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# Finite Element Modeling of Axial–Vertical Interaction Behavior of Buried Pipelines in Dense Sand

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**Three-dimensional finite element (FE) analysis of axial–vertical interaction behavior of buried pipelines in dense sand is performed. The commercially available FE software package Abaqus/Explicit is used to accommodate large displacement and to avoid convergence problems. In addition, a user subroutine is utilized to capture the pressure dependent stress–strain behavior of dense sand. The numerical model is verified by comparing the results with experimental results available in literature. The effects of pipeline burial ratio, angle of attack, and pipeline surface roughness are discussed. A normalized axial–vertical interaction diagram is also proposed.**

## INTRODUCTION

The use of subsea buried pipelines for transporting high-pressure and high-temperature hydrocarbons has increased rapidly in recent years all around the globe. The safe operation of such buried pipelines is a prime concern for the oil and gas industry. The minimization of adverse effects on the mechanical response and integrity of pipelines as a result of geohazards is one of the major challenges. Permanent ground deformation as a result of geohazards such as landslides and earthquakes can cause relative movement between the pipeline and surrounding soil, which may impose geotechnical loads onto the pipe. The geotechnical load onto the pipe increases the level of stress and strain in the pipeline, which may hinder the safe operation of the pipeline system.

In the current engineering practice (e.g., American Lifelines Alliance, 2001; Honegger and Nyman, 2004), the soil/pipe interaction is idealized by structural modeling. The mechanical response of pipeline is assessed by specialized beam elements, and the soil behavior is evaluated by discrete nonlinear springs with load-displacement relationships provided for principal directions (i.e., longitudinal or axial, lateral or horizontal, vertical upward, and vertical downward). These springs are independent and cannot account for the combined effects during a three-dimensional (3D) soil/pipe relative movement (i.e., movement under oblique loading) despite the fact that, in reality, the movement can occur in all three directions simultaneously. The oblique soil/pipe interaction cases include axial–lateral, axial–vertical, and lateral–vertical soil/pipe relative movements, which are specific cases of a general 3D (axial–lateral–vertical) soil/pipe relative movement.

A number of theoretical, experimental, and numerical investigations have been conducted on buried pipelines to evaluate the soil force-displacement relationships in both sand and clay. Most of the previous studies have focused on the axial, lateral, and lateral–vertical soil/pipe interaction behavior. For example, Trautmann and O'Rourke (1985) and Trautmann et al. (1985) conducted full-scale experiments to assess the lateral and vertical uplift force-displacement response of buried pipe. Paulin et al. (1998) performed some full-scale axial tests on steel pipe embedded in both loose and dense sand and some other tests on steel pipe embedded in clay. Hsu et al. (2001, 2006) performed large-scale tests to investigate the axial–lateral soil/pipe interaction for shallow buried pipelines in loose and dense sand. Guo (2005) conducted finite element (FE) analysis to evaluate the soil/pipe interaction behavior in clay for pipelines subjected to combined horizontal and vertical (upward) movements. Guo and Stolle (2005) performed numerical analysis of pipelines buried in sand subjected to lateral load. Wijewickreme et al. (2009) conducted full-scale and numerical investigations to evaluate the axial soil/pipe interaction in sand for buried pipes. Daiyan et al. (2011a) reported centrifuge tests and numerical analysis on axial–lateral soil/pipe interaction behavior.

Some of the previous studies on axial–lateral soil/pipe interaction have indicated that the axial load increases for low angles of attack in both sand and clay (e.g., Phillips et al., 2004; Daiyan et al., 2011a). Also, some studies (e.g., Nyman, 1984; Cocchetti et al., 2009) have indicated the importance of lateral-vertical soil/pipe interaction. For instance, Cocchetti et al. (2009) showed that the downward movement of pipe increases the lateral soil restraint on the pipeline. Daiyan et al. (2011b) observed an increase of about 50% in the ultimate axial load on the pipeline with respect to pure axial movement for small oblique angles. None of these coupling effects is considered in the current state of practice, as stated earlier. Hence, more investigations on complex loading conditions are required to enhance the current engineering practice.

The current study focuses on the axial–vertical soil/pipe interaction behavior in dense sand by 3D FE analysis. The definition of the oblique load on the pipeline in axial–vertical direction is shown schematically in Fig. 1, where $\theta$ is the oblique loading angle. A modified soil model is incorporated in the FE modeling, which is able to capture the key features of the stress–strain behavior of dense sand as observed in laboratory triaxial tests. A

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KEY WORDS: Buried pipeline, axial–vertical interaction, dense sand, modified Mohr–Coulomb model, numerical analysis, Abaqus.