Soil Dynamics and Earthquake Engineering 80 (2016) 40–55

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Effects of cross-anisotropic soil behaviour on the wave-induced residual liquefaction in the vicinity of pipeline buried in elasto-plastic seabed foundations

H.-Y. Zhao [a,b,c], D.-S. Jeng [a,b,*], C.C. Liao [d]

[a] School of Civil Engineering, South West Jiaotong University, Sichuan, 610031, China
[b] Key Laboratory of Theory and Technology of High-Speed Railway Structures, Ministry of Education, South West Jiaotong University, Sichuan, 610031, China
[c] Griffith School of Engineering, Griffith University Gold Coast Campus, QLD 4222, Australia
[d] Department of Civil Engineering, Shanghai Jiaotong University, Shanghai 200240, China

ARTICLE INFO

Article history:
Received 25 November 2014
Received in revised form
21 May 2015
Accepted 5 October 2015

Keywords:
Pipeline
Anisotropic soil
Elasto-plastic model
Phase-resolved shear stress
Residual liquefaction

ABSTRACT

In this paper, a two-dimensional integrated numerical model is developed to examine the influences of cross-anisotropic soil behaviour on the wave-induced residual liquefaction in the vicinity of a pipeline buried in a porous seabed. In the wave model, the RANS (Reynolds Averaged Navier–Stokes) equation is used to govern the wave motion. In the seabed model, the residual soil response in the vicinity of an embedded pipeline is considered with the 2-D elasto-plastic solution, where the phase-resolved shear stress is used as a source for the build-up of residual pore pressure. Classical Biot's consolidation equation is used for linking the solid-pore fluid interaction. The validation of the proposed integrated numerical model is conducted by the comparisons with the previous experimental data. Numerical examples show that the pore pressures can accumulate to a large value, thus resulting in a larger area of liquefaction potential in the given anisotropic soil compared to that with isotropic solution. The influences of anisotropic parameters on the wave-induced residual soil response in the vicinity of pipeline are significant. A high rate of pore pressure accumulation and dissipation is observed and the liquefaction potential develops faster as the anisotropic parameters increase. Finally, a simplified approximation based on a detailed parametric investigations is proposed for the evaluation of maximum liquefaction depth (z_L) in engineering application.

1. Introduction

Submarine pipelines have been widely installed for the transportation of natural oil, gas, and industrial waste water in marine engineering. With the growing demands of developments in offshore areas, the wave–seabed–pipeline interaction problem has attracted great attentions from coastal and geotechnical engineers in the last few decades. In general, when gravitational waves propagate over the ocean, they exert cyclic fluctuations of dynamic pressures on the sea floor, which further generate pore pressures in the seabed. At this time, the pore pressure may become excessive as it cannot dissipate as fast as the wave goes. With excess pore pressure and accompanying decreases in effective stress, part of the seabed may become unstable or even liquefied. Based on the observations in field measurement [1] and laboratory experiment [2], mechanisms for the wave-induced liquefaction can be classified into two categories. The first is the oscillatory liquefaction, which normally occurs in an unsaturated seabed under wave troughs and appears as a periodic response to water waves. The other is termed as the residual liquefaction, which is induced by the build-up of pore pressure due to the plastic volumetric contraction of the soil. Once the soil is liquefied, it will behave like a heavy fluid without any shear resistance. The resulting loss of shear resistance may cause catastrophic consequences such as floating up of buried pipeline. Therefore, the evaluation of wave-induced seabed response including the pore water pressure and liquefaction phenomenon are particularly important for coastal engineers involved in the design of foundations for offshore pipelines.

Conventional approaches for the wave-induced seabed response in the presence of a pipeline are based on a potential theory [3,4], which is far away from the realistic conditions of the soil and pore fluid two-phase medium. Based on different assumptions of the

* Corresponding author.
E-mail address: dsjeng@home.swjtu.edu.cn (D.-S. Jeng).

http://dx.doi.org/10.1016/j.soildyn.2015.10.004
0267-7261/

rigidity of the soil skeleton and compressibility of pore fluid, some more advanced two-dimensional numerical studies have been developed for the wave–seabed–pipeline interaction. Among these, Cheng and Liu [5] proposed a boundary integral equation method to examine the wave-induced pore pressure around a buried pipeline, in which the buried pipeline is surrounded by two impermeable walls. Later, Madga [6] considered similar cases with a wider range degrees of saturation. Considering the elasticity of the pipeline, Jeng [7] further investigated the distributions of internal stresses within the pipeline under ocean wave loading by a finite element method. This framework has been further extended to discuss more complicated cases for the wave, seabed, pipeline interaction [8–10], in which the influences of various wave and seabed conditions (such as the non-homogeneous seabed, the nonlinear wave loading, the combined wave and current loading, and the cover layer) are investigated. Besides the 2-D models, 3-D model was also developed recently for the wave–seabed–pipeline interactions, employing the influence of wave obliquity, but limited to linear wave loading [11].

All aforementioned investigations for the wave-induced seabed response around a pipeline have only considered the seabed with isotropic soil behaviour. In natural seabeds, there is a significant difference in the elastic soil properties in different directions, due to the manner of their deposition, particle shape and stress history. However, the influence of anisotropic soil behaviour on the wave-induced seabed response has not received much attention by researchers. Gatmiri [12] may be the first to carry out parametric studies to investigate the effects of cross-anisotropic parameters on the wave-induced seabed response by using a finite element model. In his paper [12], the variations of anisotropic characteristics were found to significantly affect the wave-induced soil response including the pore pressure, effective stress and shear stress. The effects of cross-anisotropic soil behaviour on the interaction between wave, seabed and buried pipeline was first investigated by Jeng [13]. Later, Wang et al. [14] extended this framework to more complicated cases with a cover layer, as well as the influences of anisotropic soil behaviour. Recently, similar work for wave (current)-induced soil response in a cross-anisotropic seabed was carried out [15]. However, in the paper, some questionable results were found. For example, the results presented in Figs. 7 and 8 in [15] did not satisfy the boundary conditions at the seabed surface. This implies that their numerical model may be incorrect. In all above investigations, only the wave-induced oscillatory mechanism was considered.

Based on the results from field measurements and laboratory tests, the mechanisms of residual soil response and the key factors affecting the residual liquefaction process have been deeply recognised in the last few decades. Seed and Rahman [16] proposed a governing equation related to the shear stress ratio τ/σ'_0, the period of cyclic loading and the cyclic number of loading reaching the liquefaction status to describe the pore pressure build-up in sand soil under wave loading. By adopting the governing equation for the pore pressure build-up proposed by Seed and Rahman [16], Sumer and Fredsøe [17] developed an analytical solution to analyse the wave-induced residual soil response through Fourier series expansion or Laplace transformation, in which classical Biot consolidation equations are used for linking the solid–pore fluid interaction. With different forms and approaches, Jeng [18] further analytically and numerically investigated the build-up of pore pressure in shallow soil, finite soil, and deep soil, as well as the effect of random wave loading. The relationship between the elasto-plastic soil behaviour and pore pressure accumulation is emphasized by Sekiguchi et al. [19] and Sassa and Sekiguchi [20] through the application of centrifuge wave testing with a one-dimensional simple elasto-plastic model. Based on this framework, Sassa et al. [21] proposed more advanced numerical model by considering the moving boundary between the liquefied soil and sub-liquefied to investigate the progressive property of wave induced residual liquefaction. All of the investigations mentioned above are limited to 1-D models where the wave-induced shear stress amplitude was used as source of pore pressure accumulation, with emphasis on pore pressure accumulation in the unit of loading cycle rather than the details among a loading cycle. This is true for the case under high frequency loading such as earthquake or experiments in centrifugal tests. However, the period of a wave is quite long compared with that during an earthquake. The wave-induced seabed response can be complicated even among a loading cycle especially when submarine structures are incorporated in the analysis of wave–seabed interaction. To overcome this limitation, some more advanced 2-D models and their application to more general cases with breakwater built on a sloping seabed were developed recently [22–24], with the new definition of the source term where a more promising prediction for the pore pressure accumulation is shown compared to the source term determined by the shear stress amplitude.

Regarding the wave-induced residual soil response around a pipeline, laboratory experiments are one of the most popular tools in which the pore pressure build up in a sandy bed, and the sinking/flotation of the pipeline could all be captured [25–28]. In their experiments, the pore pressure build-up was indicated to be significantly affected by the presence of the pipeline, particularly at the bottom of the pipeline. Numerical models were relatively rare, Dunn et al. [29] investigated the residual pore pressure near the pipeline by using the Diana-Swandyne II (Finite Element code), and assessed both the possibilities of the residual and momentary liquefactions. Zhao et al. [30] developed a two-dimensional integrated numerical model to investigate the residual soil response in the vicinity of a buried pipeline and a partially-backfill-trenched pipeline. In [30], the developments of two-dimensional pattern of liquefaction potential were discussed in detail under a certain combination of wave and soil conditions. However, the effects of anisotropic behaviour on the residual liquefaction process had not mentioned in their investigations. To date, to the authors' best acknowledgement, no theoretical studies are available in the literature for the wave-induced residual liquefaction in the soil with a cross-anisotropic behaviour.

The main purpose of this paper is to investigate the effects of cross-anisotropic soil behaviour on the residual liquefaction potential in the vicinity of a buried pipeline under ocean wave loading. Firstly, we compare the numerical results to the laboratory experiments to ensure the accuracy of the scheme for integrated 2D numerical model. Secondly, the difference in the residual mechanism including the distribution of residual pore pressure and development of liquefaction potential around a buried pipeline between isotropic and anisotropic soil will be investigated. Finally, the effects of variation of anisotropic parameters on the maximum liquefaction depth will be discussed through a detailed parametric study.

2. Theoretical formulation

In this study, we consider that a pipeline with an outer diameter (D) is fully buried within a seabed with finite thickness (h), as depicted in Fig. 1. Ocean wave trains propagation over a porous seabed may result in excess pore pressure which can be divided into two components [31], as shown in Fig. 2, which can be expressed as

$$u_e = u_e^{(1)} + u_e^{(2)}, \tag{1}$$

where u_e represents the excess pore pressure, which is induced by the phase lag between the dynamic pore pressure in seabed and the dynamic pressure induced by the wave propagating on seabed. $u_e^{(1)}$ represents the transient or oscillatory excess pore pressure, whose temporal average $\overline{u}_e^{(1)}$ over wave cycle (t/T) equals to zero.