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Axial friction response of full-scale pipes in soft clays

Jianhua Wang [a,*], Zhaohuan Yang [b]

[a] State Key Laboratory of Hydraulic Engineering Simulation and Safety, Geotechnical Engineering Institute of Tianjin University, Tianjin 300072, China
[b] State Key Laboratory of Hydraulic Engineering Simulation and Safety, Geotechnical Engineering Institute of Tianjin University, Tianjin300072, China

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ABSTRACT

The axial friction response of subsea pipelines in soft clays is a very important aspect for designers of subsea pipelines but the response is not well understood so far. There is a pressing need for the comprehension of the response. In this paper, model tests are performed using full-scale pipes coated with polyethylene (PE) to study the effects of the set-up period, the pipe diameter, the buried depth of the pipe, the shear strength of soft clays and the loading rate on the axial friction response of pipelines in soft clays. The variations of the axial friction coefficient are analyzed using the effective stress method based on model test results. The results show that the axial friction resistance increases with the increasing pipe diameter but the effect of the pipe diameter on the axial friction coefficient can be neglected. The ultimate axial resistance also increases with the increase of the buried depth of pipelines, the undrained shear strength of soft clays and the loading rate. The axial friction coefficient increases with the increasing loading rate. However, the axial friction coefficient decreases with the increasing buried depth. The method to determine the axial friction coefficient is developed by analyzing model test results, which considers the effects of the diameter, the buried depth, the undrained shear strength of soft clays and the loading rate. The study results not only extend the industry data base but also supply a basis to determine the axial friction coefficient of PE-coated pipes in soft clays for ocean engineering geological investigations.

1. Introduction

Soft clays are the typical stratum in the shallow range of deep-water seabed, which always have the high water content and the low shear strength. The subsea pipelines in soft clays generally operate at relatively high pressures and temperatures during transporting oil or gas. These conditions require pipeline to be designed to buckle in a controlled manner during its service life, especially the phase of startup and shutdown [1–4]. The axial friction resistance of pipelines has a significant impact on the axial buckling design of subsea pipelines in soft clays. The axial frictional resistance is mainly influenced by soil properties, pipe properties, the buried depth and the pipe joint type etc. [5,6]. Previous studies show that the axial friction response of subsea pipelines in soft clays is very complex but is not comprehensively understood so far [7–9]. Therefore, there is a pressing need for the comprehension of the axial friction response of subsea pipelines in soft clays.

For designers, the most important consideration is to select an appropriate axial friction coefficient to calculate the axial resistance of pipelines. In attempting to obtain the friction coefficient of pipelines, theoretical and experimental researches are available. Many researches focused on the interaction of pipe with cohesionless soil over the past several decades [2,10–15]. Only a minority of scholars studied the pipe-clay interaction using model tests. Schaminée et al. investigated the axial friction resistance of a pipe coated with the epoxy polyester in the remolded clay using small-scale model tests [16]. The pipe diameter is 10.16 cm. The axial resistance was divided into the stress-dependent friction part and the stress-independent adhesion part. The coefficients of two parts were recommended as constants without considering the effect of loading rate, the properties of soil and pipe. Model tests were performed to study the axial resistance response of the partially embedded pipe using the polyethylene (PE) pipe with 9 cm diameter and the marine soft clay taken from offshore of West Africa in the SAFEBUCK Joint Industry Project [17,18]. Results showed that equivalent friction factor which is the ratio of friction resistance to submerged weight of pipe varied from 0.1 to 1.5. Liu et al. also conducted some small-scale model tests to research the axial resistance response of steel pipes with 3, 5 and 8 cm diameter in the clay [19,20]. Because the model pipe diameter is far less than the

* Corresponding author.
E-mail addresses: tdwjh@tju.edu.cn, tdwjh@eyou.com (J. Wang), cauczhyang@sina.com (Z. Yang).

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pipe diameter in engineering and the effect of the shear strength of the clay on the axial resistance is not considered, their results have some limitation. Vipulanandan et al. conducted small-scale model tests to investigate the effects of the loading rate and the pipe weight on the axial response of plastic pipes with 4 cm diameter placed on soft clay [21]. The variations of the axial resistance with the loading rate and the pipe weight were only qualitatively analyzed based on test results.

The methods calculating axial pipe-soil resistances are recommended in some pipeline design codes [22–25]. It is assumed that the axial interaction of soft clay is described by Coulomb frictional law in the most of the specifications. However, it is not provided how to determine the friction coefficient in the axial resistance of soft clays.

Although some researches have been done on the axial interaction of pipes and soft clays, many conclusions were obtained by small-scale model tests. The effects of the shear strength of soft clays, the buried depth of pipelines etc. on the axial frictional interaction are not comprehensively understood. It is still difficult for designers to objectively determine the axial friction coefficient of subsea pipelines in soft clays. The axial interaction of pipelines in soft clays should be further researched by full-scale model tests.

In this study, the methods to calculate the axial pipe-soil resistance are first reviewed. The axial resistance responses of pipes in soft clays with different the shear strength are studied using the full-size steel pipes coated with polyethylene by model tests, which include the effects of the pipe diameter, the buried depth of pipes, the undrained shear strength of soft clays and the loading rate on the axial frictional resistance. The relationship of the axial friction coefficient of the PE-coated pipe in soft clays with these influence factors is determined based on the model test results. The results not only extend the industry's data base but also supply a basis for determining the axial friction coefficient of PE-coated pipes in soft clays for marine engineering geological investigations.

2. Reviews on methods calculating axial resistance

The peak resistance is currently determined by two different approaches, which are the total stress method and the effective stress method for buried pipelines, borrowed from the determination of skin friction for pipe piles in cohesive soils [26,27].

2.1. Total stress method

The total stress method is also called α-method. It assumes that the pipe walking axially on/in cohesive clay is undrained and the axial frictional resistance per unit length is explained to be proportional to the product of undrained shear strength of clays and contact area, without considering of the normal load applied on the interface of pipe and soil [1,28]. The axial resistance T is calculated using the equation:

$$T = \alpha s_u A_c \tag{1}$$

where α is called adhesion factor which describes the axial frictional characteristics of the pipes in soft clays; s_u is the undrained shear strength of clays; and A_c is the pipe-soil contact area per length.

The total stress method is a simplified application of the approach to calculate the piles skin friction for pipeline, not indicating the axial friction of pipe-soil is only caused by the cohesion of a soft clay.

2.2. Effective stress method

Another method currently available is the effective stress approach, or called β-method. The axial frictional resistance force is calculated based on the Coulomb frictional law and different assumptions about the distribution of the normal force around the pipe [1,10,16,26].

Peng divided the normal force acted on the pipe surface into top force and bottom force. The top force equals the weight of the soil surcharge over the pipe and bottom force includes the weight of the pipeline and soil weight above the pipeline [10]. Peng suggested that the axial resistance was calculated using Eq. (2).

$$T = \mu(2\gamma' DH + W_p)L \tag{2}$$

where μ is the axial friction coefficient; W_p is the submerged weight of the pipe; D is the outside diameter of the pipe; H is the buried depth of the pipe from the mudline to the upper of pipe; and L is the length of the pipe.

The second method assumes that the sum of normal stress around the pipe periphery equals the component along the vertical direction of weight acting on the soil around the pipe. The axial resistance is calculated using Eq. (3) [26].

$$T = \mu(W_s + W_p + W_w) \tag{3}$$

where μ is the axial friction coefficient; W_s is the weight of the prism of soil above the pipe; W_p is the submerged weight of the pipe; and W_w is the weight of the contained water or oil.

The third method asumes that the average stress acting on the side of the pipeline σ_r and the axial resistance T for buried pipelines can be expressed as Eqs. (4) and (5), respectively [26].

$$\sigma_r = \frac{1}{4}\left[2\gamma' H + 2K_a\gamma'\left(H + \frac{D}{2}\right) + \frac{W_p}{D}\right] \tag{4}$$

$$T = \mu\pi DL\left[\frac{\gamma' H + K_a\gamma'\left(H + D/2\right)}{2} + \frac{W_p}{4D}\right] \tag{5}$$

where γ' is the effective unit weight of soil; H is the embedment of the pipe from the mudline to the upper of pipe; K_a is the coefficient of earth pressure at rest; D is outer diameter of pipe; and W_p is the submerged weight of the pipe.

Both the total stress method and the effective stress approach are commonly accepted for the soil axial resistance in the practice, which use the parameter called adhesion factor or friction coefficient to describe the axial interaction between the pipeline and the soft clay. Considering the simplicity and acceptability for the subsea pipeline geotechnical designers in current ocean engineering practices [22–25], the effective stress approaches discussed above are used to analyze the axial frictional response of full-scale pipes in soft clays in the following text.

3. Model tests

3.1. Apparatus

The model test apparatus consists of the model test tank with the loading frame, the electric-servo loading system, measuring transducers and the model test control system with the data acquisition function.

In order to determine model test tank size, the influences of the tank boundary are analyzed using the finite element method before manufacturing the model test tanks. The finite element models of pipe-soil interaction with different widths and lengths are constructed, as shown in Fig. 1. The vertical boundaries are laterally constrained and the bottom boundary is vertically constrained. The non-separation in normal direction is used and the tangential slide is allowed between the outside wall of pipes and the stratum. The tangential contact parameter is determined according to the maximum shear stress which is equal to αs_u, where α is the adhesion factor between the pipe and the stratum and s_u is the undrained