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Numerical study on lateral buckling of pipelines with imperfection and sleeper

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ABSTRACT

Lateral buckling is an important issue in unburied high-temperature and high-pressure (HT/HP) subsea pipelines systems. The imperfection–sleeper method is one of the most well-known methods used to control lateral buckling of HT/HP pipelines. Pipelines–sleeper–seabed numerical models are established and verified to analyze the buckling behavior of pipelines using the imperfection–sleeper method. The influence of six main factors on lateral buckling behavior is investigated in details based on the numerical results. Equations of buckling displacement (buckling displacement is defined by the final displacement of the middle point of the pipelines), critical buckling force, and buckling stress (Mises stress) are proposed using the gene expression programming technique. These equations show good accuracy and can be used to assist in the design of sleepers and assess the compressive and stress levels of pipelines.

1. Introduction

Subsea pipelines operated under high temperature and high inner pressure will develop compressive force because of seabed soil restraining its axial expansion. If the compressive force is sufficiently high, then global buckling will occur, which is similar to the buckling of a steel bar. For unburied subsea pipelines, which are common in deep-sea conditions, global buckling usually occurs in the lateral direction [1,2]. Lateral buckling may lead to fracture, collapse, or buckling propagation [3]. With the increase in operation temperature and pressure, controlling lateral buckling becomes an essential problem in the design of subsea HT/HP pipelines.

A number of methods are used, such as snaked lay (imperfection) method [4], sleeper method [5], and distributed buoyancy method [6], to control lateral buckling responses. All of these methods are aimed at reducing the compressive force levels and buckling responses. This study focuses on the method that combines imperfections and sleepers.

For pipelines with imperfections, a number of studies on lateral buckling of imperfect pipelines have been conducted in recent years. Miles and Calladine [7] provided a design formula to calculate the maximum buckling strain on the basis of the experimental and numerical results. Karampour et al. [3] derived an analytical solution for pipelines with half-wavelength sinusoidal imperfection. Hong et al. [8] used the energy method to calculate the analytical solution for pipelines lateral buckling with a single-arch initial imperfection and indicated that a small single-arch initial imperfection is associated with snap buckling. Most of the lateral buckling studies have a reasonable two-dimensional assumption. However, the buckling problem becomes a three-dimensional (3-D) problem when a sleeper is considered. For pipelines with sleepers, Sinclair et al. [5] indicated that buckling mode 2 may occur in pipelines with sleepers, which should be ignored. One effective way to avoid mode 2 is to combine the sleeper method with the imperfection method. The initial imperfection not only reduces the critical buckling force but also guarantees that only mode 1 occurs, which will be discussed in Section 3. The proposed critical buckling force and maximum strain formulas cannot be applied directly to the pipelines with imperfections and sleepers. Therefore, formulas of critical buckling force, buckling displacement, and buckling stress are necessary to improve the design of pipelines with imperfections and sleepers.

The lateral buckling behavior of subsea pipelines with imperfection and sleeper has been investigated numerically. First, a 3-D finite element model of a 2000 m-long pipelines–sleeper–seabed system is developed in Abaqus. Then, six factors which influence the buckling response are investigated to analyze the lateral buckling behavior. Finally, on the basis of the numerical results, three formulas (critical buckling force, buckling displacement, and buckling

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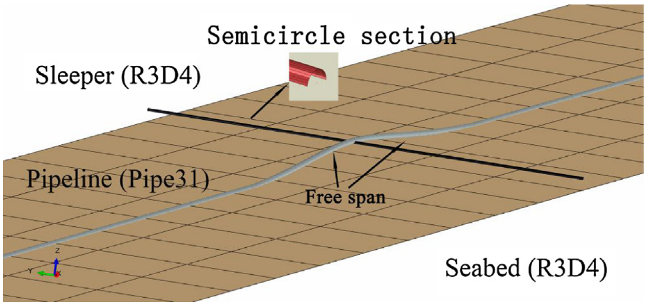

Fig. 1. The finite element model.

stress) related to pipelines with imperfections and sleepers are proposed by the gene expression programming (GEP) method. These equations can be used to design pipelines with both imperfection and sleeper.

2. Numerical model

2.1. Finite element model

The finite element model provides a convenient method to calculate the lateral buckling of pipelines. The finite element model of the pipelines with imperfection and sleeper is described on the basis of the following four aspects:

First, the element types are selected. The beam element is suitable for simulating pipelines structures because the subsea pipelines is an ultra-slender structure, which indicates that the length of one direction (pipelines axial direction) is more than the length of two other directions (pipelines cross-section). As a result, PIPE31 elements in Abaqus, i.e., two-node linear beam elements, are selected to simulate the pipelines [9]. It is noteworthy that thin-walled PIPE31 element is selected here; therefore the hoop stress is constant across the cross-section of the pipe. This assumption needs to be taken care when the section of pipelines is extremely thick, in which case the hoop stress varies across the section. The seabed is assumed to be a rigid surface, which is a common assumption in the traditional analytical method. Thus, rigid surface elements (R3D4 element in Abaqus) are selected to simulate the seabed [10]. The sleeper is also assumed to be a rigid surface with a semi-circle section, as shown in Fig. 1.

Second, the constraint and load of the finite element model are determined. Most parts of the pipelines lie on the seabed and constrained by the seabed through contact elements. The middle point of the pipelines is held by a sleeper, which results in free segments on both sides of the middle point (Fig. 1). The ends of the pipelines are both far from the middle point (1000 m). Therefore, the pin constraint at the ends of the pipelines has only a slight influence on the buckling area. The seabed and sleeper are both fixed. The contact pressure–overclosure relationship of the interaction between pipelines and seabed (sleeper) is presented as a hard contact model. The Coulomb friction model is used to represent friction. μ_1 and μ_2 represent the friction coefficients of seabed and sleeper, respectively.

A uniform temperature field, constant inner pressure, and distributed load in the z-direction are applied to the pipelines to simulate working conditions.

Third, the imperfection is selected. A sinusoidal imperfection is used to achieve lower buckling force, as shown in Fig. 2. The imperfect segment of the pipelines can be expressed in Eq. (1), as follows:

$$h = h_0 \sin\left(\frac{\pi(l + l_0/2)}{l_0}\right) \tag{1}$$

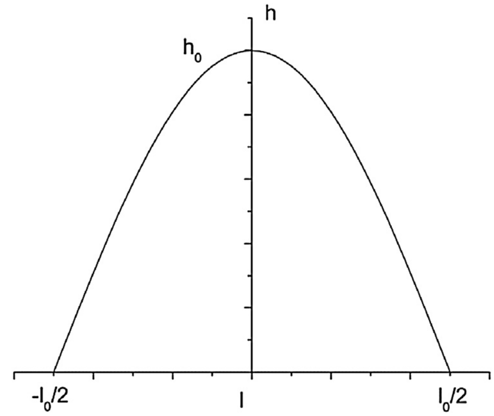

Fig. 2. The sinusoidal imperfection.

Table 1
Pipelines property for verification.

Diameter (d) (mm)	15
Wall thickness (t) (mm)	0.9
Young's modulus (E) (MPa)	191,000
Poisson's ratio (υ)	0.3
Thermal coefficient of expansion (α) (/°C)	1.73×10^{-5}
Submerged weight (q) (N/m)	3.94, 0.0
Sleeper height (h_2) (mm)	30
Seabed friction coefficient (μ_1)	0.7
Sleeper friction coefficient (μ_2)	0.1, 0.2
Temperature (°C)	35
Pressure (MPa)	12

where h_0 and l_0 are the amplitude and length of the imperfection, respectively.

Finally, the quasi-static dynamic method is selected as the calculation method to simulate the lateral buckling of the pipelines, which means dynamic. Geometric nonlinearity switch in Abaqus is turned on at the beginning of the simulation, which means geometric stiffness is considered. The stiffness matrix of the model is updated during the simulation process.

2.2. Verification of the finite element model

The same pipelines model used by De Oliveira et al. [13] in their experimental study is simulated in this section to test the accuracy of the proposed finite element model. Three of the experiments models are selected here to verify the proposed numerical model. The pipelines properties are shown in Table 1.

Fig. 3 shows the axial compressive force and displacement results of the buckling apex obtained by the experiments and simulation. Only the representative data point is selected because many fluctuations exist in the original axial force experimental data. In Fig. 3, the temperature increase is shown along the x-axis, whereas the compression force of the pipelines is shown along the y-axis. All the three experiments show a similar pattern. The compression force keeps increasing with the increase in temperature until the temperature reaches approximately 5 °C (critical buckling temperature). Then, the axial force decreases rapidly, which indicates that lateral buckling occurs. The apex of the compression force is referred to as the critical buckling force of the pipelines. Simulated critical buckling forces are 530 N, 462 N and 551 N with relative error −8.0%, −7.5% and − 9.2%. It is assumed that the differences between the simulated and experimental results are mainly due to exclusion of the pipelines coating.