

NUMERICAL MODELLING OF RESIDUAL LIQUEFACTION AROUND SUBMARINE PIPELINES AND OFFSHORE CABLES

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INTRODUCTION

Submarine pipelines have been one of the most essential marine infrastructures for the oil and gas industry for many decades. Likewise, with the advancement of offshore wind energy technology, offshore cables for power transmission have become crucially important assets, since the numbers and lengths of inter-array and grid connection cables have been increasing constantly. The diameter of an offshore cable for power transmission is generally $O(0.05-0.4)m$, whereas the diameters of oil and gas pipelines are $O(0.2-1.5)m$. Although the sizes of offshore cables are relatively small compared to those of submarine pipelines, general design guidelines for stability of submarine pipelines have been mostly adopted by the offshore wind industry for offshore cables, given the geometric resemblance of these structures.

Marine structures like pipelines and offshore cables buried in loose fine-grained seabed soil, such as silt or fine sand, may be under the threat of wave-induced liquefaction. Failures caused by wave-induced liquefaction have been experienced to lead to dramatical damages of these structures. The cyclic shear stress caused by severe waves re-arranges soil grains at the expense of pore volume. Consequently, the pore-water pressure builds up and eventually exceeds the overburden of the seabed soil, causing the loss of effective stresses in the soil (Sumer, 2014). In this case, the soil behaves like a liquid (mixture of sediment grains and seawater), and loses its load-bearing capacity. With the marine soil liquefied, the buried objects heavier than the liquefied soil sink deeper in the soil, while lighter objects float to the surface, the sinking and floatation failures.

This paper presents the results of a numerical modelling study in which the liquefaction potential around a pipeline/cable buried in seabed soil is investigated. For this purpose, a numerical model developed for modelling wave-induced liquefaction around marine structures under the NuLIMAS (Numerical Modelling of Liquefaction Around Marine Structures) Project is utilized. The model, implemented in the OpenFOAM CFD toolbox, has two components: The first component solves the Biot equations for poro-elastic medium through the biotFoam solver in OpenFOAM as implemented by Rønby (1993). The second component utilizes a mathematical model for pore-water pressure buildup (Sumer, 2014, chp. 3). Altogether, this new solver is called `pressureBuildupFoam` (Yilmaz, 2022; Shanmugasundaram, 2022). As a novel and convenient feature of the numerical model version used in the

present study, the model offers different wall boundary conditions of pipelines or cables such as smooth (slip), rough (no-slip), or partially rough (partial slip), and also the option of modelling spatially non-uniform soils such as a trench with freshly backfilled native soil.

MATERIALS AND METHODS

The definition sketch of the problem studied is presented in Fig. 1. A cylinder (a pipe or a cable) with a diameter D is buried into the seabed soil with depth d . Burial depth of the cylinder is e . The seabed soil is subjected to wave loading in terms of sinusoidal pressure variations at the mudline, $p_0(x, t)$. The structure, buried in a trench, may be backfilled by loose native soil, which can be represented in the present model as two zones defined by a zone flag, `que`. Of particular interest is the buildup of pore-water pressure inside the soil around the cylinder, and initiation of residual liquefaction.

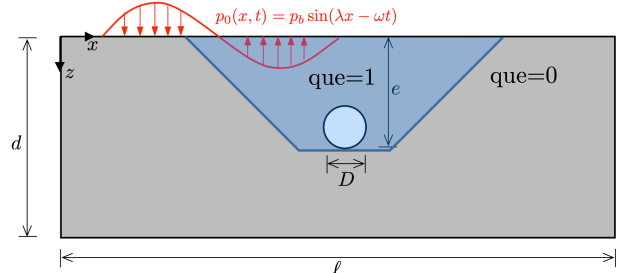


Figure 1 - Definition sketch of the problem

The solver, `pressureBuildupFoam`, solves the following governing equations for the accumulated pore-water pressure inside the soil.

$$\frac{\partial \bar{p}}{\partial t} = c_v \left(\frac{\partial^2 \bar{p}}{\partial x^2} + \frac{\partial^2 \bar{p}}{\partial y^2} \right) + f \quad (1)$$

in which \bar{p} is the period-averaged accumulated (residual) pore-water pressure, c_v is the coefficient of consolidation, and f is the source term for buildup of pore-water pressure given as

$$f = \frac{\sigma_0'}{N_l T} \quad (2)$$

$$N_l = \left(\frac{1}{\alpha} \frac{\tau_{amp}}{\sigma_0'} \right)^{1/\beta} \quad (3)$$

where σ_0' is the initial mean normal effective stress:

$$\sigma_0' = \gamma' z \frac{(2k_0 + 1)}{3} \quad (4)$$

Here, T is the wave period, γ' is the submerged specific weight of soil, k_0 is the coefficient of lateral earth pressure, N_f is number of wave cycles to cause liquefaction, τ_{amp} is the amplitude of cyclic shear stress in the soil during wave action, and α and β are the model coefficients given as a function of the relative density of soil, D_r . Eq. (1) stems from the Biot equations which consists of three equations of equilibrium for poro-elastic soil (in 3D) and a fourth equation for conservation of pore fluid, so-called storage equation. The reader is referred to Sumer (2014) for Biot equations (chp. 2) and further details of the mathematical model (chp. 3). Further details of the numerical model implementation can be found in Kirca et al. (2022) and Shanmugasundaram et al. (2022). The soil is said to be liquefied when the pore-water pressure accumulation exceeds initial mean normal effective stress:

$$\frac{\bar{p}}{\sigma_0'} \geq 1 \quad (5)$$

RESULTS

The model was first validated against the experimental results of Sumer et al. (2006). A sample result is as shown in Fig. 1.

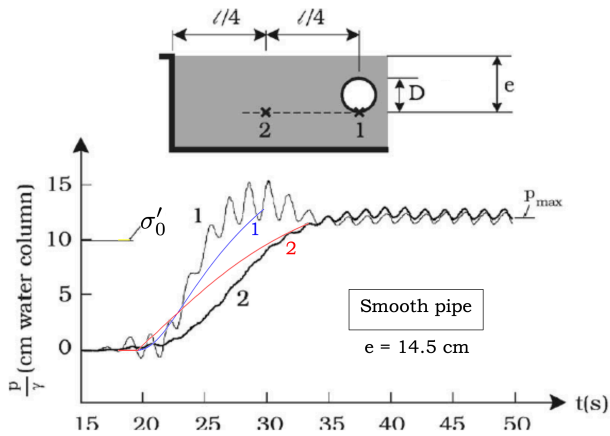


Figure 1 - Present model results vs. experiments of Sumer et al. (2006). Accumulated pressure at the bottom of the smooth pipe and at the far field at the same depth. As seen in this figure, a fairly good agreement between the experimental data and model results was observed. Once validated, the model was adapted to a structure placed in a loosely-backfilled trench with native soil. For such an application, it was seen that the liquefaction potential has substantially increased. When the trench is filled with a soil with higher relative density, this time the liquefaction susceptibility was seen to decrease substantially.

CONCLUSION

In this study, the results of a numerical modelling study that investigates residual liquefaction around an offshore cable or a pipeline buried in seabed were presented. It was seen that the model was capable of capturing the

wave-induced residual liquefaction potential around buried structures fairly successfully. It was also shown that for pipelines/cables buried in loosely backfilled trenches, liquefaction potential increases substantially.

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