bar{m}\phi(x)^2 dx \tag{2}$$

$$k = \int_0^{L_{eff}} EL(1+CSF)\phi''(x)^2 dx + \int_0^{L_{eff}} \bar{k}\,\phi(x)^2\,dx + \int_0^{L_{eff}} N\,\acute{\phi}(x)^2 dx \tag{3}$$

Where $\phi(x)$ the first mode shape; E, modulus of elasticity; I, bending moment of inertia of pipeline, $\bar{k}$ the spring stiffness per unit length; N, axial force; m, effective mass in the above equation, CSF, Concrete Stiffness Factor; L_{eff}, effective Length; L, free span length- can be calculated from the following relations according to DNV guidelines (DNV, 2006).

$$CSF = k_c \left(\frac{EI_{conc}}{EI_{steel}}\right)^{0.75} \tag{4}$$

$$\frac{L_{eff}}{L} = \begin{cases} \dfrac{4.73}{-0.066\beta^2 + 1.02\beta + 0.63} & \text{for } \beta \geq 2.7 \\ \dfrac{4.73}{0.036\beta^2 + 0.61\beta + 1.0} & \text{for } \beta < 2.7 \end{cases} \tag{5}$$

$$\beta = \log_{10}\left(\frac{K.L^4}{(1+CSF)EI}\right) \tag{6}$$

Where K is the relevant static soil stiffness (vertical or horizontal); k_c is an empirical constant accounting for the deformation/slippage in the corrosion coating and the cracking of the concrete coating. The value of k_c may be taken as 0.33 for asphalt and 0.25 for PP/PE coating.

2.2. Influence of Pipelines Specifications on Natural Frequency of Pipelines

Be considered the stiffness of the pipelines specifications in equation (3), the stiffness include following formula:

$$k = \int_0^{L_{eff}} EI(1+CSF)\left[\phi''(x)^2\right]dx \tag{7}$$

To obtain the natural frequency of the pipelines specifications, substitution of equations (7) and (2) into equation (1)

$$f_n{}^2 = \frac{\int_0^{L_{eff}} EI(1+CSF)\left[\phi''(x)^2\right]dx}{\int_0^{L_{eff}} \bar{m}(x)\left[\phi(x)^2\right]dx} \tag{8}$$

Solving the above integrals, the natural frequency of the pipelines specifications was obtained as:

$$f_n = k_1\sqrt{\frac{EI\,(1+CSF)}{\bar{m}L_{eff}^{\;4}}} \tag{9}$$

Where k_1 is a constant that depends on end conditions (C=1.57 for pinned/pinned ends, C=2.45 for fixed/pinned ends, and C=3.54 for fixed/fixed ends). The relation obtained is the same as the formula given by the DNV and ABS guidelines. Therefore, the results can be used as a basis for comparison and evaluation of the accuracy results for the effect of seabed soil on natural frequency.

2.3. Influence of Seabed Soil on Natural Frequency of Pipelines

To calculate the natural frequency of free spanning subsea pipeline due to the soil characteristics in different boundary conditions, soil-pipe interaction must be simulated by vertical and horizontal springs (Fig. 3).

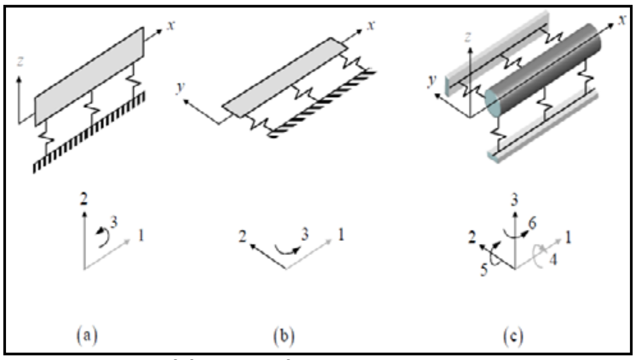

Fig. 3: Degrees of freedom of beam element in vertical plane (a), lateral plane (b) and in ABAQUS)

So, vertical springs would not allow the pipes to move upward (cross-flow) and horizontal springs were installed to prevent the pipeline from vibration in the flow direction.

When the topographical conditions are not complex, the soils are non-stratified and homogeneous, and no detailed analysis can be carried out for determination of kV and kL, the values of this stiffness in units of kN/m/m may be calculated in simplified manner described in the following formula as:

$$k_L = C_L\,(1+\upsilon)\left(\frac{2}{3}\frac{\rho_s}{\rho}+\frac{1}{3}\right)\sqrt{D} \tag{10}$$

$$k_v = \frac{C_v}{1-\upsilon}\left(\frac{2}{3}\frac{\rho_s}{\rho}+\frac{1}{3}\right)\sqrt{D} \tag{11}$$

In which the pipe diameter D is in units of meters and the coefficients CV and CL are taken according to Table1 and Table2 and ν is Poisson's ratio.

Table 1. Dynamic stiffness factor and static stiffness for pipe soil interaction in clay

Clay type	C_V *(kN/m^5/2)*	C_L *(kN/m^5/2)*	$K_{V,S}$ *(kN/m/m)*
Very soft	600	500	50-100
Soft	1400	1200	160-260
Firm	3000	2600	500-800
Stiff	4500	3900	1000-1600
Very stiff	11000	9500	2000-3000
Hard	12000	10500	2600-4200

Table 2. Dynamic stiffness factor and static stiffness for pipe soil interaction in sand

Sand type	C_V *(kN/m^5/2)*	C_L *(kN/m^5/2)*	$K_{V,S}$ *(kN/m/m)*
Loose	10500	9000	250
Medium	14500	12500	530
Dense	21000	18000	1350

Figure 4 indicates schematic of the free spanning of the pipeline on the seabed.

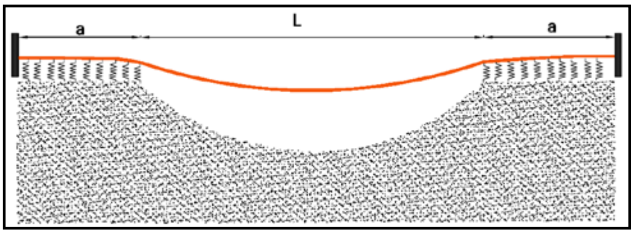

Fig. 4: A schematic representation of the free spanning of the pipeline on the seabed

The following relationship between the effective lengths (L_{eff}), free spans length (L) and length of pipe-soil (a) interaction was established (Fig. 4).

$$L_{eff} = L + 2a \tag{12}$$

Where *a* is length of pipe-soil interaction. By considering the stiffness of the pipelines specifications and soil stiffness in equation (3), the stiffness included following formula:

$$k = \frac{\int_0^{L_{eff}} EI\,(1+CSF)\varnothing''(x)^2\,dx+}{\int_0^{a}\bar{k}\,\varnothing(x)dx+\int_{L_{eff}-L-a}^{L_{eff}}\bar{k}\,\varnothing(x)dx} \tag{13}$$

Where $\phi(x)$ the first mode shape; E, modulus of elasticity; I, bending moment of inertia of pipeline, $\bar{k}$ the spring stiffness per unit length; CSF, concrete stiffness factor; L_{eff}, effective length; L, free span length which are calculated from the following relations according to DNV guidelines. Substitution of equations (13) and (2) into equation (1), without Considering axial force leads to the following formula:

$$f_n^2 = \frac{\int_0^{L_{eff}} EI(1+CSF)[\phi''(x)]^2\,dx + \int_0^a \bar{k}[\phi(x)]^2\,dx + \int_{Leff-L-a}^{Leff} \bar{k}[\phi(x)]^2\,dx}{\int_0^{L_{eff}} \bar{m}[\phi(x)]^2\,dx} \quad (14)$$

By solving the above equation, the pipe natural frequencies can be expressed by following equation:

$$f_n = k_1\sqrt{\frac{(1+CSF)EI}{L_{eff}{}^4\bar{m}}(1+k_2\frac{\bar{k}L_{eff}{}^4}{(1+CSF)EI})} \quad (15)$$

In the proposed relationship, k_2 was determined using the following equation:

$$k_2 = \frac{\int_0^a[\phi(x)]^2\,dx + \int_{L_{eff}-L-a}^{L_{eff}}[\phi(x)]^2\,dx}{(2\pi k_1)\int_0^1[\phi(x)]^2\,dx} \quad (16)$$

Equation (15) is the proposed relationship to determine the natural frequency of formula, free spanning offshore pipelines by considering the seabed soil characteristics and pipelines specifications.

2.4. Natural Frequency Analysis with Finite Element

Another method of calculating natural frequencies is finite element methods by simulation pipeline and soil interaction in the ABAQUS software. The ABAQUS model uses two-nodal 3-D beam elements from the library of ABAQUS v. 6.9.1. The pipeline at the side-spans and mid-span was modeled as a series of PIPE31-beam elements.

The beam element at the side-span were attached to PSI34 (Pipe Soil Interaction) elements with non-linear material behavior. The elements in the ABAQUS model are illustrated in Figure 5. The axial, lateral and vertical directions are given by the x-, y and z-axis, respectively.

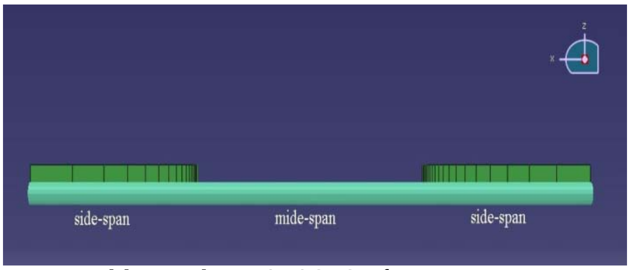

Fig. 5a: Modeling pipeline in ABAQUS software

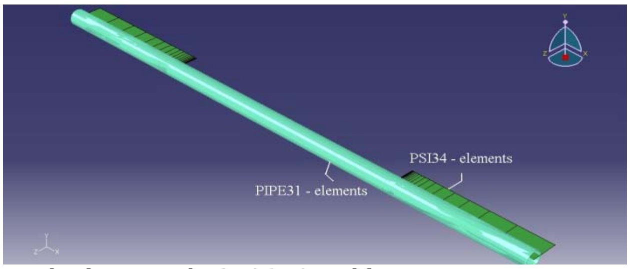

Fig. 5b: Elements in the ABAQUS Model

2.5. Boundary Conditions in the ABAQUS model

The ABAQUS model uses the boundary conditions at the pipe-ends as shown in Figure 6 but with additional restraints on the nodes of the PSI-elements since these are not restrained by default. The axial, lateral and vertical displacement of each node of a PSI-element that is away from the pipeline must be zero which are denoted with "A" in figure 6. Recall that the displacements and rotations at the pipe-ends are fixed which are denoted with "B". The remaining nodes of the pipeline are free which are denoted with "C". The red contour indicates the boundary of a single PSI-element.

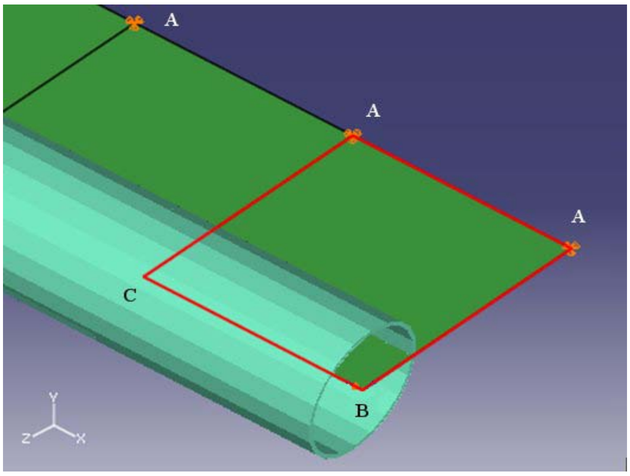

Fig. 6: Boundary conditions in the ABAQUS Model

2.6. The Mesh of the ABAQUS Model

For verifying pipeline model in ABAQUS software, used the pipeline with a length of 20 m laid on seabed with the dense sand formation is used. In the first step the pipeline is modelled with 60 elements (40 PIPE-elements and 20 PSI-elements). In this case the natural frequency of 12.241 kHz is obtained. In the second step, the Mesh increases by the increase of the number of elements.

The pipeline is modelled with 110 elements (70 PIPE-elements and 40 PSI-elements); so, the natural frequency of 12.226 kHz is calculated. In the third step, 210 elements are used for modelling pipeline and Pipe Soil Interaction (130 PIPE-elements and 80 PSI-elements). In this case the natural frequency of 12.226 kHz is obtained. Therefore, change does not occur in the natural frequency of offshore pipelines by increasing of the number of elements. Therefore, the average number of considered elements has been used (110 elements).

In the ABAQUS model, the element size along the side-spans varies from large elements at the pipe-ends to small elements at the pipe shoulder. This is referred to as a biased discretization. In addition, buffer zones with a high number of elements have been introduced at the mid-span close to the pipe shoulders in order to obtain a stable FEM-scheme. For the single-span pipeline, the ABAQUS Model uses 70 PIPE-elements and 40 PSI-elements as illustrated in Figure 7.

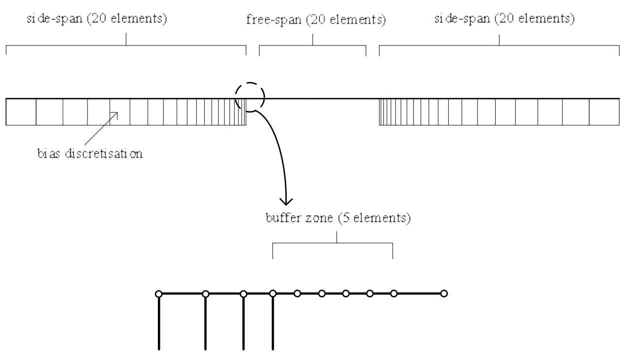

Fig. 7: Schematized illustration of mesh in the ABAQUS model for the single-span pipeline.

3. Results and Discussion

3.1. Evaluation of Results of Seabed Soil on Natural Frequency

To determine natural frequency of free spanning offshore pipelines with equations and FEA methods, the pipelines project at the Persian Gulf were considered with outside diameter of 812.8 mm and a wall thickness and concrete thickness of 20.6 mm and 68 mm, respectively. The pipelines are laid on seabed with the dense sand, dense clay, firm clay and soft clay formations. Properties of steel pipe are: 206,000 MPa for Young's modulus, 0.3 for Poisson's Ratio, and 7850 kg/m^3 for the density for steel. The density of concrete is 3,040 kg/m^3. Three combinations of end conditions, i.e. pinned/pinned, fixed/pinned and fixed/fixed, were considered for each span length.

As the Figures 8, 9 and 10 indicate, the pipeline frequency increases with shortening of pipeline length and fixity against rotation at the ends of the pipe. Seabed soil is able to change noticeably the intensity of natural frequency. The natural frequency in the pipeline increases with the increase of the soil stiffness. Therefore, dense sand has the greatest influence on the natural frequency when the free spanning support is the fixed-fixed boundary condition. Nevertheless, the soft clay has no influence on natural frequency provided that the pipeline boundary conditions in both sides of free spanning are fixed-fixed boundary condition.

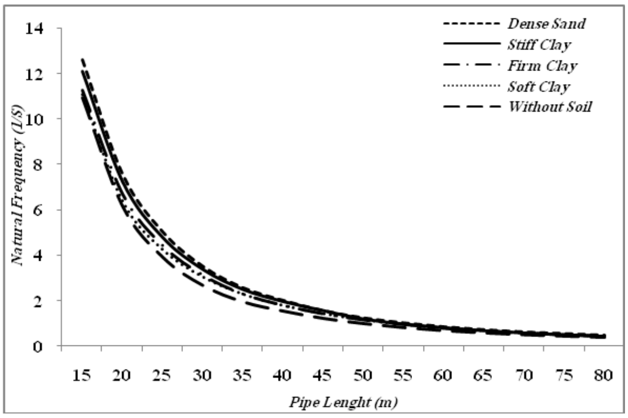

Fig. 8: Effect of seabed soil on the natural frequency in fixed-fixed boundary condition

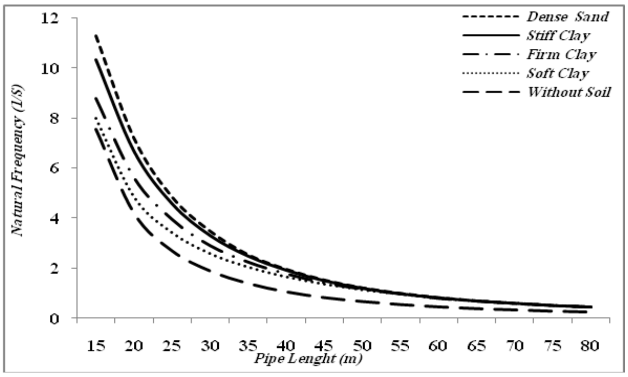

Fig. 9: Effect of seabed soil on the natural frequency in fixed-pinned boundary condition

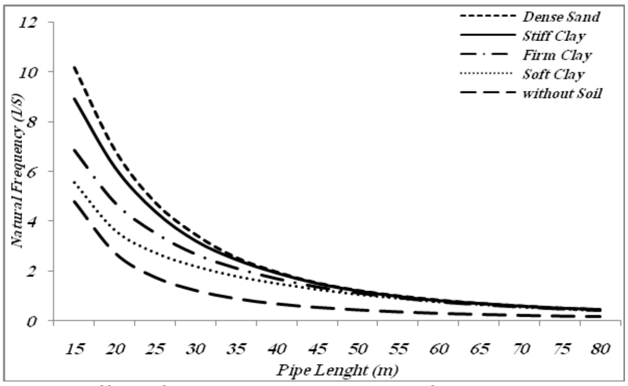

Fig. 10: Effect of seabed soil on the natural frequency in pinned-pinned boundary condition

As the Figures 11 to 14 illustrate the results of analysis in the ABAQUS software in fixed / fixed boundary conditions for the pipeline with length of 20 m Laid on seabed with dense sand, dense clay, firm clay and soft clay formations. Therefore, the natural frequency in the pipeline increases by the increase of the soil stiffness.

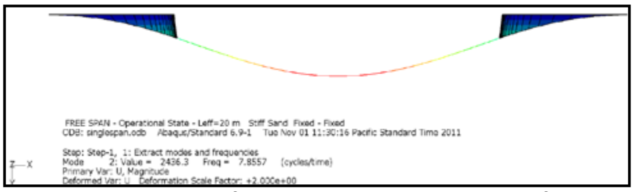

Fig. 11: The results of analysis in the ABAQUS software in fixed / fixed boundary conditions for the pipeline with length 20 m lay on seabed with the dense sand formation

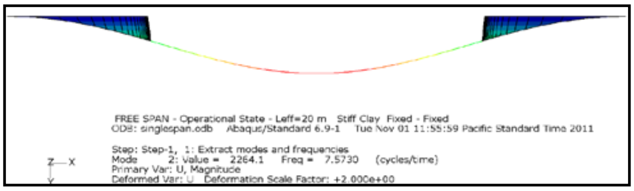

Fig. 12: The results of analysis in the ABAQUS software in fixed / fixed boundary conditions for the pipeline with length 20 m lay on seabed with the dense clay formation

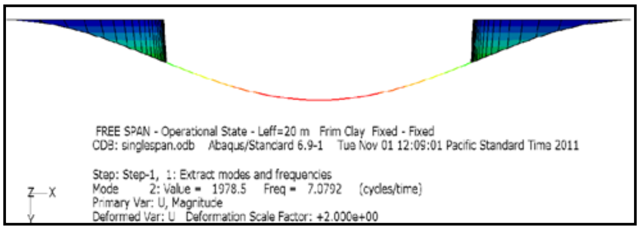

Fig. 13: The results of analysis in the ABAQUS software in fixed / fixed boundary conditions for the pipeline with length 20 m lay on seabed with the firm clay formation

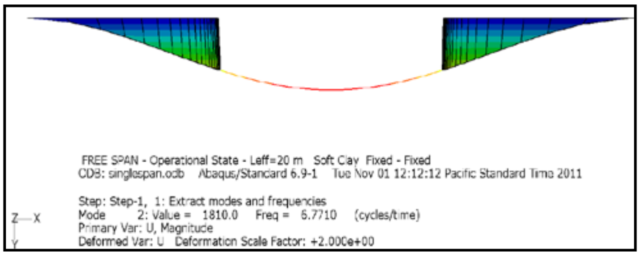

Fig. 14: The results of analysis in the ABAQUS software in fixed / fixed boundary conditions for the pipeline with length 20 m lay on seabed with the soft clay formation

The results showed that by increasing the soil stiffness, difference between the results reduces for different the natural frequency Less dependent depend on the boundary conditions of the pipeline laid on the seabed with the dense sand formations.

However, it should be reminded that this would be the case when the pipeline length is large enough. By a change in the boundary condition from pinned/pinned to fixed/fixed, influence of the seabed soil on the natural frequency decreases. It can also be stated that the soil has the minimal influence on natural frequency of the pipeline when it is laid on soft clay formation with fixed/fixed boundary condition.

Nevertheless, the highest influence is detected on the natural frequency of the pipeline when it is laid on dense sand formation with pinned/pinned boundary condition. The frequency results are plotted in Figs. 15 to 18. As the results indicate, good agreement was seen between the finite element model and theoretical frequency equation results, which demonstrated the validity of calculating pipeline frequencies with finite element model.

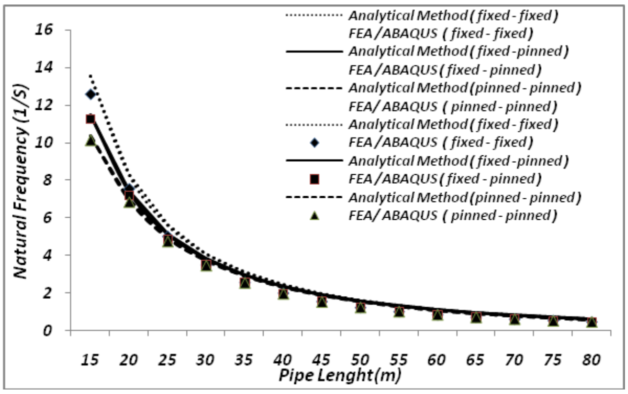

Fig. 15: Effect of dense sand on the natural frequency of pipelines

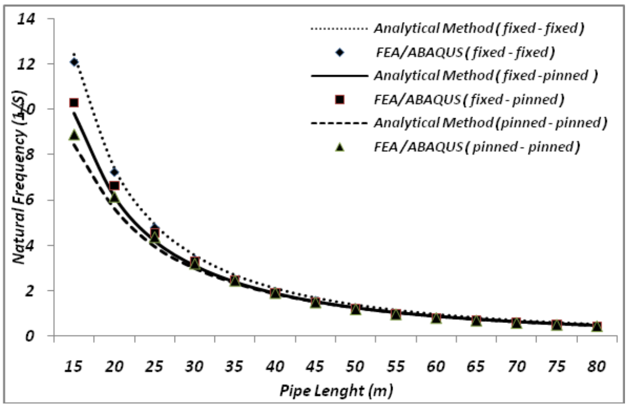

Fig. 16: Effect of dense clay on the natural frequency of pipelines

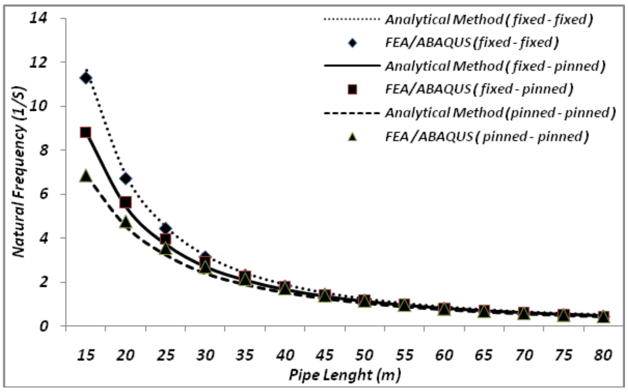

Fig. 17: Effect of firm clay on the natural frequency of pipelines

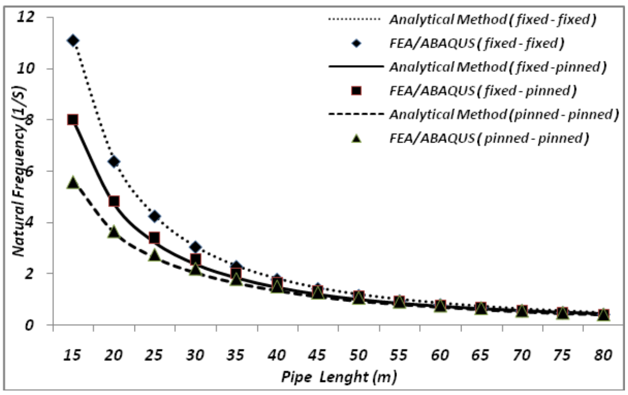

Fig. 18: Effect of soft clay on the natural frequency of pipelines

4. Conclusions

- The pipeline frequency increases with shortening of pipeline length and fixity against rotation at the ends of the pipe.
- The study Showed that the influence of soil parameter plays a significant role in estimation of natural frequency of free spamming offshore pipelines.
- Soil type had a significant influence on the determination of natural frequency of free spanning pipeline, such that the natural frequency in the pipeline increased by the increase of the soil stiffness.
- With increase in soil stiffness, difference between the results reduced for different boundary conditions, such that natural frequency would not depend on the boundary conditions of the pipeline.
- The results of finite element model and proposed analytical equation were close to each other which demonstrates the validity of the finite element model.

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