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Effect of Near-Surface Crustal Layers on Undrained Vertical Penetration Response of Subsea Pipelines

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Large deformation finite element analyses were performed to study the undrained vertical bearing capacity of subsea pipelines installed on a surficial high-shear-strength crust overlying a soft clay deposit. A detailed parametric study was carried out for different combinations of shear strength ratio of crust to underlying soil, crust thickness, and strength heterogeneity of the underlying soil. Results show that the presence of a crustal layer significantly influences the vertical penetration response of pipelines. Simple relationships are developed to predict the maximum penetration resistance and the displacement required to mobilize the maximum resistance for the assessment of punch-through failure.

INTRODUCTION

As the offshore industry is exploring hydrocarbon reserves in remote geographic locations, a thin layer of crust exhibiting an abnormally high shear strength overlying a normally consolidated soft clay deposit is often encountered. The high shear strength of the crust can be attributed to the biochemical activities of microorganisms living in the vicinity of the seabed (Kuo and Bolton, 2013). Deepwater subsea pipelines carrying hydrocarbons at very high temperatures and pressures are often directly installed on this crustal sediment, without any trenching or additional protection. Self-weight and dynamic oscillations of laying vessels (Randolph and White, 2008a) lead to partial embedment of these pipelines. The vertical penetration of the pipe during the installation process is generally an undrained phenomenon involving the formation of soil heave around the pipe. Sudden reduction in the bearing capacity of the soft soil underneath the crust could lead to the possibility of punch-through failure during installation. Thus, it is essential to accurately assess the penetration response of pipelines installed on a surficial crust for the design of on-bottom submarine pipelines.

In the recent past, researchers have conducted several studies on the vertical bearing capacity of subsea pipelines using either classical plasticity theory (Randolph and White, 2008b; Martin and White, 2012) or small strain finite element analysis (Aubeny et al., 2005; Merifield et al., 2008, 2009). Wang et al. (2010) and Chatterjee (2012) performed finite element analyses adopting the large deformation approach to simulate the change in seabed geometry and formation of soil heave around the pipe during penetration. Experimental studies in geotechnical centrifuge (Dingle et al., 2008; White and Dingle, 2011) were also carried out to understand the pipe–soil interaction, although they are limited to specific cases. Very few studies available in the literature have considered the effect of a high-strength crustal layer present near the seabed on the penetration response of offshore pipelines. Although several researchers (Teh et al., 2008, 2010; Hossain and Randolph, 2010a, 2010b; Hossain et al., 2011; Hu et al., 2014a, 2014b, 2015) have studied the punch-through potential of spudcan foundations on layered soil, there are relatively fewer studies related to other offshore foundation systems. Park et al. (2010) determined the bearing capacity factors for a shallow foundation on a stiff nonhomogeneous crustal layer overlying a very soft clay. Morrow and Bransby (2011) conducted a series of small strain analyses using the finite difference method to study the effect of different shear strength profiles and crust shear strength on vertical penetration of seabed pipelines. Recently, Feng et al. (2015) examined the influence of near-surface crust on the ultimate load-carrying capacity of mud mats, considering loads from all six directions. Many of these studies in the literature consider the pipe/foundation to be “wished in place” on the surficial crust and do not account for the change in seabed topography due to large amplitude displacement. The main objectives of the present work are to (i) perform large deformation finite element (LDFE) analyses to simulate the continuous installation of pipe in normally consolidated clay with a surficial crust layer, (ii) study the effect of the presence of a crustal layer on the vertical penetration response, and (iii) develop a simplified approach to estimate the maximum penetration resistance and the displacement required to mobilize the maximum resistance.

In this work, a technique developed by Hu and Randolph (1998a, 1998b), known as “remeshing and interpolation technique with small strain” (RITSS), is implemented to carry out large deformation finite element (LDFE) analyses. The adopted numerical approach was first validated with analytical and numerical results available in the literature. Thereafter, a parametric study was carried out by varying the relative strength ratio of the crust to the underlying soil, the crust thickness to pipe diameter ratios, and the soil strength heterogeneity of the bottom soil to investigate the effects of these factors on penetration response.

PROBLEM DEFINITION

The schematic representation of the geometry of the problem and the undrained soil shear strength (s_u) profile are shown in Fig. 1. In Fig. 1, D represents the diameter of the pipeline, w is the embedment depth below the mudline, and V is the penetration resistance per unit length. The s_u profile without the presence of crust can be expressed as $s_u = s_{um} + kz$, where s_{um} is the shear strength at seabed level and k is the gradient of shear strength. The effect of the crustal layer on the shear strength is represented

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KEY WORDS: Pipelines, large deformation, finite element analysis, crust, bearing capacity, punch-through.