Applied Ocean Research 68 (2017) 293–306

Contents lists available at ScienceDirect

Applied Ocean Research

journal homepage: www.elsevier.com/locate/apor

Three-dimensional poro-elastic integrated model for wave and current-induced oscillatory soil liquefaction around an offshore pipeline

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ARTICLE INFO

Article history:
Received 22 May 2017
Received in revised form
10 September 2017
Accepted 20 September 2017

Keywords:
WCI
WSPI
Flow obliquity
Pipeline
Burial depth
u-*p* equations
Liquefaction

ABSTRACT

To obtain a better understanding of the oscillatory soil liquefaction around an offshore pipeline, a three-dimensional integrated model for the wave–seabed–pipeline interaction (WSPI) is proposed by combining the Reynolds-Averaged Navier–Stokes equations for flow simulations and the dynamic Biot's equation ("*u*-*p*" approximation) for the poro-elastic seabed model. Compared with previous investigations, the wave–current interaction is included in the present WSPI system. At a given time step, the wave pressure extracted from the flow model is applied on the seabed surface to determine the corresponding oscillatory seabed response around an offshore pipeline. The integrated numerical model is first validated using previous laboratory experiments. Then, a parametric study is conducted to examine the effects of flow obliquity and pipeline burial depth on the soil response around an offshore pipeline. Numerical results indicate that the soil under the pipeline is more susceptible to liquefaction at a reduced flow obliquity and pipeline burial depth. Moreover, the liquefaction depth in the case where the wave travels along the current can increase by 10%–30% compared to that in the case where the wave travels against the current, when the magnitude of the current velocity is 1 m/s.

1. Introduction

Pipelines have been widely used to transport offshore gas and petroleum, and hence, are usually under the actions of dynamic oceanic loadings such as waves and current. When ocean waves propagate over the sea floor, the waves exert a cyclic wave pressure on the seabed, which could further lead to fluctuations in the pore pressure and effective stresses within the soil. Once the upward pressure gradient exceeds a specific limit, part of the seabed will be liquefied and lose the resistance to shear loads, which may further damage offshore pipelines. Therefore, an evaluation of wave and current-induced oscillatory soil liquefaction is particularly important for engineers involved in the design of offshore pipelines.

Generally, the mechanisms for wave-induced soil response can be divided into oscillatory mechanism and residual mechanism, which may further lead to oscillatory soil liquefaction and residual soil liquefaction, respectively. Oscillatory liquefaction is caused by oscillatory pore pressure, which usually occurs in an unsaturated seabed under the action of small waves. Residual soil liquefaction is generated by the progressive nature of the excess pore pressure, which is more likely to appear in a fully saturated and loosely deposited seabed under the action of large waves. Considering that the wave-induced soil response is oscillatory in nature in most marine sediments, the present study focuses on the oscillatory soil response.

In the past few decades, numerous investigations have been carried out for the wave–seabed–pipeline interaction (WSPI). Cheng and Liu [1] studied the soil response around a pipeline using a boundary integral method under the assumption of a rigid pipeline. Sumer et al. [2] investigated the sinking of pipelines in a liquefied soil under wave loading. Jeng and Rahman [3] developed a two-dimensional (2D) finite element model to examine the stress response of a pipeline and the excess pore pressure within the soil, in which the pipeline was assumed as an elastic material. This model was further extended to discuss the effects of soil nonhomogeneity and wave nonlinearity on the seabed response [4]. Later, Mattioli et al. [5,6] studied the near-bed dynamics around a submarine pipeline via laboratory experiments, in which the interactions between the turbulence structure and soil particles were examined in detail. Zhou et al. [7] conducted some flume tests to explore

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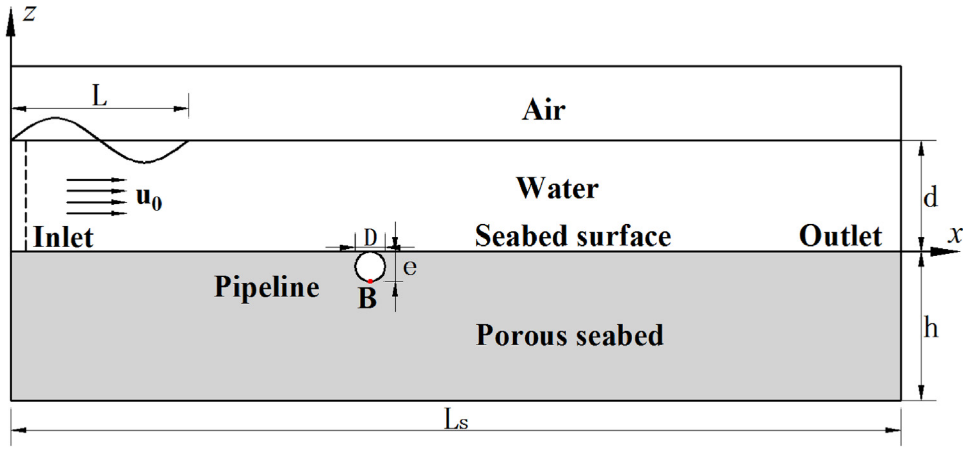
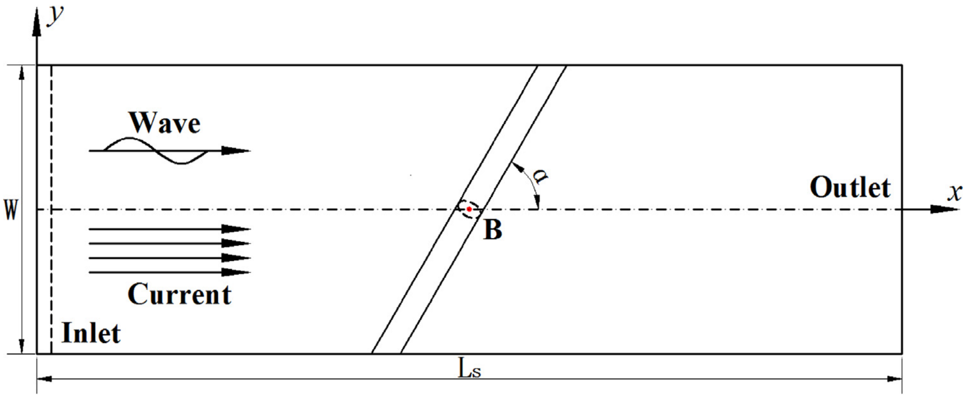
https://doi.org/10.1016/j.apor.2017.09.009



(a) Lateral view



(b) Plan view

Fig. 1. Sketch of WSPI around an offshore pipeline.

different soil responses around a pipeline under a monochromatic wave or combined wave and current loading. Zhou et al. [8] investigated the wave-induced multilayered seabed response around a buried pipeline. Recently, Zhao et al. [9] explored the influence of cross-anisotropic soil behavior on the wave-induced soil response in the vicinity of a pipeline based on a 2D integrated numerical model. Lin et al. [10] developed a 2D integrated numerical model to investigate the wave-induced transient liquefaction around a partially buried pipeline. As an extension of that study, Duan et al. [11] further developed a 2D coupled model to study the oscillatory soil response under a combined wave and current loading. All aforementioned investigations were based on 2D models, while WSPI is a three-dimensional (3D) problem in reality. As an extension of the 2D numerical model, Zhang et al. [12,13] proposed a 3D model to investigate the wave-induced soil response around a buried pipeline. However, only the wave load is included in these studies, neglecting the fact that waves and current usually coexist in the ocean environment. To enhance the knowledge on wave–current interactions (WCIs), numerous studies were conducted recently to reveal the WCI mechanism [14–19]. However, merely the WCI or wave–current–seabed interaction was considered in these studies and the pipeline was excluded.

The aim of this study is to examine the wave and current-induced oscillatory soil liquefaction around an offshore pipeline. A novel 3D integrated model for WSPI is developed in the present study, in which WCI is considered. The Reynolds-averaged Navier–Stokes (RANS) equations with the $k-\varepsilon$ turbulence model are used as the governing equations for flow simulations, and Biot's dynamic equation (known as "*u-p*" approximation) is applied to govern the soil response. In this study, the flow model is established in the computational fluid dynamics (CFD) code FLOW-3D and the seabed model is built in the finite element method code COMSOL Multiphysics. Based on the 3D integrated model, a series of analyses on oscillatory soil liquefaction potential were conducted to examine the wave and current-induced oscillatory soil liquefaction around an offshore pipeline.

2. Theoretical formulations

In this study, the 3D phenomenon of wave and current–seabed–pipeline interaction is investigated. The RANS equations combined with $k-\varepsilon$ turbulence model are employed to describe the flow model while the "*u-p*" equations [20] for poroelastic media are adopted to govern the soil response around the offshore pipeline. In this section, the governing equations for both flow simulation and seabed response will be outlined. The definition of WSPI is depicted in Fig. 1, where α is the flow obliquity (the angle between the flow propagation direction and the pipeline axial direction), h is the seabed thickness, e is the pipeline burial depth (the distance from the seabed surface to the bottom of the pipeline), d is the water depth, L is the wavelength, W is the width of the seabed, B is a point at the bottom of the