

## Numerical Parameter Study on Lateral Buckling Response of Submarine Pipe-in-Pine pipelines

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### ABSTRACT

In meeting the technical needs for deepwater conditions and overcoming the shortfalls of single-layer pipes for deepwater applications, pipe-in-pipe (PIP) systems have been developed. While, for PIP pipelines directly laid on the seabed or with partial embedment, one of the primary service risks is lateral buckling. The critical axial force is a key factor governing the global lateral buckling response that has been paid much more attention. It is influenced by global imperfections, submerged weight, stiffness, pipe-soil interaction characteristics, et.al. In this study, 3D Finite Element Models for imperfect PIP systems are established on the basis of beam elements and tube-to-tube element in Abaqus. A parameter study was conducted to investigate the effects of these parameters including structural parameters such as imperfections, clearance, and bulkhead spacing, pipe/soil interaction parameter axial and lateral friction properties between pipeline and seabed, and load parameter submerged weight on the critical axial force and post-buckling forms. Python is been used to realize parametric modeling in Abaqus. Some conclusions are obtained which can provide a guide for the design of PIP pipelines.

*Key Words:* lateral buckling, PIP, parameter study, numerical model

### 1. INTRODUCTION

With the development of offshore oil industry, offshore oil exploration has been going to marine deep water gradually in recent years. In meeting the technical challenges for deepwater conditions and overcoming the shortfalls of single-layer pipes for deepwater applications, pipe-in-pipe (PIP) systems have been developed which stresses engineering design requirements with respect to flow assurance, transient, as well as serviceability and strength (DNV OS-F101 2012). While, for PIP pipelines directly laid on the seabed or with partial embedment, one of the primary service risks is lateral buckling. Pipelines with lateral buckling may lead to final failure such as collapse, fatigue and fracture et.al (DNV RP-F110 2007). So it is important to study this behavior.

Many researchers have investigated the lateral buckling problem. Palmer and Baldry (1974) studied lateral buckling of axially constrained pipelines by theoretical analysis and experiments. He interpreted the reason that the pipe can buckle correctly and obtained an analytical solution of critical pressure. Hobbs (1984) studied lateral buckling phenomenon in perfect single-layer pipelines. He proposed that pipeline can buckle into different lateral modes. These lateral buckling modes can

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be divided into five types, as shown in Fig. 1. By solving the governing equation, he obtained five theoretical solutions corresponding to above five lateral buckling modes. Since then, a number of experimental and analytical studies on the lateral buckling of single-layer pipelines have been published, such as Taylor and Gan (1986), Taylor and Tran (1993), Taylor and Tran (1996) who carried out a series of researches for upheaval and lateral buckling behaviors. They mainly focused on the effect of initial imperfections on buckling response. Miles and Calladine (1999) proposed that initial lateral buckling is a localization phenomenon. They investigated these phenomena by means of a small-scale physical model and computer simulation. The results from experiments and simulations are consistent. Simple formulas were presented for the amplitude and wavelength of first formed lobe. Kershenbaum et al. (1996) proposed an analytical model for a single subsea pipeline lateral deviation due to thermal expansion. They applied energy variational method to determine the lateral deviation and natural wave lengths which are used to determine the pipeline sinusoidal shape, resultant pipeline stresses, and a more realistic pipeline expansion length. Plastic lateral resistance from soil friction is considered to have a small effect on the critical buckling loads. Soreide et al (2005) applied analytical as well as numerical simulations to illustrate the different modes of deformation and design parameters of lateral buckling. The effects on allowable feed-in from soil resistance, pipeline weight and initial geometry are discussed in their analyses. Karampour and Albermani (2013) carried out analytical and numerical studies on lateral buckling of subsea pipelines. By comparing the results from theoretical analysis and numerical simulation, a new interpretation of localization is presented based on an isolated half-wavelength model. They obtained a conclusion that excessive bending stress can be induced under lateral buckling. Haq and Kenny (2013) presented a calibrated numerical modelling procedure. They mainly focused on the parameters study on lateral buckling of subsea pipelines. Above studies have focused on lateral buckling behavior only in single-layer pipelines. However, these researches provide the foundation for lateral buckling problem of PIP pipelines.

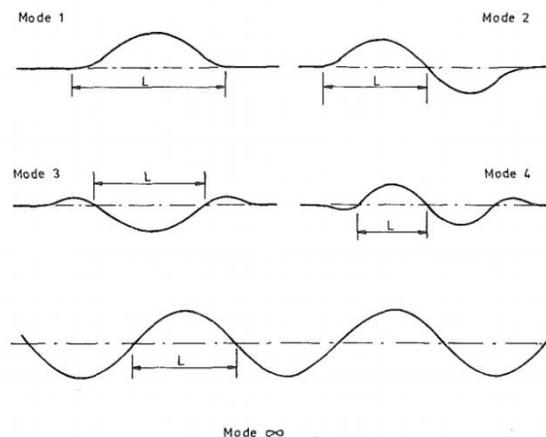


Fig. 1 Lateral buckling modes

Harrison et al (1997) investigated the thermal expansion phenomenon in insulated PIP system. They presented an analytical method, investigation results and application of thermal expansion of subsea PIP system. In their analysis, temperature gradient, pressure, soil resistance, and interaction forces between inner pipe and outer pipe are considered. But they mainly focused on the calculation of pipe elongation, stresses and strains. Vaz and Patel (1999) presented an analytical formulation of the coupled buckling instability of a PIP system on the basis of beam theory. They found that the stiffness ratio of the inner and outer pipes as well as the number of centralizers affect the global buckling form in ideal PIP system. Whereas, because of they addressed the PIP buckling problem, the presence of seabed friction and the mutual constraint axial and rotational between the inner and outer pipes as well as initial imperfections are ignored. Zhao T et al (2007) investigated the lateral buckling process induced by high-temperature using modified Risks method. Emphasis is

placed on the acquiring a more precise description on PIP system buckling process by using Finite Element models. Haq and Kenny (2014) carried out numerical parameter study on later buckling response of subsea PIP pipeline. The parameters examined include pipe embedment, pipe out-of-straightness (OOS), soil shear strength, soil peak and residual forces and displacements, variation in soil properties distributed along the pipeline route, and external pressure associated with the installation depth. The observed pipe response was a complex relationship with these parameters and kinematic boundary conditions.

From above, we know that the lateral buckling response of PIP pipelines is a considerably complicated process. Many factors can affect the lateral buckling behavior of PIP system. Previous researches manifest that it is difficult to find an analytical solution considering adequate factors to describe the buckling performance of PIP systems. However, Finite Element Methods can be employed primarily to reveal the possible lateral buckling behavior for untrenched PIP systems.

In this study, 3D Finite Element Models for imperfect PIP systems are established on the basis of beam elements and tube-to-tube element (ITT elements) in Abaqus. A parameter study was conducted to investigate the effects of these parameters including structural parameters such as imperfections, clearance, and bulkhead spacing, pipe/soil interaction parameter lateral friction property between pipeline and seabed, and load parameter submerged weight on the critical axial force and post-buckling forms. Python is been used which can realize parametric modeling in Abaqus. Some conclusions are obtained which can provide a guide for the design of PIP pipelines. This paper will provide a foundation for future studies to establish engineering guidance on PIP Pipelines lateral buckling with respect to additional parameters including installation conditions and non-linear pipe/soil interaction characteristics et.al.

## 2. ANALYSIS METHOD

### 2.1 Geometric model of PIP

The basic configuration of a PIP pipeline is shown in Fig.2. The PIP pipeline comprises inner pipe, outer pipe, thermal insulation material and a series of bulkheads and centralizers (Jukes et.al 2007). The inner pipe is used to convey the hydrocarbons and hence exposed to the internal pressure and temperature. The outer pipe is used to withstand the external pressure. The inner pipe and outer pipe are constrained by a series of centralizers. The centralizers are fixed with the inner pipe whereas the outer pipe is separated from the centralizers. So the inner pipe and the centralizers can move freely inside the outer pipe and transfer forces and displacements through the contact between the centralizer and the outer pipe. In practice, the clearance between centralizers and outer pipe may be 1mm-10mm (Vaz et.al 1999) depending on the manufacturing precision. The annulus between inner and outer pipe is filled with dry insulation material. The end bulkhead is designed to connect the inner pipe to the outer pipe at each pipeline termination. Intermediate bulkheads may be required for reeled PIP to allow the top tension to be transferred between the outer pipe and the inner pipe.

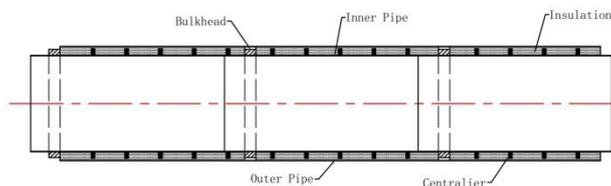


Fig. 2 Typical PIP configuration

### 2.2 Finite element model

According to the research of Palmer (1990), the finite element analysis is a convenient and effective tool to calculate the buckling of pipelines. The finite element model of the PIP system is described on the following five aspects.

### 2.2.1 Pipeline and seabed elements

In this study, the outer and inner pipes are modeled using the three-dimensional two-node linear Timoshenko beam element PIPE31 which can account transverse shear deformation and is suitable for simulating slender structure (ABAQUS 6.14 Analysis User's Guide 2014). The geometric parameters of inner and outer pipes are listed in Table 1. The outer and inner pipes are divided into 1200 equal length element respectively.

**Table 1** Geometric parameters of PIP pipeline

Parameter	Values	
	Inner pipe	Outer pipe
Length, m	1200	1200
Diameters, m	0.305	0.457
Thickness, m	0.02033	0.02285

The centralizer between the outer and inner pipes is modeled by three-dimensional one-node tube-to-tube contact element ITT31 which can model the finite-sliding interaction between two pipelines or tubes where one tube lies inside the other or between two tubes that lie next to each other (ABAQUS 6.14 Analysis User's Guide 2014). Hence, the ITT contact elements can accurately simulate the contact reaction forces and corresponding load transfer (through the centralizer) between the inner and the outer pipe. As shown in Fig. 3, ITT elements are attached to the node of the inner pipe. A slide line associated with the axial line of the outer pipe is needed to provide a path for ITT element. ITT elements have one key parameter- the clearance between ITT elements and the outer pipe. The clearance  $r_0$  is shown in Fig. 3.

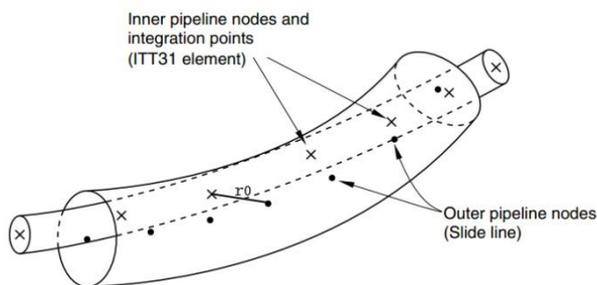


Fig.3 ITT31 element

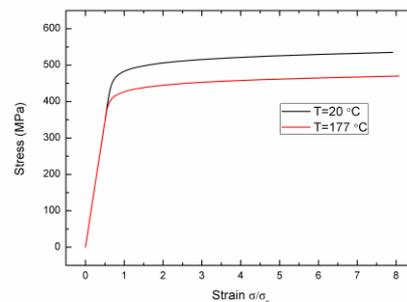


Fig. 4 The stress-strain curve

The bulkheads are modeled by tie constraints for the corresponding nodes between the inner and outer pipes. In this study, in order to research the effects of bulkheads spacing on the lateral buckling, we set the bulkheads spacing varying from 50m to 1200m.

The seabed is treated as a rigid foundation which is modeled using 3-dimensional 4-node discrete rigid element R3D4. In the research of Haq (2014), the elements with a size of 8m×6m are adopted. But a mesh topology study was carried out which manifested that the elements with a size of 20m×20m is enough. So in this study, we adopt the latter size.

### 2.2.2 Pipeline Material Properties

The pipeline material grade 483MPa (X70) is selected for both inner and outer pipes. The stress-strain curve is fitted with the Ramberg-Osgood model (Haq 2014, He 2014) defined as follows:

$$\varepsilon = \frac{\sigma}{E} \left( 1 + \frac{3}{7} \left( \frac{\sigma}{\sigma_y} \right)^{n-1} \right) \quad (1)$$

According to the study of Haq (2014), the pipe material properties related to temperature are listed in Table 2. The stress-strain relationships are shown in Fig.4. Apparently, with the increasing of temperature, the strength is decreased. Using linear interpolation method, the material properties corresponding to other temperature are obtained. In this study, the stress-strain relationship is defined as a piecewise nonlinear dataset with plastic material behavior defined by the von Mises yield criterion with isotropic hardening.

Table 2 Pipe Material Properties

Parameter	Temperature	
	20 °C	177 °C
Young's modulus, GPa	207	206
Density, kg/m <sup>3</sup>	7850	7850
SMYS, MPa	483	422
SMTS, MPa	570	499
Poisson's ratio	0.3	0.3
Coefficient of thermal expansion, °C <sup>-1</sup>	1.17E-5	1.31E-5

### 2.2.3 Pipe/Soil Interaction

As mentioned before, the seabed is modeled as rigid surface. The Coulomb friction model with isotropic property is used to model the interface contact between the pipe and seabed. While, in researching the effect of friction on the lateral buckling, that model with anisotropic properties is been adopted. According to Rong et.al (2009), the best estimate defining the pipe breakout axial and lateral friction was 0.6 and 0.8, respectively. We make the axial friction coefficient be a constant 0.6 and the lateral friction coefficient vary from 0 to 1.2.

### 2.2.4 Loads and Boundary Conditions

The loads include the PIP submerged weight, internal and external pressure, operating and ambient temperature. The PIP submerged weight is modeled by downward forces per unit which is identical and evenly distributed linear loads with its value varying form 1500N/m to 10500N/m. The ambient seawater temperature and operating temperature is set as 20 °C and 177 °C, respectively.

In the first load step, the initial conditions are defined that including the ambient seawater temperature and linear loads due to the submerged pipe weight. In the second load step, the external and internal pressure loads, and operating temperature are defined.

In the entire simulation, the ends of inner and outer pipe are fixed in X, Y and Z direction including three translational degrees of freedom and three rotational degrees of freedom.



Fig. 5 The Finite Element Model of PIP pipeline

### 2.2.5 Initial imperfection

In this study, one symmetric full-contact imperfection profile function is selected to account for undulations of the seabed. The function is (Karampour 2013)

$$f_2(x) = \frac{w_0}{2} (1 + \cos(\frac{2\pi x}{L_0})) \quad -\frac{L_0}{2} \leq x \leq \frac{L_0}{2} \quad (2)$$

Where  $w_0$  denotes maximum height of imperfection, and  $L_0$  denotes wave length of imperfection. Hence  $w_0/L_0$  denotes the out-of-straight (OOS) of pipelines. In this study in order to research the effect of OOS on lateral buckling, we set  $w_0$  varying between 0.1m to 3m.

Finally the Finite Element Model is established, as shown in Fig.5. In the next section, we will use this model to conduct parameter study.

### 2.3 Calculation method

The lateral buckling of PIP system is an unstable nonlinear and localized problem. Therefore, a local transfer of strain energy occurs from one part of the model to near parts. Pure Newton-Raphson method may lead to the problem of the convergence difficulty or the un-convergence during the calculating. Additional an automatic stabilization method specifying dissipated energy fraction has been used for solving this nonlinear equilibrium problem.

## 3. PARAMETER STUDY

From previous researches of lateral buckling of the PIP pipelines, we know that the buckling behaviors of PIP pipelines are affected by these factors, namely submerged weight  $Q$ , pipeline stiffness ratio  $\beta$  (as shown in equation (3)), pipeline initial imperfections OOS, lateral friction coefficient  $\mu$ , clearance  $c$  between inner and outer pipe et.al. In this study, we keep the diameters and wall thickness of inner pipe and outer pipe constants. So the stiffness ratio  $\beta$  is a constant 0.2514.

$$\beta = \frac{EI_{inner}}{EI_{outer}} \quad (3)$$

According to previous research Vaz (1999), Jukes (2009), sinusoidal buckling or helical buckling won't happen when the stiffness ratio take this value. We mainly study the effects of rest parameters  $Q$ , OOS,  $\mu$ ,  $c$ , and an additional parameter bulkhead spacing  $h$  on the later buckling critical force and buckled forms of PIP system. The range of these parameters is listed in Table 3. A totally, more than 2000 finite element models are performed.

Python, the programming language within the ABAQUS is used to create and manage the parametric study's files. The results are also processed by Python because of amazing amount of data. The results will be discussed in nest section.

Table 3 Parameter range

Parameter	Temperature							
Submerged weight $Q$ (kN/m)	1500	3000	4500	6000	7500	9000	10500	
OOS	0.001	0.002	0.005	0.008	0.01	0.015	0.02	0.03
lateral friction coefficient $\mu$	0	0.2	0.4	0.6	0.8	1.0	1.2	
clearance $c$ (m)	0.001	0.002	0.005	0.008	0.016	0.024	0.032	0.048
bulkhead spacing $h$ (m)	50	100	200	300	400	600	1200	

## 4. RESULTS AND DISCUSSION

The lateral buckling behaviors of PIP pipelines have been simulated successfully. As shown in Fig. 6, when the temperature reach to 177°C, a typical contour of the axial stress and displacement of PIP pipelines are plotted. Apparently, the lateral buckling of PIP pipelines occurred. The effect of different factors on the lateral buckling critical force and buckled forms of PIP system will be analyzed in this section.

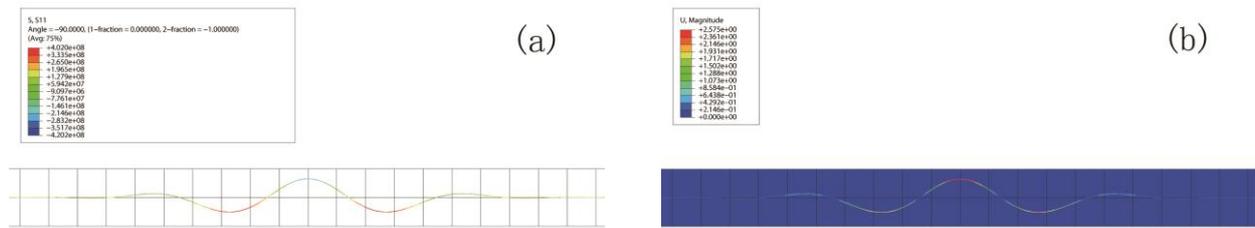


Fig. 6 Contour plot of the axial stress and displacement. (a) axial stress; (b) displacement

#### 4.1 Influence of submerged weights

The lateral buckling response of PIP pipelines with different submerged weight  $Q$  is shown in Fig.7. From Fig. 7 (a) we know that the heavier the submerged weight is, the more evident of the “snap through” phenomenon occurs, and the smaller the lateral displacement is when the temperature reaches to 177°C. When the submerged weight is over 9000N/m, the maximum lateral displacement almost doesn’t change. According to the critical temperature, the critical axial force is calculated as follows (Hobbs 1984)

$$F_c = EA\alpha\Delta T \quad (4)$$

The critical temperature and critical force are listed in Table 4. From Table 4, we know that the submerged weight varying from 1500N/m to 10500 N/m, the critical force changes corresponding from 1.03E+6 to 5.23E+6. Therefore, the submerged weight significantly influences the critical force.

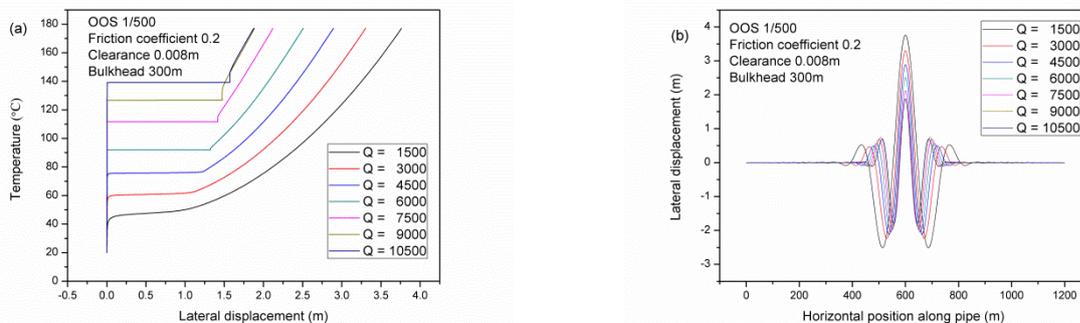


Fig. 7 Lateral buckling response with different submerged weight. (a) Temperature-lateral displacement of mid-point of outer pipeline curves; (b) post-buckling forms

Table 4 The critical temperature and force with different submerged weight

Item	Value						
Submerged weight $Q$ (N/m)	1500	3000	4500	6000	7500	9000	10500
Critical temperature $T_c$ (°C)	43.5	60.5	75.0	92.0	111.7	126.3	138.8
Critical axial force $F_c$ (E+6N)	1.03	1.78	2.42	3.17	4.03	4.68	5.23

The post-buckling form is shown in Fig. 7 (b). From this figure, it is clearly that the buckling

modes are not change when the submerged weight varying from 1500N/m to 10500N/m. This buckling mode is same with Mode 3 which Hobbs (1984) presented, as shown in Fig.1. The heavier the submerged weight is, the smaller the lateral buckling area is, and the smaller the maximum lateral displacement is. It is manifested that the post-buckling form is sensitive to the submerged weight.

#### 4.2 Influence of imperfections

Previous research manifested the initial imperfection shape and OOS affect the upheaval buckling behavior (Hobbs 1984, Taylor and Gan 1986, Taylor and Tran 1993, Taylor and Tran 1996). Likewise, the initial imperfection shape and OOS also affect the lateral buckling behavior. In this study, we only consider the effect of OOS on the lateral buckling behavior. The effect of imperfection shape will be discussed in future work.

The lateral buckling response of PIP pipelines with different OOS is shown in Fig.8. From this figure we know that the smaller the OOS of pipeline is, the more evident of the “snap through” phenomenon occurs, the higher the critical temperature is, and the smaller the lateral displacement is when the temperature reaches to 177°C. The critical temperature and critical force is listed in Table 5. From Table 5, we know that the OOS of pipeline varying from 0.001 to 0.03, the critical force changes corresponding from 4.81E+6 to 0.28E+6. Therefore, the OOS of pipeline also significantly influences the critical force.

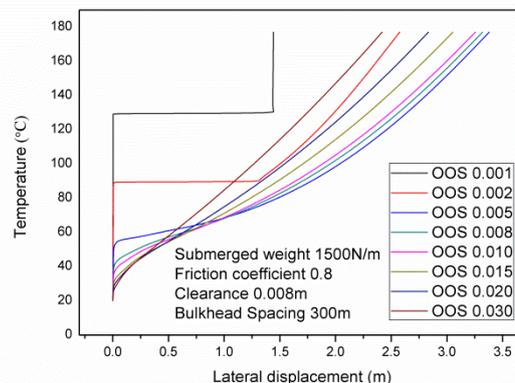


Fig. 8 Temperature-lateral displacement of mid-point of outer pipeline curves with different OOS

Table 5 The critical temperature and force with different OOS

Item	Value							
OOS	0.001	0.002	0.005	0.008	0.01	0.015	0.02	0.03
Critical temperature $T_c$ (°C)	129.2	89.3	50.9	39.7	36	31.2	28.7	26.5
Critical axial force $F_c$ (E+6N)	4.81	3.05	1.36	0.87	0.70	0.49	0.38	0.28

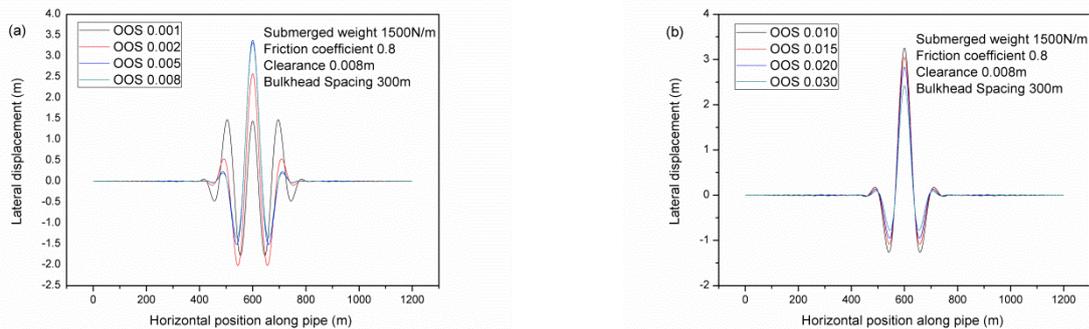


Fig. 9 Post-buckling forms with different OOS. (a) OOS from 0.001 to 0.008; (b) OOS from 0.01 to 0.03

The post-buckling form with different OOS is a little complicated which totally can be divided into two types, as shown in Fig. 9. When the OOS of pipeline is less than 0.01 (see Fig. 9 (a)), the lateral buckling mode with different OOS of pipeline looks like the evolution of Mode 3. The lateral buckling area is not change. When the OOS of pipeline is more than 0.01 (see Fig. 9 (b)), the lateral buckling mode with different OOS of pipeline is same with Mode 3. The lateral buckling area is also not change. The only difference is that they have different maximum buckling displacement values. It is also manifested that the lateral buckling is sensitive to the OOS of pipeline.

### 4.3 Influence of friction

The lateral buckling response of PIP pipelines with different lateral friction coefficient (isotropic) is shown in Fig. 10 (a). From this figure, we can see that the larger the lateral friction coefficient is, the more evident of the “snap through” phenomenon occurs, the higher the critical temperature is, and the smaller the lateral displacement is when the temperature reaches to 177°C. The critical temperature and critical force are listed in Table 6. From Table 6, we know that the lateral friction coefficient varies from 0.0 to 1.2, the critical force changes corresponding from 0.057E+6 to 4.66E+6. Therefore, the lateral friction coefficient of pipeline also significantly influences the critical force.

The lateral buckling response of PIP pipelines with anisotropy friction property and the comparison between that and related isotropic friction property is shown in Fig. 10 (b). From this figure we can find out that axial friction coefficient doesn't affect the critical temperature or critical axial force, but does affect the post-buckling lateral displacement.

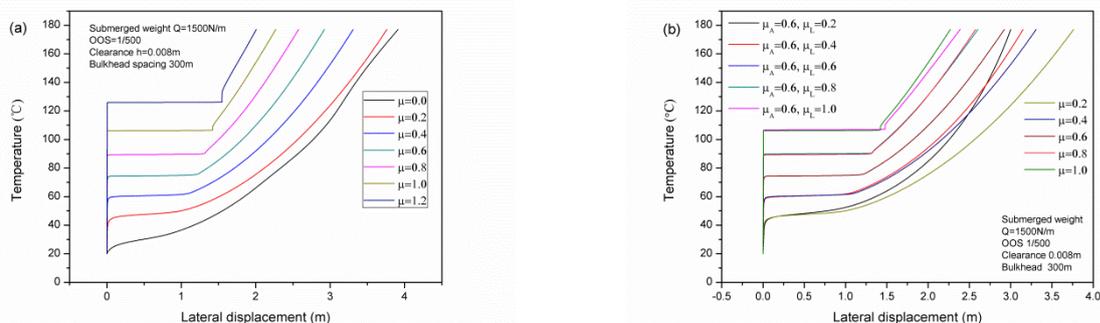


Fig. 10 Temperature-lateral displacement of mid-point of outer pipeline curves with different lateral friction coefficient. (a) friction with isotropic property; (b) friction with anisotropy property

Table 6 The critical temperature and force with different lateral friction coefficient

Item	Value						
Lateral friction coefficient	0.0	0.2	0.4	0.6	0.8	1.0	1.2
Critical temperature $T_c$ (°C)	21.3	39.8	56.6	72.7	88.9	106.0	125.9
Critical axial force $F_c$ (E+6N)	0.057	0.87	1.61	2.32	3.03	3.79	4.66

The post-buckling form with different lateral friction coefficient is more complicated. As shown in Fig. 11 (a), when the lateral friction coefficient is in the range from 0.2 to 1.2, the lateral buckling mode is same with Mode 3. Moreover, the smaller the lateral friction coefficient is, the larger the lateral buckling area is, and the bigger the maximum buckling displacement value is. Apparently, the buckling form with lateral friction coefficient 0 is very different with others. In order to see the evolutionary process more clearly, an additional analysis was conducted where the lateral friction coefficient varying from 0.0 to 0.1. The results are shown in Fig. 11 (b). When the lateral friction coefficient is in the range from 0.0 to 0.1, more lobes appear and the length and amplitude of lobes are all decreased with the increasing of lateral friction coefficient. The amplitudes and length of lobes are decayed from middle to two sides. The lateral buckling areas are also decayed with the increasing of lateral friction coefficient.

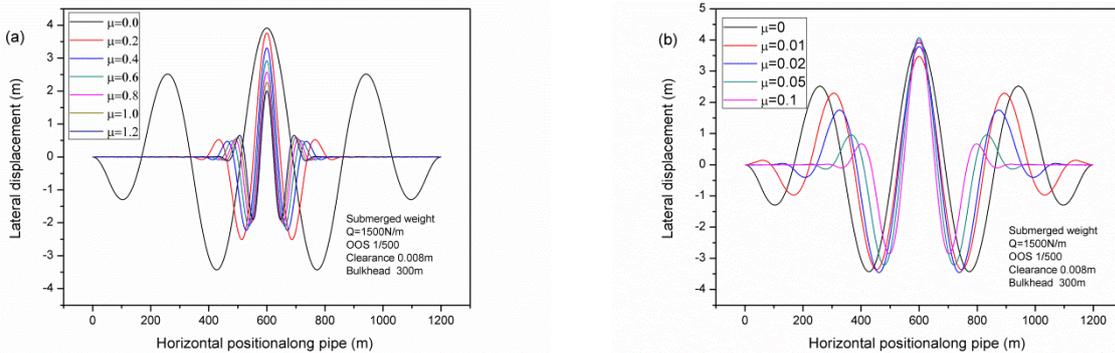


Fig. 11 Post-buckling forms with different lateral friction coefficient.  
 (a) lateral friction coefficient from 0 to 1.2; (b) lateral friction coefficient from 0 to 0.1

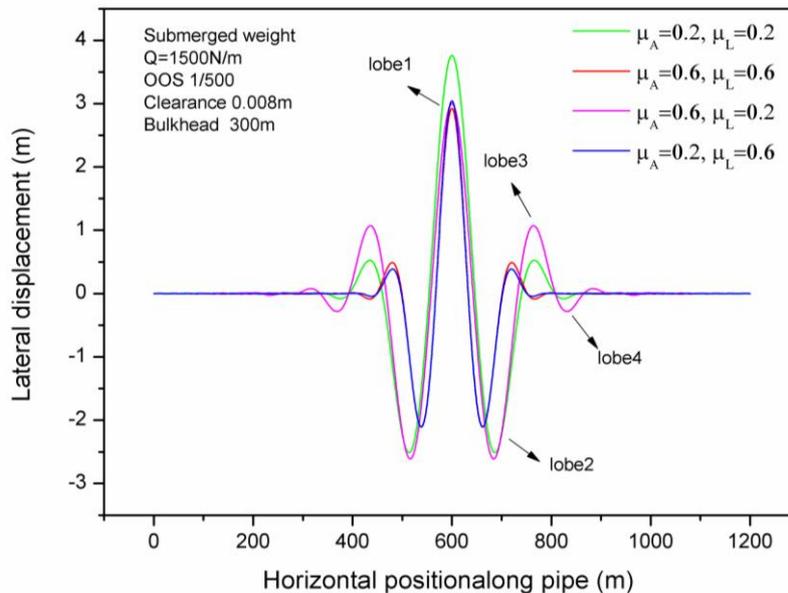


Fig. 12 Post-buckling forms with anisotropy friction property

The post-buckling forms with anisotropy friction property are shown in Fig. 12. If we put two and two together, we can find out that the axial friction coefficient affects the amplitude of lobes and feed-in response, but doesn't affect the length of lobes. While, the lateral friction coefficient affects the length and amplitude of other lobes except the middle lobe (lobe 1). This may be because of the phenomenon of "Lobe-extinction" of middle lobe has occurs, while other lobes are growing when temperature reached to 177°C (Miles 1999). The ratio of axial friction coefficient and lateral friction coefficient also affects the response of lateral buckling.

#### 4.4 Influence of clearance

The clearance is an important structural parameter of PIP pipelines. The lateral buckling response of PIP pipelines with different clearance between the inner and outer pipe is shown in Fig.12. As illustrated in Fig. 12, the smaller the clearance is, the higher the critical temperature is, and the smaller the lateral displacement is when the temperature reaches to 177°C. But different from other parameters, the clearance doesn't affect the degree of evident of the "snap through" phenomenon occurs. The critical temperature and critical force is listed in Table 7.

Table 7 The critical temperature and force with different clearance

Item	Value							
Clearance	0.001	0.002	0.005	0.008	0.016	0.024	0.032	0.048
Critical temperature $T_c$ (°C)	94.7	93.6	90.6	88.8	87.4	87.0	82.3	76.4
Critical axial force $F_c$ (E+6N)	3.29	3.24	3.11	3.03	2.97	2.95	2.74	2.48

From Table 7, we know that the clearance between inner pipe and outer pipe varies from 0.001 to 0.048, the critical force changes corresponding from 3.29E+6 to 2.48E+6. Therefore, the clearance of pipeline also significantly influences the critical force.

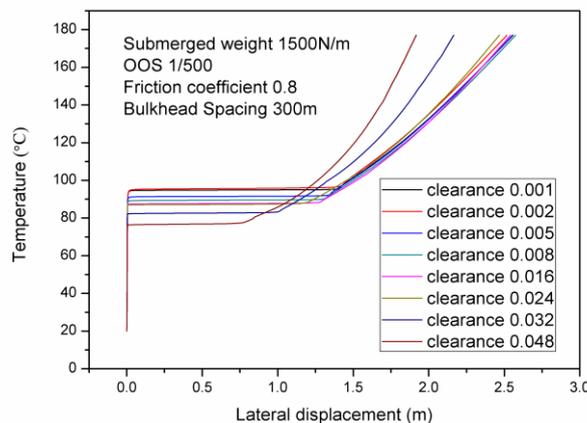


Fig. 12 Temperature-lateral displacement of mid-point of outer pipeline curves with different clearance

The post-buckling forms with different clearance are more complicated. Totally, they can be divided into two types. As shown in Fig. 13 (a), when the clearance is in the range from 0.001 to 0.024, the lateral buckling modes are almost same which are like the evolution of Mode 3. While, when the clearance is in the range from 0.024 to 0.048, the lateral buckling forms display very different, as shown in Fig. 13 (b). With the increasing of clearance, the number and amplitude of lobes also increase. The difference of inner radius of outer pipe and outer radius of inner pipe is

0.053 which is almost twice the value of turning point 0.024. So we can get a conclusion that the turning phenomena of post-buckling forms will be happen. When the clearance is in the range from 0 to turning point, the post-buckling forms are not sensitive to clearance, while, the clearance is above the turning point the post-buckling forms are sensitive to clearance. The value of turning point is approximate to half of the difference of inner radius of outer pipe and outer radius of inner pipe.

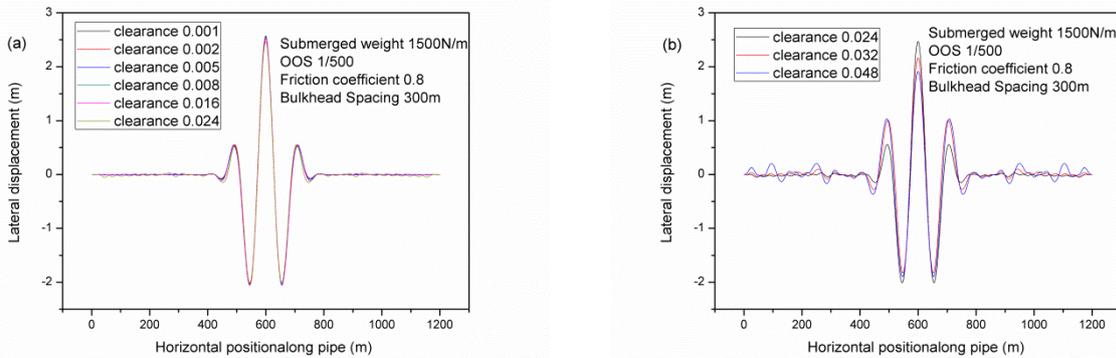


Fig. 13 Post-buckling forms with different clearance.  
 (a) clearance from 0.001 to 0.024; (b) clearance from 0.001 to 0.048

#### 4.5 Influence of bulkhead spacing

The bulkhead spacing is also an important structural parameter of PIP pipelines. The lateral buckling response of PIP pipelines with different bulkhead spacing is shown in Fig.14. From Fig. 14 (a) we know that with the increasing of bulkhead spacing from 50m to 1200m, the critical temperatures do not change. The maximum lateral buckling displacement with different bulkhead spacing when the temperature reached to 177°C has little difference. This manifests that the critical force of lateral buckling is not sensitive to bulkhead spacing.

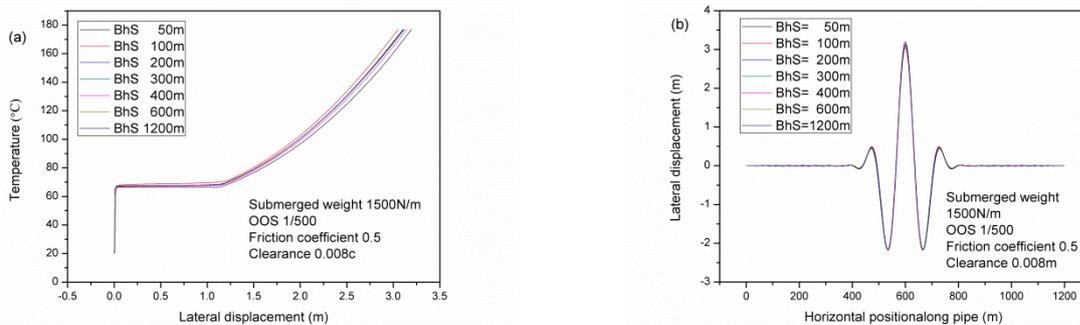


Fig. 14 Lateral buckling response with different bulkhead spacing. (a) Temperature-lateral displacement of mid-point of outer pipeline curves; (b) post-buckling forms

The post-buckling forms with different bulkhead spacing are shown in Fig. 14 (b). We can see that the lateral buckling forms with different bulkhead spacing are all same with Mode 3. This manifests that the lateral post-buckling form is also not sensitive to bulkhead spacing.

From above, we know that the lateral buckling critical force is sensitive to these parameters including submerged weight, OOS of pipelines, lateral friction coefficient and clearance. The bulkhead spacing almost doesn't affect the behaviors of lateral buckling including critical force and post-buckling response. The relationships between critical force and these parameters are shown in Fig. 15. It is suggested that there exist two positive correlations between critical axial force and

submerged weight and between critical axial force and lateral critical coefficient. However, there also exist two negative correlations between critical axial force and OOS of pipeline and between critical axial force and clearance. Meanwhile, there exists a turning point in the relationship curve between critical axial force and clearance where the relationship between critical axial force and clearance changed. The lateral buckling forms are mainly observed to be Mode 3 or its evolution which represented the lowest energy configuration.

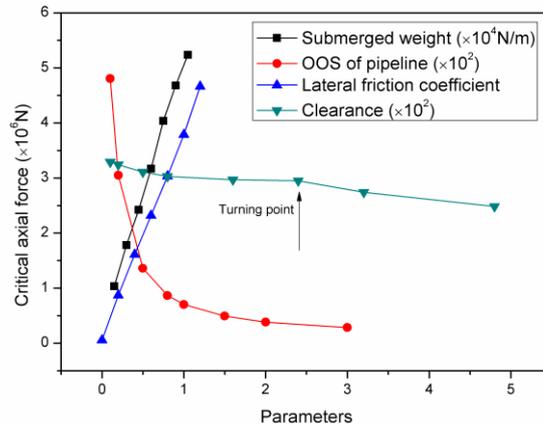


Fig. 15 The relationship between critical force and these parameters

## 5. CONCLUSIONS

Structural based finite element modeling procedures have been developed to investigate a range of parameters on the lateral buckling response of PIP system. The parameters included the submerged weights, OOS of pipeline, lateral friction coefficient between pipelines and seabed, clearance between the outer pipe and inner pipe and bulkhead spacing.

The lateral buckling critical force is affected by these parameters including submerged weights, OOS of pipeline, lateral friction coefficient and clearance. Two of them submerged weights and lateral friction coefficient have a positive correlation to the critical axial force. While, the others parameters OOS of pipelines and clearance have a negative correlation to the critical axial force. There exists a turning point in the relationship curve between critical force and clearance where the relationship between critical force and clearance changed.

The lateral buckling forms are mainly observed to be Mode 3 or its evolution which represented the lowest energy configuration. The submerged weight doesn't change the buckling mode, but affects the buckling area and amplitude. Smaller OOS affect the buckling mode and amplitude, while larger OOS do not change buckling mode, but affect buckling amplitude. The lateral friction coefficient not only affects the buckling mode but affects buckling area and amplitude. Smaller clearance doesn't change buckling mode, buckling area and amplitude. While, larger clearance makes buckling mode more complicated and different buckling area and amplitude. The value of turning point is approximate to half of the difference of inner radius of outer pipe and outer radius of inner pipe.

The lateral displacement and critical axial force of PIP pipelines are not affected by the bulkhead spacing. The post-buckling forms of PIP pipelines are not affected by the bulkhead spacing.

Future work will focus on refining the modeling procedures to incorporate pipe/soil nonlinear interaction model (for example vertical penetration, lateral and axial force-displacement relationships, et.al.). The parameter study will investigate other factors that include imperfection shape, seabed topography and installation residual forces, et.al.

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