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Parametric study of the wave-induced residual liquefaction around an embedded pipeline

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ABSTRACT

Wave-induced liquefaction in a porous seabed around submarine pipeline may cause catastrophic consequences such as large horizontal displacements of pipelines on the seabed, sinking or floatation of buried pipelines. Most previous studies in relation to the wave and seabed interactions with embedded pipeline dealt with the wave-induced instaneous seabed response and possible resulting momentary liquefaction (where the soil is liquefied instantaneously during the passage of a wave trough), using theory of poro-elasticity. Studies for the interactions between a buried pipeline and a soil undergoing build-up of pore pressure and residual liquefaction have been comparatively rare. In this paper, this complicated process was investigated by using a new developed integrated numerical model with RANS (Reynolds averaged Navier–Stokes) equations used for governing the incompressible flow in the wave field and Biot consolidation equations used for linking the solid–pore fluid interactions in a porous seabed with embedded pipeline. Regarding the wave-induced residual soil response, a two-dimensional poro-elastoplastic solution with the new definition of the source term was developed, where the pre-consolidation analysis of seabed foundation under gravitational forces including the body forces of a pipeline was incorporated. The proposed numerical model was verified with laboratory experiment to demonstrate its accuracy and effectiveness. The numerical results indicate that residual liquefaction is more likely to occur in the vicinity of the pipeline compared to that in the far-field. The inclusion of body forces of a pipeline in the pre-consolidation analysis of seabed foundation significantly affects the potential for residual liquefaction in the vicinity of the pipeline, especially for a shallow-embedded case. Parametric studies reveal that the gradients of maximum liquefaction depth with various wave and soil characteristics become steeper as pipeline burial depth decreases.

1. Introduction

One of the most important processes that must be considered in the design of submarine pipelines is that of potential for liquefaction in offshore foundation due to the build-up of excess pore pressure caused by the direct action of ocean waves. It has been well known that gravity water waves propagation over the ocean will further generate excess pore pressure in marine sediments due to the much faster rise time of the surface water pressure compared to the drainage time of excess pore pressure [1]. Once the pore pressure becomes excessive with accompanying decreases in effective stresses, a sedimentary bed may become liquefied and behave like a heavy fluid without any shear resistance, thus precipitating failure of the supported structure. Evidence of such failures of a 10-ft diameter steel pipeline in Lake Ontario is available in Christian et al. [2], where floatation of sections of the pipeline to the surface of the soil was noted during storms, apparently because of liquefaction. Therefore, the evaluation of the wave-induced soil response is particularly important for offshore engineers involved in the design of foundations for offshore pipelines.

The variation of properties within the soil profile under wave action were normally investigated by incorporating Biot's consolidation equations into the analytical procedure in the early stage [3–8]. However, the analytical solutions can only deal with simple boundary conditions. For more complicated boundary value problems with submarine structures embedded in the seabed (e.g., submarine pipeline), numerical methods would be the only feasible method. Among available investigations, Cheng and Liu [9] numerically investigated the wave-induced seepage force on a pipeline, using a boundary integral equation method. Later, Jeng [10] developed a 2-D finite element numerical model for the wave-induced soil response around the pipeline and the internal stress within the pipeline, with a more reasonable assumption considering the pipeline itself as an elastic material. This approach has been further

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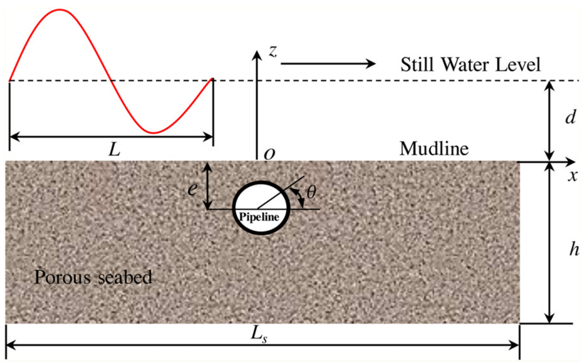

Fig. 1. Definition sketch of wave–seabed–pipeline interaction.

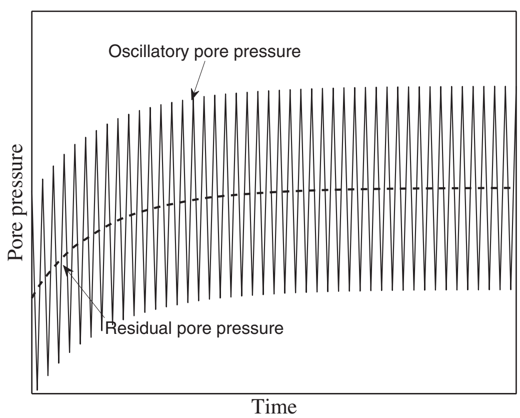

Fig. 2. Mechanisms of wave-induced pore pressures (not in scale).

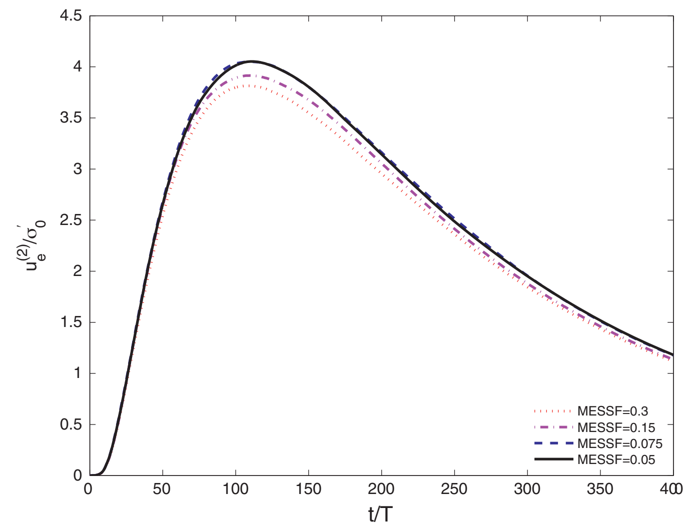

Fig. 3. Convergent test of FEM mesh.

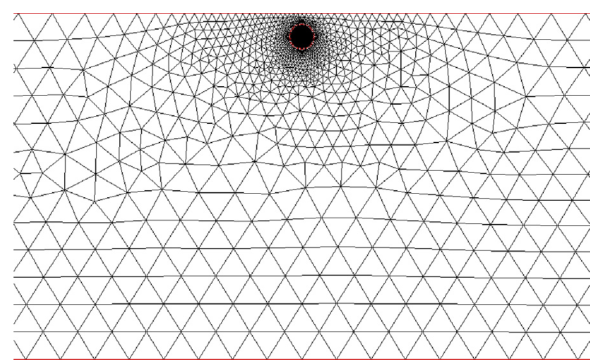

Fig. 4. FEM mesh used in computation for sandy bed in the vicinity of an embedded pipeline.

extended to more complicated cases under various wave and soil conditions such as non-linearity of the wave [11,12], anisotropic seabed [13], as well as combined wave and current loading [14]. In addition to 2-D models, a few researchers have attempted to investigate the effect of wave obliquity on the wave–seabed–pipeline interaction problem with 3-D models recently [15,16]. However, all aforementioned investigations were based on poro-elastic theory and only the wave-induced oscillatory soil responses were investigated.

Cumulative contraction of soils under the action of cyclic waves leading to the build-up of pore pressure in marine sediments has also been intensively investigated in the last few decades. One of the earliest publications is one by Seed and Rahman [17], who observed an empirical relationship between the build-up of pore pressure and elastic soil behavior. This approach has been widely used in the past with consideration of the theory of poro-elasticity [18–20], where a one-dimensional dynamic consolidation equation incorporated into the build-up pattern of pore pressure in the case of undrained soil is solved either by analytical approximations or by numerical modelling. The relationship between the cyclic plasticity and pore pressure accumulation was emphasized by Sekiguchi et al. [21], who derived a closed-form poro-elastoplastic solution for the standing wave-induced liquefaction in cohesionless deposits due to the build-up of pore pressure, using a Laplace transformation. Zienkiewicz et al. [22] and Pastor et al. [23] developed another kind of complicated non-associated elasto-plastic model (PZIII), with emphasis on simulating the drained or undrained behaviour of soil under cyclic or monotonic loading. Later, Sassa and Sekiguchi [24] extended PZIII model by considering the effect of rotation of principle stress axis on the soil behaviour. However, all of the aforementioned investigations could only describe the soil behaviour well before the liquefaction status is reached, they are incapable of describing the behaviour of liquefied soil due to the significant difference on the constitutive relationship as well as density and viscosity between the liquefied and sub-liquefied soil. The progressive nature of liquefaction was first demonstrated by Sassa and Sekiguchi [25] through the application of centrifuge wave tank tests on loose deposits of fine grained sand. The application of a high-speed CCD camera to the centrifuge wave testing allowed them to capture the boundary between the liquefied soil and sub-liquefied soil, which were found to move downward with vibration. They argued that the amplitude of this vibration increased markedly in the course of progressive liquefaction until reaching a steady-state value. Based on those tests, Sassa et al. [26] proposed numerical model incorporated with the post-liquefaction process to investigate the progressive property of wave-induced residual liquefaction, in which the moving boundary between the liquefied soil and sub-liquefied soil was taken into consideration.

The sinking/floatation of submarine pipeline due to the wave-induced residual liquefaction in its supporting deposits have been intensively investigated in previous experimental investigations [27–29], where the pore pressure build-up was indicated to be significantly affected by the presence of the pipeline. Adopting the elasto-plastic model PZIII, Dunn et al. [30] investigated pore pressure accumulation in sandy bed near the pipeline, and assessed the possibility of residual liquefaction under linear progressive wave loading. Recently, Zhao et al. [31] developed a two-dimensional integrated numerical model to investigate the build-up of residual pore pressure and resulting liquefaction in marine sediment with embedded pipeline and partially backfill trenched pipeline under