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Three-dimensional poro-elasto-plastic model for wave-induced seabed response around submarine pipeline

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ABSTRACT

The evaluation of the wave-induced excess pore pressure around a buried pipeline is particularly important for pipeline engineers involved in the design of offshore pipelines. Existing models for the wave-induced seabed response around submarine pipeline have been limited to poro-elastic soil behavior and de-coupled oscillatory and residual mechanisms for the rise in excess pore water pressure. To overcome the shortcoming of the existing models, in this study a three-dimensional poro-elasto-plastic soil model with submarine pipeline is established, in which both oscillatory and residual mechanisms can be simulated simultaneously. With the proposed model, a parametric study is conducted to investigate the relative differences of the predictions of the wave-induced pore pressure with poro-elasto-plastic model. Based on numerical examples, it can be concluded that the poro-elasto-plastic behaviors of soil have more significant influence on wave-induced pore pressure of seabed around submarine pipeline. As the seabed depth increases, the normalized pore pressures decrease rapidly at the upper part of seabed, and then change slightly at the lower part of the seabed. Soil permeability and wave period have obvious influence on the wave-induced normalized pore pressure.

1. Introduction

Wave-induced seabed instability is one of the key factors that must be considered in the design of foundation in the vicinity of marine structure such as pipelines and breakwaters. It has been well documented that ocean waves propagating over the ocean surface exert dynamic pressure fluctuations on the sea floor. The dynamic pressure fluctuations further induced excess pore pressure within the soil skeleton, and then subsequently lead to the variation of stresses in seabed. This mechanism involved in this process is rather complicated since it is a coupled problem among soil, pore fluid and structures. Furthermore, it is vital because that it could lead to the reduction of strength or even liquefaction of the foundation around marine structures. It has also been reported that the soil supporting the pipeline may fail due to liquefaction, resulting in the self-burial of the entire pipeline [1,18]. Moreover, it has been observed that a deep scour hole exists near the tip of a marine structure [5]. Without proper maintenance at these sites, failure of structures may occur.

Generally speaking, two mechanisms of the wave-induced seabed response in the rise in pore water pressure have been observed in the field measurements and laboratory experiments, depending upon the way the excess pore pressure is generated [15,23]. One is caused by residual or progressive nature of the excess pore pressure, which appears at the initial stage of cyclic loading. This type of soil response is similar to that induced by earthquakes, which resulted in the build-up of the excess pore pressure. The other is generated by transient or oscillatory excess pore pressure that is accompanied by the damping of amplitude and phase lag in the pore pressure [22,7,8].

Numerous investigations for the wave-induced seabed response have been carried out since the 1970s. Among these, analytical approximations have been developed by various researchers such as Madsen [11], Yamamoto et al. [22], Mei and Foda [14], and Jeng [7,8]. Numerical simulations also have been widely applied to examine such a problem in recent years. Cheng and Liu [4] considered a buried pipeline in a region that is surrounded by two impermeable walls. Magda [13] considered a similar case with a wider range of degree of saturation. Luan et al. [10] considered soil–pipeline contact effects and inertial forces in a new model. At the same time, experimental work has attracted attention from researcher and pipeline engineers. Teh [19] considered the two recent contributions to the problem of the on-bottom stability of marine pipelines on liquefied seabed.

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All the aforementioned investigations have been limited to poro-elastic model. It has been well known that poro-elastic models are only valid for small deformation. For large deformation, especially for the case of seabed of seabed instability, the modeling of the soil behavior requires a more sophisticate model such as elasto-plastic models. To further investigate dynamic response of three-dimensional poro-elasto-plastic model for seabed around submarine pipeline under wave loading, a finite element program DYNE3WAC (DYNamic Earthquake Analysis Program 3D Window Version for ACadiemic) [16] is used in this paper. The 3D poro-elasto-plastic model is based on the fully implicit u–p approximation of the Boit formulation [3]. The fully coupled Boit dynamic equations were employed, together with the u–p approach (skeleton displacement u and pore pressure p), in which the fluid acceleration relative to the solid skeleton is negligible. The model can be used for static, consolidation and dynamic situations under drained and undrained conditions.

The contribution of this study is putting forward a 3D poro-elasto-plastic model for the wave–seabed interaction around submarine pipeline. With the proposed model, a parametric study is conducted to examine the effects of wave and soil characteristics on the wave-induced soil response around submarine pipelines.

2. Boundary value problem

In this study, a three-dimensional problem is considered. A fully buried pipeline (with a radius 0.5D) is located in a porous seabed of finite thickness h laid upon an impermeable rigid bottom and surrounding by four impermeable walls (see Fig. 1). The wave crests are assumed to propagate in the x-direction on the surface of the seabed, while the z-direction is measured positive upward from the surface of the seabed.

2.1. Boundary condition

For a porous seabed of finite thickness, as shown in Fig. 1, to evaluate the wave-induced seabed response around a buried pipeline, the following boundary conditions are considered.

Firstly, zero displacements and no vertical flow occur at the impermeable horizontal bottom, i.e.

$$u_{sx}=0\ u_{sy}=0\ u_{sz}=0\ \frac{\partial p}{\partial z}=0, z=-h \tag{1}$$

Secondly, we assume that the bottom frictional stress is small and negligible. The vertical effective normal stress and shear stress vanish and pore pressure is equal to the wave pressure at the

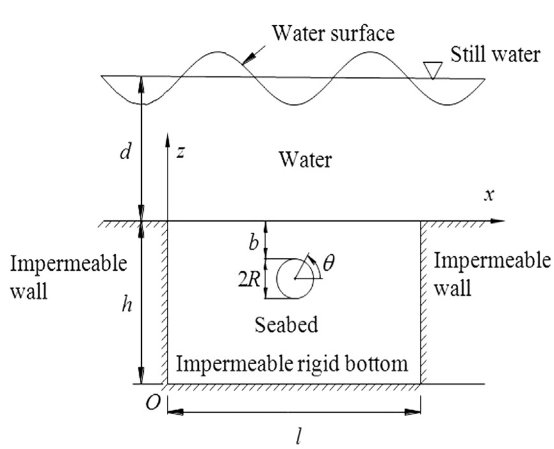

Fig. 1. Definition sketch of a submarine buried pipeline with boundary conditions under wave loading.

surface of the seabed, i.e.

$$\sigma'_{sz}=\tau_s=0 \tag{2}$$

$$p=\frac{\gamma_w H}{2\cosh(kd)}\cos(kx-\omega t), at\ z=0 \tag{3}$$

where $p_0=\gamma_w H/2\cosh(kd)$ denotes the amplitude of the wave pressure at the surface of the seabed, d is water depth, H is wave height, k is the wave number and ω is the wave frequency.

Thirdly, we assume that there is no flow through the pipeline wall. This assumption is valid because the pipeline is considered as elastic impermeable material. Thus, the pore pressure gradient on the surface of the pipeline (r=R) should vanish, i.e.

$$\frac{\partial p}{\partial n}=0, \quad r=\sqrt{(x-x_0)^2+(y-y_0)^2+(z-z_0)^2}=R \tag{4}$$

where r is the parameter of polar coordinate of the pipeline, x_0 and z_0 denote the coordinates of the center of the pipeline and n is the normal direction to the surface of the pipeline.

Fourthly, we consider the lateral boundary is impermeable, i.e.

$$u_{sx}=0, \frac{\partial p}{\partial x}=0,\ \text{at}\ x=0\ \text{and}\ x=l \tag{5}$$

$$u_{sy}=0, \frac{\partial p}{\partial y}=0,\ \text{at}\ y=0\ \text{and}\ y=m \tag{6}$$

2.2. Soil–pipeline contact effects

In the analysis of seabed–pipeline interaction, there may exist shear sliding at the interface between soil column and pipeline under wave loading. Most previous investigations for the soil–pipeline interaction did not consider the contact effects between soil and pipeline [4]. To simulate the contact effects along soil–pipeline interface, a contact element can be established to link two materials in the finite element analysis. Meanwhile, the effects in normal and tangential directions are considered. In the tangential direction, the contact effects include the relative sliding and frictional shear stress. In numerical calculations, the segment method is used. To simulate the effects of interaction at the interface, we need to select the contactor surface and target surface. An important distinction between a contactor surface and a target surface is that in the converged solution, the material overlap at the contactor nodes is zero; the target nodes can overlap the contactor body. In general, the contactor surface should select the surface of fine mesh. Thus, herein, the outer surface of the pipeline is the contactor surface, and the soil column with pipeline is considered as target surface. According to the Coulomb friction theory, the friction shear stress at the interface of seabed and pipeline (τ_c) can be expressed in terms of frictional coefficient (μ) and contact pressure at two contact surface (p_c), i.e., τ_c=μp_c (μ=0.7 in this study). The shear sliding only occurs when surface drag force is greater than frictional shear stress.

3. Poro-elasto-plastic model

3.1. u–p model

In general, the three-dimensional poro-elasto-plastic computer program DYNE3WAC [16] is based on the fully implicit u–p approximation of the Biot formulation [3]. The dynamic governing equations for the u–p approximation of the Biot formulation are basically the momentum equations for the soil–fluid "mixture" and the mass balance of the flow. In this section, we only provide a