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Critical upheaval buckling forces of imperfect pipelines

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ABSTRACT

A buried pipeline may have upheaval buckling when it works in high temperature and high pressure (HT/HP) conditions. The upheaval buckling behavior is sensitive to initial structural imperfections. There have already been some approximation formulas of critical axial forces for some particular shape imperfections. However, these formulas did not take into account of the imperfection out-of-straightness (OOS) as a whole. Based on dimensional analysis and finite element (FE) analysis some brand new formulas are presented for the critical axial forces. These formulas are different from the traditional formulas in form and they include the out-of-straightness directly and integrally. Finally a case study is presented which illustrates the application of these formulas.

1. Introduction

It is well known that the high operating temperature and pressure usually cause a buried pipeline to have upheaval buckling. That is because large axial compressive forces are produced by the constrained expansion setting up by the thermal and internal pressure loads in the pipeline. With a small structural imperfection the pipeline will uplift from its initial position suddenly if the large axial compressive forces are bigger than the critical buckling forces, that is called a snap. The snap is a dramatic dynamic behavior which may cause damage to an in-service pipeline, so it is important to study this behavior.

In the past 30 years, a lot of analytical results have been presented on the pipeline upheaval buckling problem. Hobbs [1] analyzed both lateral and upheaval buckling problems of ideal straight pipelines based on the related work about railroad tracks. He found that for normal friction coefficients the lateral mode occurred at a lower axial load than the upheaval mode and was dominant in pipelines unless the pipelines were buried. He also proposed some useful theoretical solutions for the critical axial forces. Yun and Kyriakides [2] studied the upheaval buckling of buried pipelines through a large deflection extensional beam nonlinear formulation. The pipelines were assumed to possess some different localized imperfections, and their influence on the critical axial forces was analyzed. They showed that the critical loads were imperfection sensitive. However, they did not give out any analytical solution or approximation formula. Taylor et al. [3–6] did a series studies on the upheaval buckling problem of pipelines with structural imperfections. They pointed out that the out-of-straightness of the imperfection w_0/L_0 is an essential imperfection parameter. However their critical axial force formulas did not include the parameter integrally. Palmer et al. [7] presented a semi-empirical simplified design method based on numerical analysis. They defined two dimensionless parameters for the critical axial force and the buckling wavelength, and they pointed out that the specific shape of an imperfection only affects the coefficients and not the general form of the parameters. However, the two parameters took into imperfection height and length in separating form as well. Richards [8] studied the imperfection shape effects on the upheaval buckling behavior. He pointed out that the imperfection shape has a big influence on the buckling behavior again. Maltby and Calladine [9] did an investigation into the upheaval buckling of buried pipelines by experiments and theoretical analysis. They suggested some critical axial force formulas for the initial imperfect pipelines. However, these formulas still did not have out-of-straightness as a whole. Croll [10,11] presented a simplified model for the imperfect pipeline upheaval buckling analysis. He reinterpreted the classical Martinet analysis and extended the approach for the imperfect pipelines. He provided two simple and explicit analytical expressions for the upper and lower buckling load bounds in which the out-of-straightness was still separating in two equations. Wang et al. [12,13] investigated the vertical buckling of pipelines with soft seabed. The initial straight and imperfect pipelines were both studied, and the soil resistance effects on pipelines' stability, buckling mode and amplitude were presented. They showed a big influence of imperfections in their models again. Liu et al. [14,15] analyzed the pipeline upheaval buckling by the nonlinear finite element method. They showed that for the same imperfection height the pipeline with one point support is most likely to have upheaval buckling. Most recently, Karampour et al. [16] studied the lateral and

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Nomenclature

w_0	height of pipeline imperfections
L_0	wavelength of pipeline imperfections
w_0/L_0	out-of-straightness of pipeline imperfections
EI	flexural rigidity of pipeline section
q	distributing load on pipelines (including self-weight per unit length)
P_L	critical axial force of pipeline upheaval buckling
P_{L1}	critical axial force of pipeline upheaval buckling with imperfection No. 1
P_{L2}	critical axial force of pipeline upheaval buckling with imperfection No. 2
P_{L3}	critical axial force of pipeline upheaval buckling with imperfection No. 3
F	axial force of pipeline
T	temperature load on pipeline
α	thermal expansion coefficient of pipeline steel
E	elastic modulus of pipeline steel
I	second moment of area of pipeline section
A	area of pipeline section

upheaval buckling of pipelines respectively. For the upheaval buckling, some analytical solutions were given out and the response under three types of localized initial imperfections was compared. The shape influence on the critical loads was verified again in their work.

From the previous researches it is clear that the critical axial forces of pipeline upheaval buckling are sensitive to the imperfection shape and the out-of-straightness of the imperfection. The previous researchers such as Palmer, Maltby, Taylor, Croll et al. have shown some critical axial force formulas for some particular shape imperfections, in which the imperfection height was only taken into consideration [5,7,9,10]. However, the imperfection wavelength also has a big influence on the critical loads, and it should be included into the formulas. In a word, the out-of-straightness should be included as a whole in the critical axial force formulas. In this paper, the imperfection influence on upheaval buckling of buried pipelines is researched. The upheaval buckling effects of three groups of pipeline segments with different shape imperfections are simulated by using the finite element software ABAQUS. Using the numerical results some design-oriented approximation formulas are figured out for the critical axial forces. Finally a case study which illustrates the usage of these formulas is presented.

2. Dimensional analysis

As mentioned above, both the imperfection shape and the out-of-straightness of the imperfection have big influences on the critical loads of pipeline upheaval buckling. However, the critical load formulas presented by previous researchers are usually corresponding to the sinusoidal profile imperfection and did not include the out-of-straightness directly and integrally. In this section a new form dimensionless parameter for the critical axial force is deduced according to the basic procedure of dimensional analysis [17].

Based on Euler buckling theory and the previous research results on the pipeline upheaval buckling problem [5,7], it is known that for a particular shape imperfection the critical axial force P_L of a upheaval buckling pipeline is only related to EI, q and w_0/L_0. That is to say these parameters form a complete set of independent quantities, then we get,

$$P_L = f\left(EI, q, \frac{w_0}{L_0}\right) \tag{1}$$

Adopting the system of units M, L, t (mass, length and time), the dimensions of the each quantity in Eq. (1) are listed:

$$\text{Independent}: [EI] = ML^3t^{-2}, [q] = Mt^{-2}, \left[\frac{w_0}{L_0}\right] = 1,$$

$$\text{Dependent}: [P_L] = MLt^{-2}.$$

The two quantities EI, q comprise a complete dimensional independent subset of the three independent variables. The dimensions of the remaining independent variables w_0/L_0 and the dependent variable P_L can be made up of them, viz.:

$$\text{Independent}: \left[\frac{w_0}{L_0}\right] = 1,$$

$$\text{Dependent}: [P_L] = MLt^{-2} = \left(ML^3t^{-2}\right)^{1/3}\left(Mt^{-2}\right)^{2/3} = \left[(EI)^{1/3}(q)^{2/3}\right].$$

According to Buckingham's Pi-theorem [17], finally a dimensionless equation which has only one independent variable can be derived:

$$\frac{P_L}{(q^2EI)^{1/3}} = g\left(\frac{w_0}{L_0}\right). \tag{2}$$

So the critical axial force formula has the following form:

$$P_L = g\left(\frac{w_0}{L_0}\right)\left(q^2EI\right)^{1/3}. \tag{3}$$

Notice that Eq. (3) is very different from the traditional critical axial force formulas, such as, $P_L = 4.092\ (EIq/w)^{1/2}$, $P_L = 2.828\ (EIq/w)^{1/2}$, $P_L = 3.478\ (EIq/w)^{1/2}$ [5,10,11]. In Eq. (3) the powers of q, w and EI are $2/3$, 0 and $1/3$ respectively, rather than all $1/2$. The coefficient $g\ (w_0/L_0)$ is a function which depends on the out-of-straightness integrally, rather than a constant or a function depending on imperfection height only. On the other hand, as indicated by Palmer et al. [7,8], the imperfection shape only affects the coefficients and not the general form of the critical axial force formulas. So this coefficient function is unique for a particular shape imperfection. That implies if the imperfection shape is determined, this function can be determined, and if this function is determined, the critical axial force formula of a pipeline with a particular shape imperfection can be determined. To determine a coefficient function $g\ (w_0/L_0)$, we need to know a set of values of $P_L/(q^2EI)^{1/3}$ which are corresponding to a set of values of w_0/L_0. In fact, the critical axial forces are usually unknown, and the others are known. So we can set some sets of out-of-straightness values and find out the corresponding critical axial force values. In the following section the FE buckling simulation of some imperfect pipeline segments has been carried out by ABAQUS.

3. FE modeling

According to the previous researchers, such as Palmer [7], the finite element analysis results are convenient to form approximations of the function $g\ (w_0/L_0)$. Here we consider three different shape imperfections to determine the coefficient function $g\ (w_0/L_0)$.

3.1. Shape of imperfections

In this paper the following three typical imperfections have been assumed in the upheaval buckling analysis [16]. Notice that among them imperfection No. 2 is the most common initial imperfection assumption used by the previous researchers, the sinusoidal profile