Applied Ocean Research 48 (2014) 292–300

Contents lists available at ScienceDirect

Applied Ocean Research

journal homepage: www.elsevier.com/locate/apor

Refined analytical models for pipe-lay on elasto-plastic seabed

Feng Yuan[a,*], Mark F. Randolph[b], Lizhong Wang[a], Liang Zhao[c], Yinghui Tian[b]

[a] *College of Civil Engineering and Architecture, Zhejiang University, China*
[b] *Centre for Offshore Foundation Systems, The University of Western Australia, Australia*
[c] *School of Civil Engineering, Tianjin University, China*

ARTICLE INFO

Article history:
Received 14 March 2014
Received in revised form 15 July 2014
Accepted 12 October 2014
Available online 7 November 2014

Keywords:
Analysis
Elasto-plastic seabed
Pipe-lay
Pipelines
Pipe–soil interaction

ABSTRACT

This paper presents a refined analytical solution for pipe-laying on an elasto-plastic seabed. The solution builds on previous work, extending it to include elastic rebound of the pipe. The approach simplifies the pipeline as the combination of four segments: a natural catenary through most of the water column; a boundary-layer segment in the water close to the seabed where the bending stiffness of the pipe modifies the shape of the catenary; a beam under uniform tension through the touch down zone up to the point where maximum pipe–soil load concentration occurs, within which the soil responds plastically; and finally a rebound segment, also modelled as a beam under uniform tension, where the soil rebounds elastically as the pipe–soil contact force reduces back to the submerged pipe weight. Continuity of displacement, gradient, bending moment, shear and deduced tension along the pipeline are preserved. In comparison with previous models, such as a rigid-plastic seabed model, the distribution of seabed resistance is continuous. Results from the solution are presented for the case of seabed resistance to pipe penetration increasingly proportionally with depth, as is approximately the case at very shallow depths within the seabed. The lower the gradient of seabed resistance, the greater is the pipe embedment, but the maximum contact force and curvature of the pipe both reduce. Analyses also show that the rebound stiffness can have a marked effect on pipeline embedment, which increases with increasing rebound stiffness. However, the effect on pipe embedment becomes small beyond a certain ratio of rebound stiffness to shear strength.

1. Introduction

Pipe–soil interaction is of great importance during pipeline installation, as it influences the pipeline shape and internal force distribution, as well as the pipeline embedment and stability during subsequent operations. Analytical solutions are complicated by the need to consider non-linear, plastic response of the seabed, and to allow for the effects of cyclic remoulding of the soil due to the dynamic pipe motions in the touchdown zone [1,2]. The earliest solutions for pipe-lay assumed the seabed as rigid, which greatly simplified the pipe–soil interaction problem [3,4]. Such solutions exaggerate the maximum pipe–soil contact force and the curvature at the point of contact. Later, solutions based on linear elastic seabed response were developed [5–7]. These solutions, in particular the closed form solution and analysis framework of Lenci and Callegari [5], were relatively simple and easy to implement, and represented a significant advance. From these solutions it is possible to obtain reasonably accurate estimates of the pipe shape and distribution of pipe–soil contact force through the touchdown zone (TDZ). Preliminary estimates of pipe embedment could be made by adopting values of secant stiffness that reflected the non-linear response of seabed sediments, although the solutions could not capture the pipeline profile in the seabed beyond the TDZ.

As the exploitation of oil and gas has moved from shallow to deep water, where the seabed typically comprises soft, fine-grained sediments, the importance of capturing the plastic response of the seabed has increased. Palmer [8] suggested an analytical pipe–soil interaction model for pipelines on rigid-plastic seabeds. Although certain simplifications were adopted in the model, including uniformly distributed soil resistance and limited consideration of the overall pipeline shape, it represented an important step towards improved analytical modelling of pipe–soil interaction in the TDZ. Wang et al. [9] and Yuan et al. [10] combined the models of Lenci and Callegari [5] and Palmer [8] to establish an analytical solution for the complete pipeline for a rigid-plastic seabed where the pipe-soil resistance was assumed to increase proportionally with pipeline embedment. This model explored the effects of cyclic remoulding of soil in the TDZ, as suggested by Westgate et al. [1], by considering softened soil resistance profiles. The main limitation was that, in order to simplify the solution process, the rebound compliance of the seabed was neglected. This resulted in a discontinuity in the soil resistance, as detailed later. The solution presented here has

---

[*] Corresponding author. Tel.: +86 571 88206229; fax: +86 571 88206240.
E-mail address: yuanfen5742@163.com (F. Yuan).

0141-1187/$ – see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apor.2014.10.003

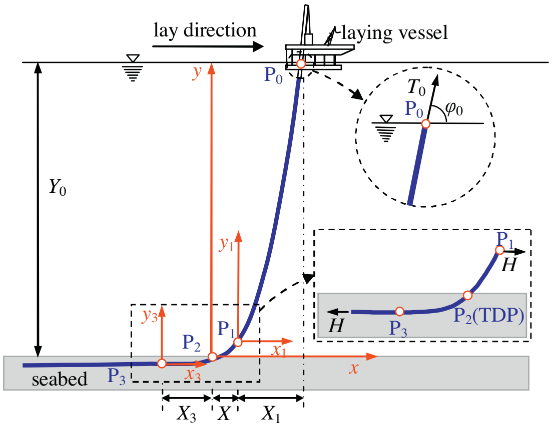
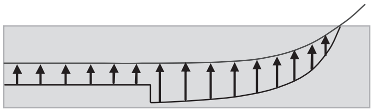
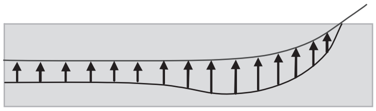


Fig. 1. Overall scheme of pipeline and coordinate systems.



(a)Rigid-plastic seabed with discontinuous soil resistance



(b)Elasto-plastic seabed

Fig. 2. Contrast in pipe–soil contact force profiles.

improved the analytical model of Yuan et al. [10] by considering the rebound stiffness of the seabed, thus preserving continuity of soil resistance. It has also considered a different assumption for the axial force in the pipe segments close to the seabed, as discussed in the following section.

2. Analytical solutions

The analytical boundary layer solution of Lenci and Callegari [5], on which the present work is based, adopted an assumption of constant axial tension in the segments close to the seabed, with the tension fixed at the value (T) at the transition to the catenary section (point P_1 in Fig. 1). The assumption is reasonable, since the angle of the pipeline to the seabed is relatively small there, but it leads eventually to a tension in the near-horizontal pipeline along the seabed that is incompatible with the horizontal component in the catenary segment. An alternative assumption is adopted here, taking the 'constant' axial force in the boundary layer segments equal to the horizontal component, H, in the catenary. This leads to a discontinuity in the pipeline tension, as far as the solution is concerned, but the true tension, continuous at P_1, may be recovered by taking account of the pipeline gradient. Differences between the assumptions of constant force (i.e. 'T' or 'H') are quantified later, since the algebraic developments are essentially identical.

2.1. Governing equations

The overall solution scheme is shown in Fig. 1. The water depth is Y_0, the (true) tension at P_0 is T_0 and the inclination to the horizontal there is φ_0 so that the horizontal component of tension is $H = T_0 \cos\varphi_0$. For convenience in the analysis, three coordinate systems are used in the model: a global coordinate system (x, y) with its origin at the touchdown point (TDP – first contact of the pipeline with the seabed, also labelled P_2); and two local coordinate systems (x_1, y_1) with its origin at P_1, the transition point between catenary and boundary layer, and (s_3, y_3) with its origin at P_3 where the maximum pipe embedment occurs. Note that although the coordinate, x is measured horizontally, force equilibrium is considered in cross-sections normal to the pipe axis [8,11]. Since the pipeline inclination from the seabed is small for the boundary layer segments, the horizontal distance, x, is essentially identical to the true lengths measured along the axis of the pipe.

The analytical model consists of four segments:

(1) Catenary segment: the segment suspended in water from P_0 to P_1 is long and flexible, and is simplified as a natural catenary. The horizontal length of this segment is represented by X_1, and the calculation is based on the coordinate system (x_1, y_1).

(2) Boundary-layer segment: the pipeline from P_1 to the P_2 (TDP) is treated as a separate segment, within which the bending stiffness of the pipe is important [5]; this segment behaves like a beam under uniform tension (assumed as H) and with small inclination relative to the seabed. The boundary-layer segment is defined through its horizontal length X_2, which becomes one of the unknowns to be resolved as part of the final solution. The calculation of this segment is based on the global coordinate system (x, y).

(3) Touchdown segment: this segment, which involves increasing soil resistance from the TDP to point P_3 (the point of deepest penetration), is also modelled as a low-inclination beam under constant tension H, neglecting the axial soil resistance which is very small compared with the tension. Both elastic and plastic seabed deformations occur in this area, but are modelled here using a (plastic) linear relationship between soil resistance and pipe penetration into the seabed. The length of this segment is defined by its horizontal length X_3, which is resolved as part of the final solution. The global coordinate system (x, y) is used for the calculation.

(4) Rebound segment: the final segment continues from the touchdown segment, with the mobilized soil resistance reducing gradually from a maximum at P_3 down to the submerged pipe weight. Therefore the seabed, which has previously been subjected to the maximum contact force during the lay process, undergoes elastic rebound and the pipe penetration reduces slightly. For this segment, the calculation is based on the local coordinate system (x_3, y_3). Note that this segment represents the key difference from the rigid-plastic solution of Yuan et al. [10], which assumed that the pipeline remained horizontal beyond P_3 without rebound. This removes the discontinuity in pipe–soil contact force from the latter solution, as indicated in Fig. 2.

2.1.1. Catenary segment

The catenary shape of the pipeline in water can be expressed as [12]:

$$\frac{d(\tan\varphi)}{ds} = \frac{p}{H} \tag{1}$$

where φ is the inclination, s is the arc length of the pipeline, p is the submerged weight of the pipe (per unit length) and H is the