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Research Paper

Influences of strain rate and soil remoulding on initial break-out resistance of deepwater on-bottom pipelines

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ABSTRACT

Large deformation finite element analyses have been conducted to study the initial break-out resistance of on-bottom pipelines. Soil model that takes strain rate and soil remoulding into consideration was implemented. Results from detailed parametric study are presented in terms of failure envelopes in vertical-horizontal load space. The maximum vertical and horizontal resistance responses normalized by an equivalent shear strength incorporating the rate and softening parameters lead to a narrow band of values. Obtained results are generalized and fitted to simple equations. The proposed methodology predicts undrained break-out resistance with maximum error limited to 10% for wide range of parameters.

1. Introduction

As the offshore energy industry is venturing into deeper waters, the capital expenditure for the field development is increasing heavily with water depth. Subsea pipelines in any offshore field development project require a huge fraction of the capital investment. In deeper waters, pipelines are installed on the seabed directly without any trenching or additional protection. These as-laid seabed pipelines convey hydrocarbons at very high pressure and temperature. The thermal stresses generated due to change in temperature causes lateral buckling if adequate resistance is not available from the surrounding soil. This lateral movement, if controlled, can provide a cost efficient solution to thermal stress induced problems as compared with the conventional methods of preventing the buckling by means of mechanical devices such as expansion spools, and anchors. Reliable appraisal of soil resistance during lateral buckling of pipelines is very essential in the design of submarine pipelines for controlled buckling. The soil resistance due to lateral movement of pipes can be broadly divided into the initial break-out resistance and the steady state residual resistance. The peak resistance observed during the initial movement, i.e. when the pipe breaks away from the soil behind it, is termed as break-out resistance. Whereas, the steady resistance observed after the pipe has undergone a large lateral motion is termed as residual resistance.

In the recent past, researchers have extensively studied the steady-state lateral resistance of subsea pipelines shallowly embedded in clay (e.g. Wang et al. [19], White and Dingle [20], Chatterjee et al. [5]). The large deformation effects associated with the steady state lateral movement have been captured and quantified in these studies. On the other hand, most of the previous studies on break-out resistance in the literature, either based on classical plasticity theory (Randolph and White [18]) or small strain analyses using finite element approach (e.g. Aubeny et al. [1], Merifield et al. [14]) consider the pipe to be 'wished-in-place' and do not capture the change in seabed geometry due to large amplitude displacement during installation. The vertical penetration during the installation process is generally an undrained phenomenon involving formation of heave around the pipelines that influences the vertical bearing capacity as well as the lateral resistance. During this penetration, the environing soil gets remoulded that influences the operative shear strength of the soil significantly and thus the initial break-out resistance. The rate of pipe penetration also enhances the undrained soil shear strength near the pipe. The combined effects of penetration rate and soil remoulding during the pipe installation on the initial break-out resistance have not been systematically addressed previously in the literature. The main aim of the present study is, therefore, to provide a generalized framework to predict the initial break-out resistance of pipelines in clay seabed incorporating the effects of (i) change in seabed geometry in the form of heave, (ii) rate of penetration and (iii) soil remoulding on the undrained shear strength of soil.

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Nomenclature

Symbol

a, b, c, d fitting parameters for obtaining maximum break-out and penetration resistance for different shear strength profiles
D pipeline diameter
E deformation modulus of soil
f_r average operative shear strain during each increment of pipe displacement
f_s softening factor accounting for equivalent plastic shear strain
H break-out resistance
H_{max} maximum break-out resistance
s_u undrained shear strength
s_{u0} original soil shear strength at pipe invert
s_{um} undrained shear strength at mudline
$s_{u0,eq}$ equivalent shear strength
S_t sensitivity of soil
v_p velocity of pipe
V vertical penetration resistance
V_{max} maximum vertical penetration resistance
w embedment depth
z penetration depth below seabed level
α interface roughness coefficient
β_1, β_2 skewness parameter for failure envelopes
γ' buoyant unit weight of soil
$\dot{\gamma}_{ref}$ reference shear strain rate
$\dot{\gamma}_{max}$ maximum shear strain rate
δ_{rem} fully remoulded to original shear strength ratio
κ soil strength heterogeneity
μ rate of increase of shear strength per decade
ξ accumulated absolute plastic shear strain
ξ_{95} accumulated plastic shear strain to achieve 95% remoulding

Abbreviation

ALE Arbitrary Lagrangian Eulerian
LDFE Large Deformation Finite Element
RITSS Remeshing and Interpolation Technique with Small Strain
SPR Superconvergent Patch Recovery

In this study, large deformation finite element analysis (LDFE) using 'Remeshing and Interpolation Technique with Small Strain' (RITSS, Hu and Randolph [11,12]) was carried out to assess the initial break-out resistance of on-bottom pipelines in clayey soil. The adopted numerical methodology was first substantiated with available theoretical and experimental results. After that, a detailed and systematic parametric study was carried out. Normalized pipe velocity, rate parameters, sensitivity and ductility of soil were varied to investigate the influence of these factors on initial break-out resistance. The influence of soil heterogeneity on break-out resistance was also explored in this work. Simple relationships were developed for estimating non-dimensional vertical penetration resistance and initial break-out resistance as a function of normalized penetration.

2. Numerical modelling

2.1. RITSS method

The LDFE method adopted in the present work involves a technique known as 'Remeshing and Interpolation Technique with Small Strain' or RITSS, Hu and Randolph [11,12] which is basically a form of 'Arbitrary Lagrangian Eulerian' (ALE) approach reported by Ghosh and Kikuchi [9]. In this approach, the large deformation problem is discretized into number of small strain Lagrangian analyses and the geometric and material points of a mesh move arbitrarily to overcome severe mesh distortions. After each analysis, remeshing of deformed geometry is performed and stresses, strains and material properties are interpolated from original geometry to the deformed geometry. Initially the state variables are recovered from integration points to nodal points of an old mesh by a technique called 'Superconvergent Patch Recovery' (SPR [23]) and thereafter interpolated from old nodal points to integration points of new mesh [19]. In the present study, each incremental small strain analysis is carried out using finite element package Abaqus [6]. The entire large deformation procedure is operated by a master Fortran program which repeatedly calls Abaqus [6] (through several python scripts) and Fortran subroutines to accomplish the RITSS process.

In the present study, incremental pipe displacement is taken as $0.01D$ for each small strain analysis, where D is the pipe diameter. It was ensured that the adopted incremental displacement was small enough for obtaining accurate results, by running a set of analyses with smaller displacement increments. Negligible difference in the penetration resistance responses were observed for incremental displacements less than 1% of pipe diameter.

2.2. Mesh details and material properties

The geometry of the problem and undrained shear strength (s_u) profile of soil considered for the present study are shown in Fig. 1. A plane strain two-dimensional (2D) model was used in the study (see Fig. 2). The left and right boundaries of the model were horizontally restrained but free to move vertically, whereas the bottom boundary was restrained in both the directions. The 2D plane strain quadratic triangular element (CPE6 in Abaqus element library) was chosen for discretization. The distances of the boundaries of the model from the centre of the pipe and the mesh density was optimized after trying several options. The pipe was considered as a rigid body and soil as a deformable body in the model. The friction in the pipe-soil interface was simulated using penalty method in Abaqus [6]. The shear stress at the pipe-soil interface,

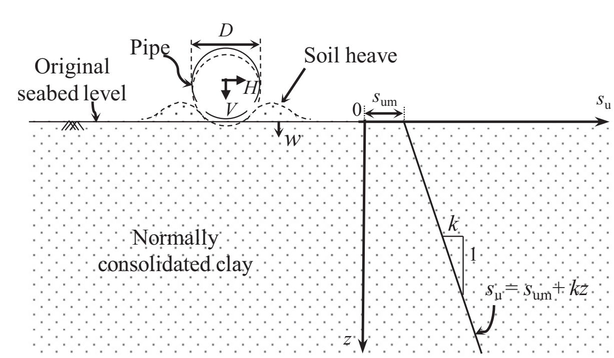

Fig. 1. Schematic diagram of problem geometry and undrained shear strength profile of soil.