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Free spans monitoring of subsea pipelines

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Abstract. The objective of this work is to investigate the possibility of using the longitudinal strain on the surface of a pipe to determine the inception of dangerous free spanning. The long term objective is to develop an online monitoring technique to detect the development of dangerous free spanning in subsea pipelines. This work involves experimental study as well as finite element modeling. In the experiments, the strains at four points on a cross section of a pipeline inside the free span zone are measured. Pipes with different boundary conditions and different diameter to length ratios were tested. The pipe is treated as a simple beam with fixed-fixed or simply supported boundary conditions. The variation of the strains as a function of the diameter to length ratio gives a pointer to the inception of dangerous free spanning. The finite element results agree qualitatively with the experiments. The quantitative discrepancy is a result of the difficulty to replicate the exact boundary conditions that is used by the finite element program.

Keywords: free spans; pipelines; subsea; monitoring - strain.

1. Introduction

Development of free spanning is one of the major challenges that face the design and safe operation of undersea pipelines, especially in the North Sea area. Free spanning is usually caused by a combination of seabed movement, wave action, and current effects. The analysis of free spanning of underwater pipes is a complex problem that requires the use of tools from the areas of hydrodynamics, soil mechanics, and structural analysis. There is a great interest in the study of free spanning to understand the mechanics behind it and how to predict its development. Not only the initial design has to be sound, but it is important to assess the condition of the development of free spanning so that interventions can be made at appropriate times. A number of studies which deal with different aspects of the problem free-spanning can be found in the literature. The design of subsea pipelines usually includes a static as well as dynamic analysis. The allowable static free span is determined from strength considerations using the maximum bending moment acting on the pipe. In most cases, the dynamic allowable free span is determined such that the fundamental natural frequency of the pipe is greater than the vortex shedding frequency.

Park and Kim (1997) developed an analytical method for determining the allowable free span length using simple beam equation. The ends of the beam are supported by an elastic foundation

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which is modeled using linear and rotational springs. Kapuria *et al*. (1998) used the beam equation to determine the allowable free span or a pipe loaded both in the transverse and axial directions. He considered the cases of both tensile as well compressive axial forces. Choi (2001) used the beam-column equation to study the effect of both tensile and compressive axial forces and various possible boundary conditions on the natural frequency of undersea pipeline free spans. Søreide *et al*. (2001) investigated the structural behavior of pipelines having a high span to diameter ratio. They indicated that for a span to diameter ratio of more than 100, the pipe behavior changes from a beam to a cable. This gives rise to a multi-mode vibration pattern excited by vortex shedding. Fyrileiv and Mørk (2002) explained the concept of effective free span length and used it to explain the theoretical background for the approximate formulas given by DNV (DNV-RP-F105 2002). The effective span length is defined as the length of a fixed-fixed pipe which has the same structural response of the pipeline span resting on elastic support. Mørk *et al*. (2003) discussed the response models developed by DNV (DNV-RP-F105 2002) to predict the vibration amplitudes due to vortex shedding. They concluded that these response models are valid tools for calculating the response amplitudes for long free spanning pipelines.

In 2006, Det Norske Veritas issued a recommended practice for the design and assessment of free spanning pipelines, (DNV-RP-F105 2006). The objective of the document is to provide rational design criteria and guidance for assessment of pipeline free spans subjected to combined wave and current loading. The origin of this document lies in the DNV guideline No. 14 which was issued in 1998, and subsequently updated in 2002. These guidelines were arrived at using finite element modeling, experimental results, and actual field data. The problem of free spanning was also dealt with using a finite element approach. Li *et al*. (2008) studied the seismic response of free spanning submarine pipelines experimentally and analytically. They used a finite element approach to the study the water-pipe interaction and determine the pipe acceleration and strain. They also performed experiments on a pipe model using an underwater shaking table. Zeinoddini *et al*. (2008) developed a finite element model which incorporates the pipe, the seabed, the free spanning and the surrounding water to study the water-pipeline interaction under the effect of seismic excitation. Pereira *et al*. (2008) developed a suite of programs to assess the allowable free spans for pipelines having high span diameter ratios and for multi-spanning pipelines. The software performs eigen-value analysis to calculate the natural frequencies, mode shapes, and the corresponding stress.

Recently the problem of monitoring the development of free-spans in operating pipeline garnered a great deal of interest. Jin *et al*. (2003) discussed a basic strategy for real-time monitoring of long distance submarine pipeline. The Monitoring system has a diagnostic and auto-alarm capabilities. The strategy is built on the use of distributed optical fiber sensors capable of monitoring strain and temperature along the pipeline. Felix-Henry and Lembeye (2004) discussed a corrosion monitoring of flexible steel risers technology. The strategy is based on monitoring variables like temperature and dynamic risers curvature distribution. Nikles and Briffod (2005) developed a method for extending the reach of an optical time domain refelectometry (OTDR) to monitor the temperature and strain of a long pipeline. Jin and Shao (2003) discussed an algorithm for the analysis of data obtained using optical fiber sensors. They also showed an application of the system for an existing pipeline. Feng *et al*. (2008) proposed the use of statistical pattern recognition methods for the analysis of the vibratory response of free spanning submarine pipeline as a tool for the structural condition monitoring. Job and Hawkins (2008) discussed a measurement program in which the actual response of the submarine pipeline to environmental conditions is monitored using accelerometers over a period of months.

The objective of this paper is to develop a methodology for the use of the strain measurements on the surface of a subsea pipeline to detect the inception of dangerous free spanning conditions. The feasibility of using this approach is studied using a finite element simulation of a subsea pipeline excited by random sea waves. The finite element model has been tested first using an experimental program to ascertain its accuracy in detecting variations in the strain levels on the surface of a pipeline. The paper describes the methodology, the development of the finite element model and the experimental program that was carried out to test the finite element model.

2. Using strain to monitor free spanning

The change in the strain along a pipeline can be used as a measure for the occurrence of dangerous free spans of subsea pipes. Optical fiber sensors are available and can be used to measure the strains. Two types of sensors are available: one measures the strain only and the other measures both the strain and the temperature. The distributed optical fiber sensor is not only used to obtain measurements for the strain and temperature but is also used to transfer the results for further analysis. Jin *et al*. (2003) developed a basic strategy to monitor the strain and temperature along a pipeline using distributed fiber optics. They also introduced a methodology for instrumenting pipelines with fiber optic sensors. Fig. 1 shows the location of sensors around the perimeter of the pipe (Jin *et al*. 2003).

In this paper we propose to use the mean and standard deviation of the measured strain values at four points on the pipe wall as an index to monitor the change in the pipeline free span condition. Fig. 1 shows a cross section of a pipe and the points where the strain was measured. When the free span is short, the pipe behaves as a simple beam. The strain in the pipe will be caused by bending. Since points 1 and 3 are on the neutral axis of the pipe, the strain at these points will be very small and the strain at points 2 and 4 will be nearly equal in magnitude but will have opposite signs. The strain at point 2 will be compression while that at point 4 will be tensile. As the free span increases, the pipe behaves more like a cable. A large tensile axial force develops in the pipe. The strain caused by the axial force will be tensile and it will override the strain caused by bending. Thus, the mean values of the strain at the four points will increase and tend to approach the same value.

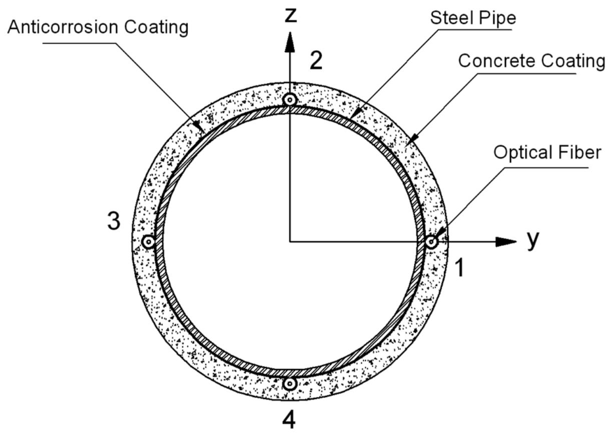


Fig. 1 Pipeline instrumentation

3. Experimental work

An experimental program was designed to test and calibrate the finite element model. The experiments were carried out using three pipes having different diameters and wall thicknesses, as shown in Table 1. Only the results obtained for two of the three pipes are presented in this work. A special aluminum support was manufactured to hold the pipe ends simulating a fixed support, as shown in Fig. 2.

An electromagnetic exciter was used to generate a random transverse load having a Pierson-Moskowitz spectrum. Four strain gages were attached to the pipe midsection as shown in Figs. 1 and 3. The load was applied to the pipe at a point at mid length. A load cell was used to measure the applied load during the test as shown in Fig. 4. The pipe was tested in air as shown in Fig. 5.

Table 1 pipe sizes

Pipe #	Total length	Diameter	Wall thickness
1	20 ft	5/8 inch	0.095 inch
2	20 ft	1.00 inch	0.095 inch
3	20 ft	1 1/2 inch	0.120 inch

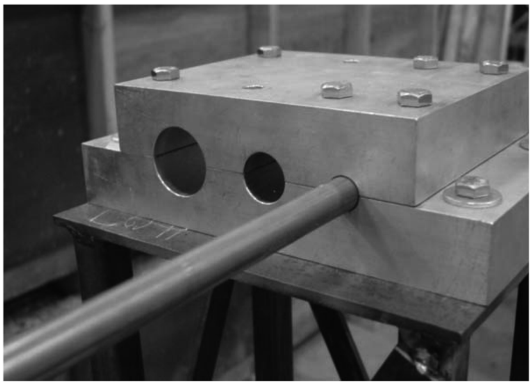


Fig. 2 Special support used to hold the pipes

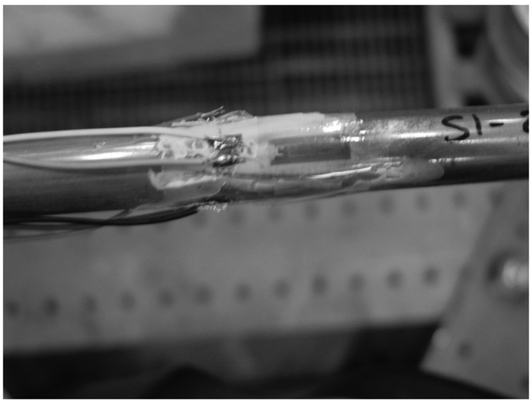


Fig. 3 Strain gages affixed to the pipe at midsection

The load cell was calibrated before the start of the test. A time history of 400 seconds was recorded for each strain gage and the load cell at a frequency of 100 Hz.

The standard deviations of the strain obtained experimentally at points 1 and 3 were compared with the standard deviations of the strain obtained from the FE model. The same random load used in the experiment was used as an input to the finite element model. The full transient method was applied to solve the problem. A time step of 0.02 seconds was used in the theoretical solution. The details of the finite element model will be mentioned in next section.

Figs. 6 and 7 show comparisons of the non-dimensional standard deviation, σ (ε) of the strains at points 1 and 3 for the small and medium pipes with the corresponding FE results, respectively. The nondimensional standard deviation of the strain is obtained as

$$\sigma(\varepsilon)_n = \frac{\sigma(\varepsilon)}{\sigma(F)}\frac{EI}{D_o^2} \tag{1}$$

Where σ (.) stands for the standard deviation, ε is the strain, F is the applied concentrated force, E is the modulus of elasticity of the pipe material, I is the area second moment of the pipe section, and D_o is the outer diameter of the pipe.

Figs. 6 and 7 show that the values obtained experimentally for the non-dimensional standard

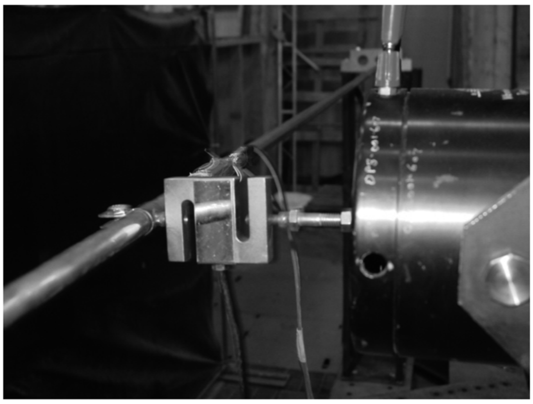


Fig. 4 Measuring the load using load cell

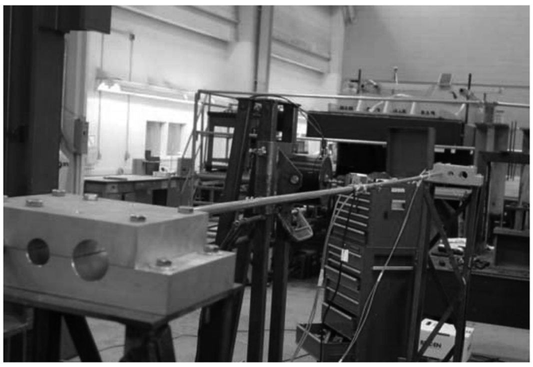


Fig. 5 Pipe # 1 under test

deviation of the strain are bracketed by the values obtained from the finite element calculations for the simply supported and fixed end pipes, respectively. This is to be expected, since the actual setup for the end supports used in the experiment does not ensure complete end fixity for the pipe.

The values for the non-dimensional standard deviation of the strain for the simply supported pipe are higher than that for the fixed ends case. This is expected, in view of the values of the axial force developed in the pipe as shown in Fig. 8. The axial force is larger for the simply supported

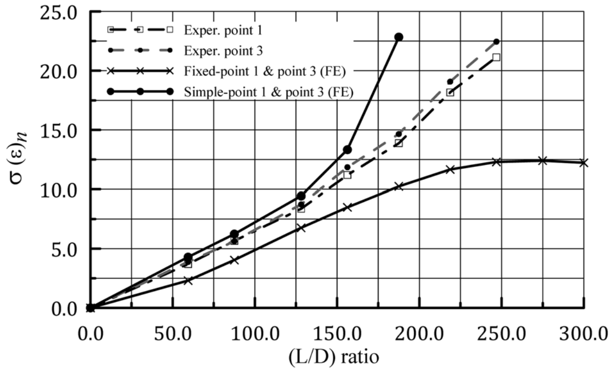


Fig. 6 Non-dimensional strain vs. (L/D) ratio, for pipe # 1

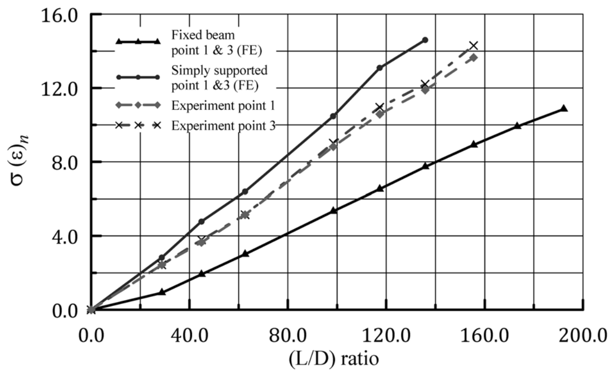


Fig. 7 Non-dimensional strain vs. (L/D) ratio for pipe # 2

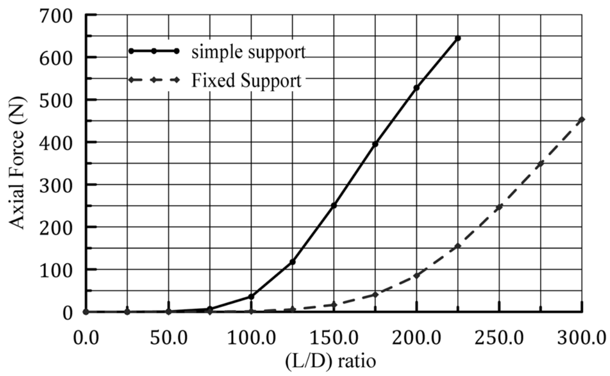


Fig. 8 Development of axial force with free span

pipe than for the fixed ends pipe.

The purpose of these experiments is to use the experimental results to evaluate the finite element model. These results give us confidence in using the finite element developed in predicting the strain levels in subsea pipeline excited by random waves.

4. Finite element model

4.1 FE model for in-air tests simulations

The pipeline segment was modeled using ANSYS software. PIPE16 element was chosen to model the pipe. PIPE16 is a uniaxial element with tension-compression, torsion, and bending capabilities. The element is defined by two nodes. The element has six degrees of freedom at each node: translations in X, Y and Z directions and rotations about the nodal x, y and z axes. The material of the pipe is assumed to be steel with modulus of elasticity and Poisson's ratio of 0.30. The density is assumed to be 7850 Kg/m^3. The element sizes did not exceed 0.10 m. The acceleration due to gravity was taken as 9.80 m/s^2. The transient dynamic analysis was used with the full method option activated. The maximum time step was 0.025 s. If required, smaller time steps are used but the results were recorded at 0.025 s time interval. The nonlinear geometry was activated during the solution.

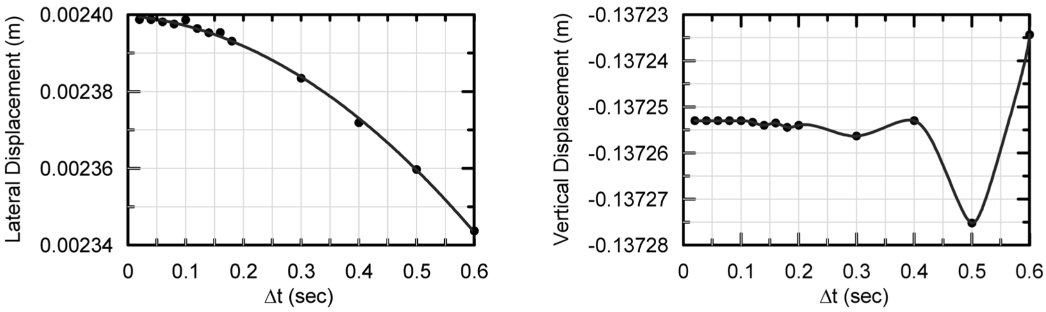
4.2 FE model for subsea pipelines

The finite element model used in the previous section was extended to determine the response of an actual subsea pipeline excited by random wave loading. The extension involves modeling the excitation that a subsea pipeline would be subjected to using a Pierson- Moskowitz spectrum, the material of concrete coating, and the oil fluid flowing inside the pipe. The pipeline model considered in these calculations consisted of a pipe segment having an outer diameter of 0.3556 m (14") and a wall thickness of 9.525 mm (3/8"). The density of the internal fluid was assumed to be 900 Kg/m^3 and the mass per unit length of internal fluid plus additional hardware was considered to be 80.06 Kg/m. The latter value was used for mass matrix calculations. The concrete coating was 0.05 m thick and its density was considered to be 2200 Kg/m^3. Other parameters such as soil supporting conditions are discussed in the following sections.

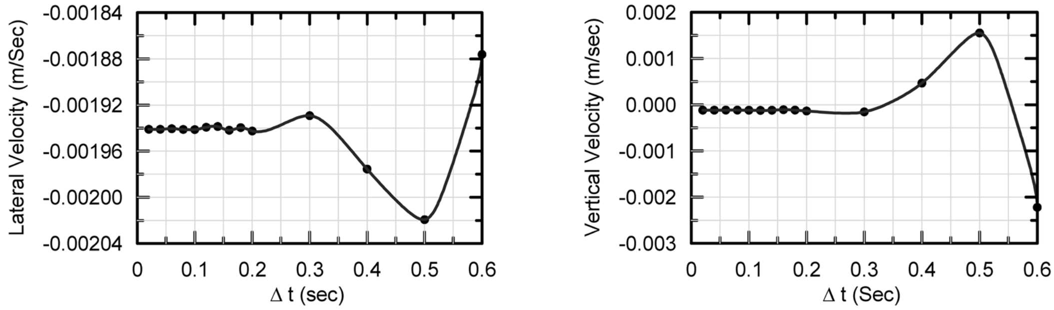
The pipe was modeled using a PIPE59 element available in ANSYS software. PIPE59 is a uniaxial element with tension-compression, torsion, and bending capabilities. The element allows waves and current excitations. The element has six degrees of freedom at each node; translations and rotations. The random waves can be introduced using the water motion table for the element. A study was performed to determine an appropriate time step for the numerical model. The convergence of the values of the deformation and velocity at the midpoint of the pipe were taken as criteria for a suitable time step. A balance should be struck between the computation time, the size of output files, and the accuracy of the solution. It can be seen from Fig. 9 that a time step of 0.025 seconds is a good compromise for the problem at hand.

5. The loads

The undersea pipe model was subjected to random waves in a direction perpendicular to the un-



(a) Change of displacement against time interval at midpoint of free span (time 47.80 seconds)



(b) Change of velocity against time interval at midpoint of free span (time 32.80 seconds)

Fig. 9 Choosing time interval for finite element solution

deformed axis of the pipe. The random waves were generated numerically from the Pierson-Moskowitz spectrum. The spectrum is expressed as

$$S(\omega) = \frac{A}{\omega^5} e^{-\left(\frac{B}{\omega^4}\right)} \tag{2}$$

where

$$A = 4\pi^3 \frac{H_s^2}{T_z^4} \text{ and } B = \frac{16\pi^3}{T_z^4}$$

The significant wave height H_s was taken as 5.00 meters and the mean zero-up crossing period T_z is taken as 9.00 seconds. ω is the frequency of the wave component.

6. Case studies

The results of two case studies are presented in this section to illustrate the use of the suggested technique. In the first case study, the boundary conditions are assumed to be Fixed-Fixed. In the second case study, the two ends of the pipe are assumed to be resting on springs and dashpots representing the soil effects.

6.1 Fixed-Fixed boundary conditions

In this example a pipeline with fixed-fixed ends is studied under random wave loading. The strains were calculated for different free span lengths. Since, the load is a random process, the response is also a random process with mean value equal to the static response. By averaging the time history of the response, the dynamic component of the response is averaged out and the static response remains. The average strain responses were found to coincide with the static results. From the static response, the free span can be estimated. This is valid for random loads with zero average. Usually, the sea level for relatively short intervals can be considered a random variable with zero mean. When the free span is small, the standard deviation values for points 1 and 3 are coincident and also for point 2 and 4. It was also found that the difference between the standard deviations for the strains at points 1 and 3 increases with the increase of free span. This may be caused by lateral vibrations of the pipe. It should be noted that the standard deviation of the strain for this case study was not normalized since, we have used a load having the same standard deviation in all runs. Fig. 10 shows the development of axial tension force in the pipe with the developing of free span. Figs. 11 and 12 show the average (static) strain and the standard deviation of strains developed at different points with the developing of free span. Fig. 13 shows the change of the ratio of the standard deviations of the strain at points 1 and 3 ($\sigma 1/\sigma 3$), as a function of the pipe length to

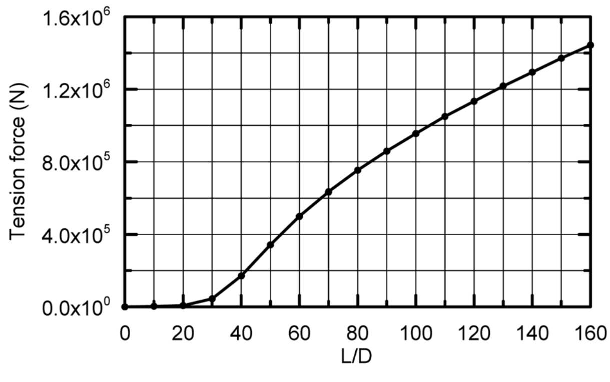


Fig. 10 Developing of tension force with L/D

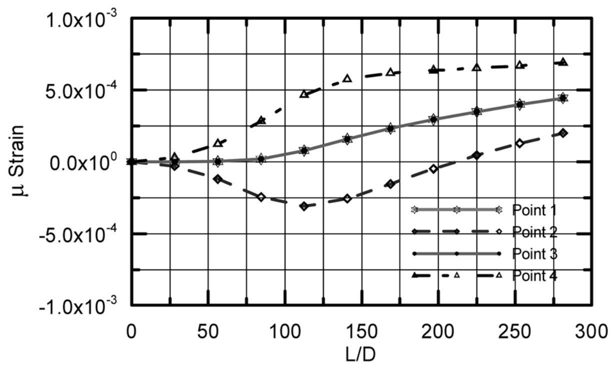


Fig. 11 Average strains (static) vs. Non-dimensional span Fixed-Fixed pipe segment

diameter ratio. For short free spans the ratio is equal to 1.0. The ratio of the standard deviations of the strain increase rapidly as the ratio of L/D increases. Fig. 14 shows the change of the ratio of the standard deviations of the strain at points 2 and 4 as a function of the pipe length the diameter ratio. For short free spans the ratio is equal to 1.0. As the L/D increases, the ratio of the standard

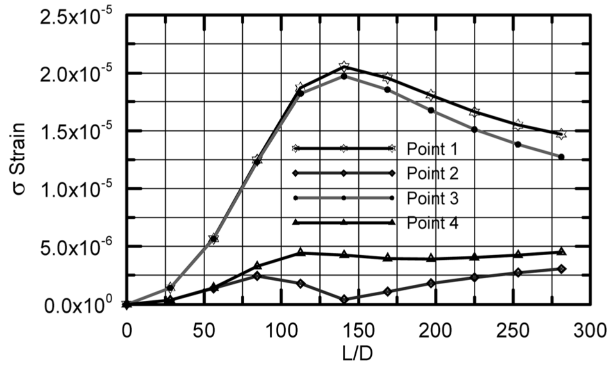


Fig. 12 σ of strains (static) vs. Non-dimensional Span Fixed-Fixed pipe segment

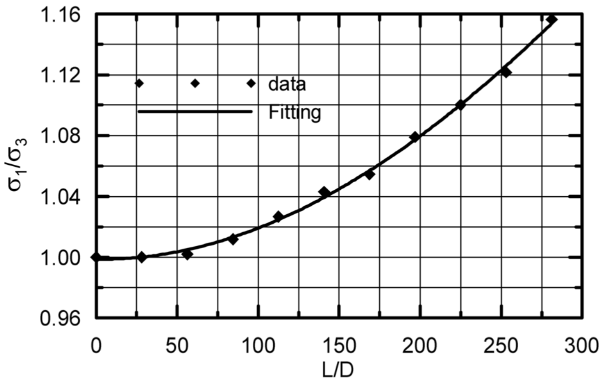


Fig. 13 Standard deviations ratio of strains at points 1 and 3

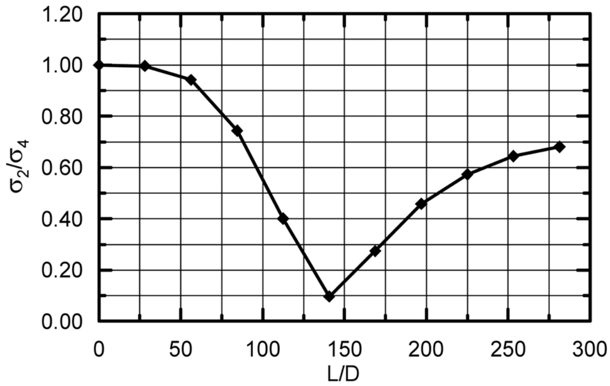


Fig. 14 Standard deviations ratio of strains at points 2 and 4

deviations decreases. The ratio of the standard deviations reaches a minimum value at a value of L/D of about 140. The ratio of the standard deviations of the strain start increasing as the L/D ratio exceeds 140.

6.2 Soil supported boundary conditions

The soil was modeled as springs and dashpots in both the vertical and horizontal directions. In the vertical direction, the spring works only if it is subjected to compression forces. This property is used to allow the pipe to be raised above the seabed level. The stiffness of each of the springs was calculated according to DNV-RP-F105 (2006). This code deals in details only with free spanning of undersea pipelines. The pipe model is shown in Fig. 15. It should be noted that half of the pipe segment is modeled assuming symmetrical boundary conditions at the center of the free span. The following equations were used to calculate the springs' constants in the vertical and lateral directions. This equation can be used when the topological conditions of the seabed are simple and the soil is not stratified.

$$K_V = \frac{C_V}{1-\nu}\left(\frac{2}{3}\frac{\rho_s}{\rho}+\frac{1}{3}\right)\sqrt{D}\ \text{(KN/m/m)} \tag{3}$$

$$K_L = C_L(1+\nu)\left(\frac{2}{3}\frac{\rho_s}{\rho}+\frac{1}{3}\right)\sqrt{D}\ \text{(KN/m/m)} \tag{4}$$

D is the external pipe diameter in (m), C_V is 10500 KN/m$^{5/2}$ and C_L is for 9000 $KN/m^{5/2}$ loose sand. The pipeline was allowed to move up freely to simulate the real case. The ratio ρ_s / ρ is the specific mass ratio between the pipe mass and the displaced mass of water. ν is Poisson's ratio for soil. Its value was taken 0.35 (DNV-RP-F105 2006). The pipeline segment was assumed to be coated with a layer of concrete having thickness of 5.0 cm and a density of 2200 Kg/m^3. Oil of 900 Kg/m^3 density of was assumed to flow through the pipe. The specific mass ratio of the pipe to water was found to be 1.805 which is within the range of validity of eqs. (3) and (4). The damping considered including the pipe material, coating and inside material was 2%. The soil damping is taken as 3% for L/D <40 and 2% for L/D between 40 and 160 for the vertical direction. For the

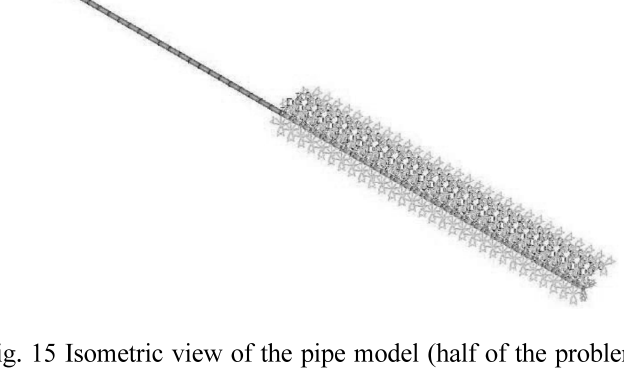


Fig. 15 Isometric view of the pipe model (half of the problem)

horizontal direction the values were 2% and 1.4%, respectively. Similar results are obtained in this case. Figs. 16, 17, 18 and 19 show the changes of the average strain values, standard deviations of the strain, and the ratio of the standard deviations as functions of L/D.

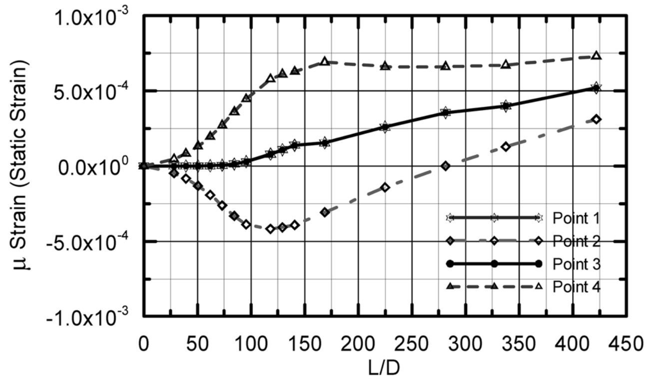


Fig. 16. Mean values of axial strains (pipe supported by soil)

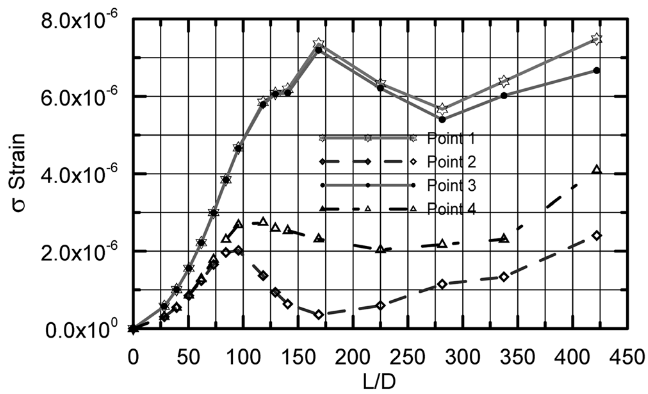


Fig. 17 Standard deviation of axial strains (pipe supported by soil)

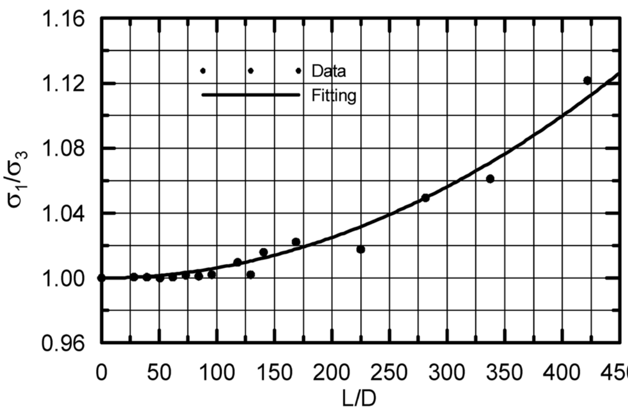


Fig. 18 Ratio of standard deviations of axial strains of point 1 and point 3 (pipe supported by soil)

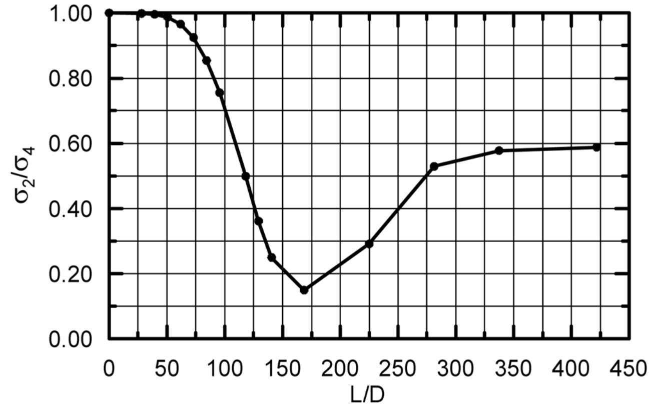


Fig. 19 Ratio of standard deviations of axial strains of point 2 and point 4 (pipe supported by soil)

7. Conclusions

This paper introduces a method for the analysis of measured strain on the surface of a subsea pipeline to monitor the inception of dangerous free span levels for the pipeline. Strain developing in a subsea pipeline is monitored and the values for the measured mean and standard deviation for the strain are obtained. Criteria for acceptable values of the mean and standard deviation for the strain should be set using industrial guidelines e.g., (DNV-RP-F105). The measured values for the mean and standard deviation of the strain are continuously compared with those set in the acceptability criteria. Dangerous levels of free spanning can be detected when the acceptable levels are crossed.

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