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Perturbation analysis for upheaval buckling of imperfect buried pipelines based on nonlinear pipe-soil interaction

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ABSTRACT

Submarine pipelines are often operated under conditions of high temperature and high pressure, which may induce considerable axial compressive force. If the lateral movement is constrained, for instance, burying pipe or dumping gravel, upheaval buckling may happen. Pipe-soil interaction affects the upheaval buckling behavior of submarine pipelines. However, pipe-soil interaction models currently existing fail to reflect the drop process of uplift resistance when the vertical displacement is over mobilization distance. To solve this problem, a new nonlinear pipe-soil interaction model is presented and the governing differential equation of an imperfect pipeline on soft foundation is deduced. The solution to the governing differential equation is proposed based on nonlinear perturbation expansions. The effect of soil conditions, burial depth and initial imperfections on critical force as well as localization pattern of upheaval buckling are discussed. Results show that the capacity of pipeline against thermal buckling increases with the burial depth or maximum uplift resistance and decreases with the OOS of pipeline or mobilization distance. Critical buckling force is almost unaffected by pipe-soil interaction form, but the post-buckling response depends on pipe-soil interaction forms. The pipe-soil interaction model can be used not only in pre-buckling design but also in post-buckling control.

1. Introduction

Submarine pipelines are often operated under the conditions of high temperature and high pressure to avoid wax or hydrate problems. This inevitably causes very large axial compressive force in the pipelines and may lead to snake laterally since this mode happens at a smallest axial compressive force. To avoid this situation, a common engineering technique is to bury pipelines below the seabed or to dump gravel on the top of the pipelines. (Palmer et al., 1990, 2003; Zhao and Feng, 2015). However, for the buried submarine pipelines, if there is not enough resistance against uplift movement, upheaval buckling happens. And this may lead to ultimate failure modes of pipelines, such as collapse, fracture or fatigue (Det Norske Veritas.DNV Recommended Practice RP-F110. 2007). So it's significant to study this phenomenon.

In the past four decades, a lot of researchers have investigated the upheaval buckling problem. Hobbs (1984) analyzed upheaval buckling of heated submarine pipeline on a rigid seabed based on the work of railroad track. The analytical solutions to critical force, buckled length and amplitude were obtained. But in his research, the initial imperfections of pipelines were not taken into account, which makes the critical force from his theory more conservative than the real value. To overcome this shortage, a series of theoretical and experimental studies were performed by Taylor and Gan (1986, 1987), Taylor and Tran (1993, 1996), whose focuses were put on the effect of initial imperfections on upheaval buckling. Their studies manifest that the amplitude and wavelength of an initial imperfection are very important parameters for upheaval buckling behaviors. By modeling the pipeline as a long heavy beam rested on a rigid foundation, Ju and Kyriakides (1988) studied the upheaval buckling behaviors and obtained the conclusion that critical force of upheaval buckling was sensitive to the imperfection shape and amplitude. Palmer et al. (1990) presented a semi-empirical design method by defining two dimensionless parameters for critical axial force and buckling wavelength. Croll (1997), Karampour et.al. (2013) and so forth, presented different design formulas with separated parameters for initial imperfection. Zeng et al. (2014) took into account the parameters of initial imperfection as a whole and presented some new formulas for critical force of upheaval buckling based on finite element analysis results. Zhang and Duan (2015) defined a new parameter to quantify the imperfection shape and proposed a general formula to express the integrated effects

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Nomenclature

D	Pipe diameter
H	Cover height for cohesiveness soil (It equals to the depth to top of trench minus depth to top of pipe)
K	Lateral earth pressure coefficient
Nc	Theoretical bearing capacity coefficient
F_m	Maximum uplift resistance
u_m	Mobilization distance
F	The uplift resistance of pipe caused by soil
u	Vertical displacement of pipe
F_q	Dimensionless form of F;$F_q=F/F_m$
q	Dimensionless form of u; $q=u/u_m$
P	Axial compressive force
P^C	Critical axial force
W	Weight of pipe, per unit length
L_0	The initial imperfection wave length
L	The total length of pipe
t	Pipe wall thickness
w_0	Initial imperfection shape function
w	Deflection of pipe in vertical plane (not including initial deviation)
w_{00}	Initial imperfection maximum amplitude
$f(w)$	Nonlinear uplift resistance, per unit length
α	Coefficient of thermal expansion of pipe material
β	Fraction of failure displacement
γ	Submerged unit weight of soil
δ	Fraction of uplift capacity F_m
η	Empirical factor based on field tests
ϕ	Angle of internal friction
s	Perturbation parameter; $s=\sqrt{P^C-P}$
s_u	Undrained shear strength at center of pipe
E	Young's modulus of pipe material
I	Second moment of area of cross-section of pipe
OOS	Out-of-straightness, it equals to w_0/L_0
ΔT	Temperature rise

of imperfection on critical force of upheaval buckling using the new parameter and the out-of-straight (OOS) parameter. However, in these studies, the seabed under the pipelines is seen as a rigid foundation, which has a little difference in the real situation.

Actually the pipe-soil interaction is another key factor which affects the upheaval buckling behaviors. Force-displacement relation model, as the most essential reflection of pipe-soil interaction, has attracted a lot of attentions of many investigators. Kondner (1963) presented a rectangular hyperbola model to express the relationship between uplift resistance and pipeline displacement. Tvergaard and Needleman (1980) discussed the problem of elastic column on a softening foundation and pointed out that the nonlinear pipe-soil interaction was important for localization of buckling patterns. In their studies, the piecewise linear model was adopted as the pipe-soil interaction model. Trautmann et al. (1985) presented bilinear model from experimental results of buried pipelines. Maltby and Calladine (1995) studied the upheaval buckling behaviors of buried pipeline by experiments and theoretical analysis and presented an exponential model to express the uplift force-displacement relation. A formula was presented for predicting the critical force of buried pipeline which involves three parameters: the flexural stiffness of the pipe, the initial imperfection amplitude of the pipe and the "plateau" value of the soil resistance curve. While according to Schaminee et al. (1990) who did full-scale laboratory tests on the uplift resistance embedded in saturated soil for a wide range of soil conditions, their test results manifested that the uplift resistance in clay, as a function of the pipe displacement, showed a peak when the pipe displacements were up to mobilization distance, and then appeared a drop process when the pipe displacements were over the mobilization distance. Therefore these pipe-soil interaction models failed to reflect this characteristic. Palmer et al. (2003) pointed out the uplift peak of resistance and the mobilization distance were two important parameters for upheaval buckling. Around the two parameters, many investigators carried out a series of experimental and theoretical research, for instance Cheuk et al., (2007, 2008), Merified et al. (2008), White and Cheuk (2008) as well as White et al. (2008). Their works made the mechanism of soil failure better to be understood and the datum of pipe-soil interaction more abundant which brings us a good chance to analyze the effect of pipe-soil interaction on upheaval buckling behaviors more deep. Wang et al. (2011), Shi et al. (2013) analyzed the effects of seabed soil resistance as the critical temperature increases. In their analysis, the soil resistance was supposed to be constant with depth. Although, some theoretical solutions were given out, their model couldn´t reflect the real pipe-soil interaction characteristic. Zeng and Duan (2014) studied the lateral buckling of submarine pipeline and proposed a nonlinear force-displacement relation that contained cubic and quantic terms based on the tri-linear model. Their pipe-soil model was suited to analyze lateral buckling with not large lateral displacements and didn't work well for upheaval buckling. Liu et al., (2014, 2015) carried out a series of vertical and axial pullout tests on pipe buried in soft clay which was similar to the soil present in Bohai Gulf, China. Based on the results of laboratory test, they proposed nonlinear force-displacement relations by piecewise

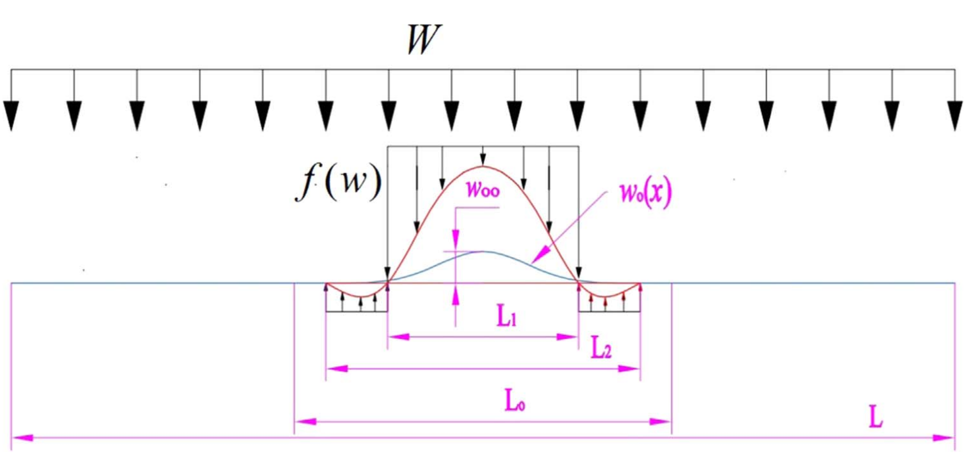

Fig. 1. Configuration and loads of the upheaval buckling model.

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