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Consideration for On-Bottom Stability of Unburied Pipelines Using a Dynamic Fluid-Structure-Soil Simulation Program

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The modeling of pipe-soil interaction in current industry practice is still based on Coulomb friction models and passive resistance. Analysis of the ultimate resistance capacity of the pipeline subjected to wave and current loading is taken as the criterion for on-bottom stability design. This approach is widely used in industry, and considerable experience has been accumulated. However, a sounder theoretical basis and more thorough understanding of pipe-soil behavior are still required. This paper provides considerations and discussion regarding the analysis of unburied pipeline stability using an integrated fluid-structure-soil interaction program. It also emphasizes the advantages of stability design based on a displacement limit state, a method encouraged in DNV (2007). The aim of this paper is to illustrate important issues for pipeline on-bottom stability, and to highlight alternate results using this integrated modeling approach. The example analyses discussed include optimizing the pipe weight for increased self-burial, the effect of a free span on pipe movements, and the influence of additional vertical load during a pipe installation.

NOMENCLATURE

A = wave amplitude
$_C$ = (subscript) conjugate point
D = pipe diameter
$\mathbf{D}$ = stiffness matrix
$D(\omega, \theta)$ = spreading function
E = Young's modulus of pipe steel
^e_e = (superscript/subscript) elastic
F = hydrodynamic force
$\mathbf{F}$ = force vector $= \{V, H\}^T$
F_b = bounding surface
f_b = bubble (yield) surface
g = plastic potential surface
H = horizontal force
$_h$ = (subscript) horizontal
k = stiffness
$_M$ = (subscript) centre point of bounding surface
m = aspect ratio of plastic potential surface
$_N$ = (subscript) centre point of bubble surface
^p_p = (superscript/subscript) plastic
r = scale ratio of bubble surface to bounding surface
S = wave spectrum
T_{peak} = peak spectral period
th = pipe thickness
$\mathbf{U}$ = displacement vector $= \{V, H\}^T$
u = horizontal displacement
V = vertical force
V_0 = size of bounding surface
W = self-weight
w = vertical displacement
β = shape parameter of bounding surface
Δ = increment
ε = random phase
η = wave elevation
θ = spreading angle
μ = shape parameter of bounding surface
μ_t = aspect ratio of plastic potential surface
ω = angular frequency

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KEY WORDS: Pipelines, on-bottom stability, pipe-soil interaction, Fourier model, calcareous sand, force-resultant model.

INTRODUCTION

One of the most fundamental engineering tasks of pipeline design is to ensure on-bottom stability under the action of hydrodynamic loads. In many offshore engineering projects throughout the world pipeline stabilization is a major cost driver. A typical example is the North West Shelf of Australia, where shallow water, complex seabed soil characteristics due to the calcareous sediments, and severe environmental loading from annual tropical cyclones, can drive the Capital Expenditure (CAPEX) cost of stabilization up to 30% of the total pipeline CAPEX (Brown et al., 2002). These scenarios provide strong motivation for new models, which potentially reduce conservatisms inherent in the traditional design approaches.

Predicting on-bottom pipeline stability is complex with many disciplines requiring integration, including soil constitutive modeling, seabed liquefaction, scour and sediment transport, structural mechanics and prediction of ocean waves and hydrodynamic loads. Considering this complexity, most pipelines are designed using very simplistic methods. For instance, the traditional pipeline stability design approaches, such as those found in early design codes (DNV, 1981), use a simplistic Coulomb friction model to describe pipe-soil behavior and adopt force balance methods to ensure the pipe does not displace horizontally, i.e. the stability failure criterion is defined such that the hydrodynamic loading does not exceed the soil resistance. More recent updates, such as DNV-RP-E305 (1988) and DNV-RP-F109 (2007), retain simplistic stability charts, but highlight the advantages of dynamic time domain and 3D stability analysis. A lateral displacement limit-state is set as a "failure" criterion in this latter analysis methodology preferred by DNV (2007).

Although recommended for some time, and considered the most comprehensive method, dynamic lateral stability analysis is still not widely used in practice. Tørnes et al. (2009) ascribed the reason to limited software availability and also limitations within