Study of Lateral Buckling of Submarine Pipeline

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Abstract. The upheaval buckling of marine pipelines caused by the temperature stress is one of the main failure modes of pipelines. When a pipeline is operated at high internal pressure and temperature, it will attempt to expand and contract for differential temperature changes. Normally the line is not free to move because of the plane strain constraints in the longitudinal direction and soil friction effects. For positive differential temperature it will be subjected to an axial compressive load and when this load reaches some critical value, the pipe may experience vertical (upheaval buckling) or lateral (snaking buckling) movements that can jeopardize the structural integrity of the pipeline. In these circumstances, an evaluation of the pipeline behavior should be performed in order to ensure the pipeline structural integrity during operation in such demanding loading conditions. Performing such analysis, the correct mitigation measures for thermal buckling can be taken into account either by acceptance of bar buckling but preventing the development of excessive bending moment, or by preventing any occurrence of bending.

Introduction

Because the pipeline thermal upheaval buckling involves in pipe-soil interaction, the mechanism of pipeline deformation is quite complicated. Many researchers have done some researches in this area since the early eighties of the last century, which can be classified into two categories.

One is focused on the soil resistance during pipeline movement. Taylor et al.[1] chose sand as the supporting medium in view of North Sea conditions and a discrete element of 48.3 mm O.D. steel pipe with 3.2 mm wall thickness representing the pipeline. Pull out tests and axial friction tests have been undertaken and the force-displacement relationships of the pipe for different embedment depths have been produced and a semi-empirical design formula thereby has been proposed. In paper Boer et al. [2] described the results of full scale pull-out tests for a 2 m long test section of a 12.75 inch O.D. concrete coated pipe covered with gravel. Schaminee et al. [3] presented the results of a full-scale laboratory test program on the uplift and axial resistance of a 4 inch pipe embedded in cohesive or cohesionless soil in 1990. Some centrifuge model tests were conducted by Dickin, Moradi and Craig, Bransby et al., Palmer et al. and Cheuka et al. [4-9] to assess the uplift capacity of pipelines. Although based on the tests results, several empirical formulas to calculate the uplift resistance and the axial friction of the pipe have been proposed, there are great differences among the results calculated by these various formulas. The differences are owing to the following reasons. One is that the understandings of the soil failure mechanism are at variance, the other is that the soil properties are quite different in different region.

The other is the pipeline thermal upheaval buckling. Hobbs[10]presented a summary of the basic models of buckling in a long pipeline based on the similar problems occurred in railway tracks. In the following 10 years, Many researches have been done on imperfect pipelines, such as, Taylor and Tran [11] summarized three basic types of initial imperfection for subsea buried pipeline and deduced their own analytical solutions. However, all analytical solutions depend on the

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simplification and assumption, which cause differences with the practices. Little domestically research work has been reported.

In this paper, based on analytical solutions to lateral buckling of ideal subsea pipelines, the second buckling mode is analyzed by establishing numerical method and practical project, and the effects of friction coefficients of foundation soil to pipeline is also presented.
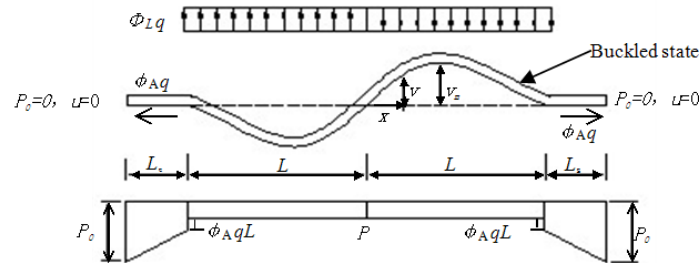

Fig.1 Deformation and force distribution for the second lateral buckling mode

Analysis on the Second Lateral Buckling Mode

Since the second lateral buckling mode is an antisymmetric mode, a half of the buckled region can be analyzed for convenience.

General solution of the second lateral buckling mode can be written as:

$$v = A_1 \cos nx + A_2 \sin nx - \frac{\phi_L q}{2n^2 EI} x^2 + A_3 x + A_4 \ . \tag{1}$$

In which EI denotes flexural rigidity, m4; v is the lateral deformation of the buckled zone, m; q is the self-weight of per unit length, kN; $P=n^2 EI$ is the axial force in the buckled region, kN; ϕ_L is the fully mobilized lateral friction coefficient of foundation soil to pipeline; L is the buckle length, m.

And the constants A_1 to A_4 can be obtained in accordance with boundary conditions: $v|_{x=0} = 0$, $v_{,xx}|_{x=0} = 0$, $v|_{x=L} = 0$, $v_{,x}|_{x=L} = 0$. Take those constants into Eq. 1, and employ the antisymmetrical condition $v_{,xx}|_{x=L} = 0$, it can be obtained that:

$$nL = 2\pi \ . \tag{2}$$

Use Eqs. 1-2, and the buckle deformation v can be obtained as:

$$v = \frac{\phi_L q L^4}{16\pi^4 EI} \left\{ 1 - \cos \frac{2\pi x}{L} + \pi \sin \frac{2\pi x}{L} + 2\pi^2 \left[\frac{x}{L} - \left(\frac{x}{L} \right)^2 \right] \right\} \quad 0 \le x \le L \tag{3}$$

x=0.3464L, where there is the buckle amplitude, can be obtained from boundary condition $v_{,x} = 0$ ($x \in (0, \ L)$), and take value of this x into Eq. 3

$$v_m = 5.531 \times 10^{-3} \frac{\phi_L q L^4}{EI} \ . \tag{4}$$

Where v_m is the buckle amplitude in the buckled length.

Analysis of Project

General Conditions of the Project

The pipe considered has an outer diameter of 323.9mm, and a wall thickness of 12.7mm. The designed internal pressure and temperature difference are 4.60MPa and 80°C respectively. Parameters of pipeline and foundation soil have been presented in Tab.1

Table 1 Properties of pipeline and subsoil

Parameters of pipeline									Parameters of foundation topsoil	
Young's modulus	Poisson ratio	Internal radius	External radius	Wall thickness	Thermal Coefficient	Bulk density	Sectional area	Inertia moment	Effective bulk	Internal friction

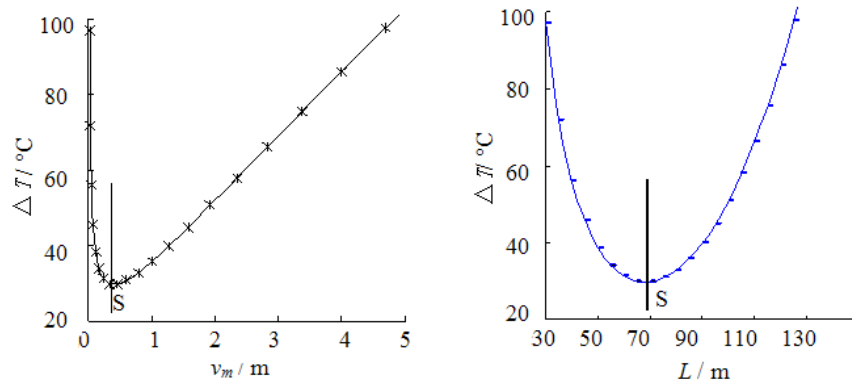| (E/kPa)	(v)	(r/m)	(r/m)	(t/m)	(a/°C)	(kN/m^3)	(A/m^2)	(I/m^4)	density /(kN·m^3)	angle(φ°)
2.06e108	0.3	0.149	0.162	0.0127	0.000011	7850	0.0124	0.000301	5.5	35

Results

Fig.2 Relationship between the buckle shape and the temperature difference

The coefficient of foundation soil to pipeline is 0.4 according to the geology conditions. Fig.2 details the relationship of vm and L vs. ΔT respectively of the second lateral buckling mode.

It can be known from Fig.2 that each curve is divided by "S" point. The temperature difference corresponding to the separation point is the safe temperature.

Equal the internal pressure into temperature difference, and the total temperature difference will be 85°C. Fig.2 indicates that safe temperature of this lateral buckling mode is 30°C, which is lower than the designed temperature difference. Therefore, this pipeline will occur lateral buckling.

Effects of Friction Coefficient on Buckling Shapes

In the analysis of buckling, friction coefficient is a parameter of vital importance. To know its effects on pipeline buckling, choose different friction coefficients: 0.01, 0.10, 0.30, 0.50, 0.70 and 1.00 to analyze. Fig.3 presents temperature difference △T against buckle amplitude v$_m$ curves.

As to unburied pipelines, friction force is the only restraint to limit its deformation, which is showed as boundary condition in calculation. So condition of friction coefficient has great impact on buckling characteristics. Fig.3 details that the larger the friction coefficient, the less possibility of pipeline buckles. But calculation of stress indicates that the stress corresponding to a fixed temperature difference increases evidently with increasing of friction.
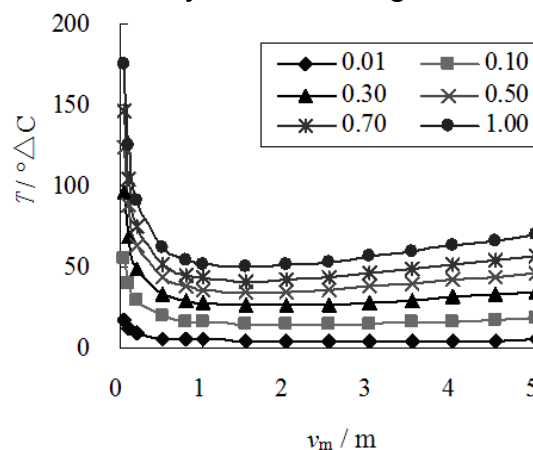

Fig.3 Relationships of vm vs. △T

Conclusions

Lateral buckling of subsea pipelines under thermal stress is analogous to the buckling stability of a column. The temperature difference against buckle length and amplitude curves are both in "U" shape, which can be divided by "S" point into two buckling conditions. The first condition is an unstable buckling mode, and it's hard to occur; while the second condition is a stable buckling

mode, which is easy to occur in practice. Since the friction between the pipeline and subsoil is only restraint to limit unburied pipelines to deform, the friction coefficient has a great impact on the lateral buckling characteristics. Generally, the larger the friction coefficient, the larger the restraint of foundation soil to the pipeline, and the higher the safe temperature.

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