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Study on the contact behavior of pipe and rollers in deep S-lay

Hui Liang [a,*], Qianjin Yue [a], Gerry Lim [b], Andrew C. Palmer [c]

[a] State Key Laboratory of Structural Analysis for Industrial Equipment, Dalian University of Technology, Dalian, 116023, China
[b] Subsea 7 com., Singapore
[c] Department of Civil & Environmental Engineering, National University of Singapore, Singapore, 117576, Singapore

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ABSTRACT

S-lay is a widely used method for offshore pipe installation. In recent years, S-lay has gradually applied to the deepwater condition. Because of the increasing pipe weight in deep S-lay, there exist severe and complex contact problems between the overbend pipe and roller supports of the stinger. In deep S-lay design, it is difficult to solve this nonlinear mechanics problem, and there remain confusion and difficulties to predict the roller contact forces and the pipe strain level in S-lay design.

The present paper develops a refined finite element model with the framework of ABAQUS, which considers the complex surface contact behaviors in the overbend section. The features of the contact state of different rollers within one roller box are discussed, and the resultant support forces from each roller box are calculated and compared with the commercial design code. The overbend strain level of five S-lay cases is investigated and the pipelaying safety is checked by DNV rules. The simulation results show that the proposed model can provide more accurate and reasonable predictions on roller forces and pipe strain distribution for deepwater S-lay design.

1. Introduction

As a conventional pipe installation technique, S-lay occupies an important position in the market of offshore pipe installation. In a S-lay construction, the pipe is welded together on the lay barge, and then laid down over the lay ramp and stinger to the seabed. The pipeline is supported by many rollers from the roller boxes of the stinger, and bent to form an "S" shape, as shown in Fig. 1. The entire pipeline from the lay barge to the sea bed is mainly divided into two sections: the overbend section supported by the stinger, and the sagbend section suspended in water.

Great efforts have been devoted to the study of S-lay problems in the past few decades. Many early literatures focused on the analytical solutions of the sagbend pipeline. The beam theory [1,2], the elastic rod theory [3] and the catenary theory [4] are applied to derive the governing equations of the unsupported free span. The boundary layer issue of this span is discussed in Re. [5]. And different numerical algorithms, such as the asymptotic expansion method [2–4], the finite differential method [6], and the finite element method [7–9], are developed to solve the boundary-value problem of S-lay.

The nonlinear effects are also concerned in the analysis of S-lay. During S-lay, the ovalization of the cross sections in the overall pipeline is taken account of in Re. [10]. Analytical contact models are proposed for the hypothetical contact in the overbend part [11]. Moreover, the finite element method is competent for building more complex contact models of S-lay [7,12]. On the basis of the enhanced numerical models, sensitivity analysis and optimization design of the laying factors are investigated. The influences of the tension force, the stinger geometry, the roller heights [13], as well as the ocean currents and the seabed conditions [14–17] on the overall configuration and strain of the pipeline are studied. Mathematical programming method [18,19] and the particle swarm optimization method [20] are used to optimize the S-lay design.

The dynamic effects from hydrodynamic loads and the vessel motion are another major concerns for S-lay. Quasi-static analysis is suitable for solving the dynamic problems of S-lay with the assumption of small motions of the pipeline [21,22]. The vibration frequencies of the pipeline induced by wave are derived in Re. [23], and the dynamic behavior of the submarine pipelines is studied by the frequency-domain method [24–26]. However, the frequency-domain method cannot provide an accurate solution for the dynamic problems of S-lay due to the linearization of the nonlinear laying factors. Therefore, the time-domain algorithm is

* Corresponding author.
E-mail address: lianghui@mail.dlut.edu.cn (H. Liang).

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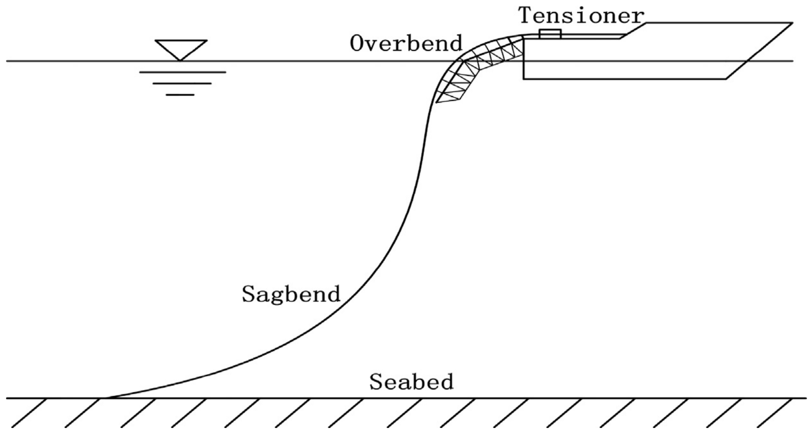

Fig 1. Sketch of S-lay method.

developed to take the nonlinear laying factors of S-lay into consideration [27–30].

However, the aforementioned methods still exist some uncertainties, because they simplified surface contact behavior between pipeline and rollers as the idealized point contact or line contact, and assumed the contact pressure in each contact area uniformly distributed for convenience. As a result, strain concentrations on the pipe section are prone to be overestimated, which may lead to serious and unreasonable design failures.

This paper adopts a refined contact model to study the contact behavior of the overbend part in deepwater S-lay, and discusses the influences from stinger stiffness and roller box rotations on the roller contact force and pipe strain level.

2. Mathematical model of S-lay

In deep S-lay cases, the pipeline generates very large deflection and rotation, which belongs to a geometrically nonlinear problem. Based on the nonlinear beam theory, the equilibrium conditions of a pipe element are used to establish the governing equations of the submarine pipeline. Considering the reasonable boundary conditions, the deformation and internal forces of the pipeline can be solved with the aid of mathematical techniques.

The left picture in Fig. 2 is a sketch of the entire pipeline of S-lay. O,A and B are denoted as the tensioner exit, the inflection point and the touch-down point respectively. Set O as the origin of the rectangular coordinate system. X-axis is along the horizontal direction and Y-axis is along the vertical direction.

For the sagbend region (which is the curve “AB”), an arbitrary pipe element is picked out. If the hydrodynamic effect and the ocean current are neglected, we can get a free-body diagram as the right picture in Fig. 2. Based on the force equilibrium condition, the following equations are derived:

$$\sum F_x = (H + \mathrm{d}H) - H = 0 \tag{1a}$$

$$\sum F_y = (V + \mathrm{d}V) - V - W\mathrm{d}s = 0 \tag{1b}$$

$$\sum M_A = (M + \mathrm{d}M) + W(\mathrm{d}s)^2 \cos\left(\theta\right)/2 + V\cos\left(\theta\right)\mathrm{d}s - M - H\sin\left(\theta\right)\mathrm{d}s = 0 \tag{1c}$$

Where H is the horizontal force, V is the vertical force, M is the bending moment, W is the wet weight in unit pipe length.

From Eq. (1a), the horizontal force in sagbend is a constant value.

From Eq. (1b), the vertical force in sagbend is a function of W and s:

$$\mathrm{d}V = W\mathrm{d}s \tag{2}$$

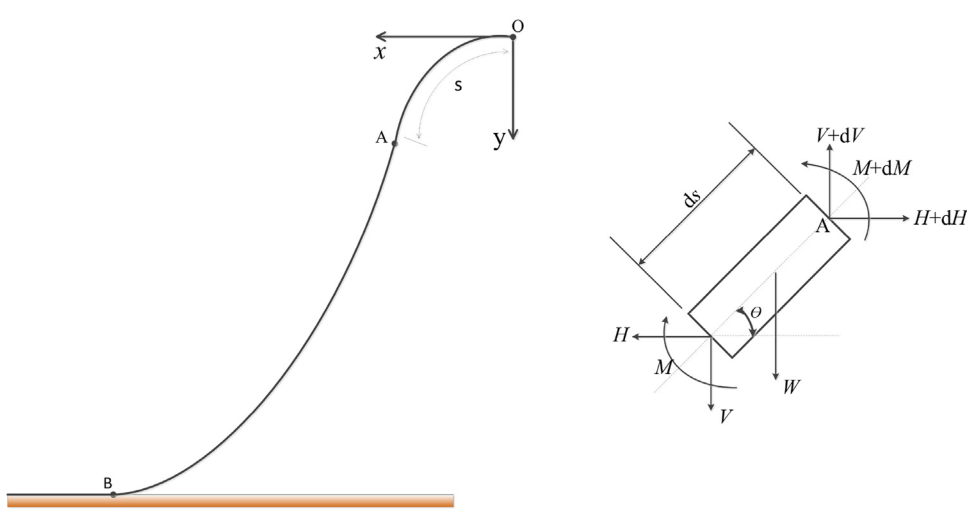

Fig. 2. Force equilibrium diagram of a pipe element.