Wave-induced Dynamic Response of a Layered Poroelastic Seabed around an Offshore Pipeline

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ABSTRACT

The main objective of this paper is to investigate the wave-induced dynamic response of seabed around a pipeline in a multi-layered porous seabed. Biot's poro-elastic theory is employed to describe the phenomenon of wave-seabed-pipeline interaction in a layered porous seabed. To explore the mechanism of the pipeline instability, the partly dynamic model, \( u-p \) model is adopted, where the soil displacement \( (u) \) and the pore pressure \( (p) \) are the primary variables and it is capable of considering the acceleration of soil skeleton. A parametric study is carried out to examine the influences of various representative seabed and wave parameters. The influence of pipeline buried depth on seabed response is also investigated. The results show that the pore pressure decreases when permeability decreases. The pore pressure concentration reduces as the buried depth \( e \) increases, while the vertical stress on the pipeline surface increases as the buried depth increases.

KEY WORDS: Wave loading; Layered poro-elastic seabed; Dynamic response; \( u-p \) formulation.

INTRODUCTION

The evaluation of wave-induced seabed response is one of the important factors in the design of offshore pipeline. When water waves propagate over a porous seabed, the dynamic wave pressure acting on the seabed surface will further induce excess pore pressure and effective stresses. When the pore pressure increases with accompanying decrease in effective stress, part of the seabed may become unstable or even liquefied. Then, the seabed around pipeline will become unstable and further cause the instability of the structure. Thus, it is important to accurately predict the dynamics and stability of such pipelines during the design phase.

Many researchers have focused particularly on understanding the instability of an offshore pipeline subjected to wave loadings. However, this problem has not been fully understood because of the complicated soil behavior. There have been extensive studies on the modeling and analysis of the vibrations of pipeline systems over the past half-century (Yamamoto et al., 1978; Madsen, 1978; Thomas, 1989; Raman-Nair and Sabin, 1991; Jeng and Seymour, 1997; Luan et al., 2008, Zhou et al., 2010; Zhang et al., 2011, Zhou et al., 2011). In the literature, various approaches, including analytical, numerical and experimental studies, have been used to investigate the wave-induced liquefaction potential. The response of porous seabed is usually formulated in the frame work of the theory proposed by Biot (1941), who then extended them to include dynamics (Biot, 1956, 1962). Jeng and Cha (2003) developed the analytical solution for the full dynamic model based on the dynamic poro-elastic theory (Biot, 1956). In the paper, they clarified the applicable range of full-dynamic and quasi-static models with a simple relation for engineering practice. Zhou et al. (2011) proposed the TRM method to investigate the wave-induced response of a multi-layered porous seabed with arbitrary number of layers.

Based on Biot's model, the wave-induced pore pressure around a pipeline has been studied by some researchers (Turcotte et al., 1984; Cheng and Liu, 1986; Sumer and Fredsøe, 1991; Magda, 1997; Sumer et al., 2001). Among these, Magda (1997) studied the behaviour of hydodynamic uplift force acting on a submarine pipeline in a sandy soil and concluded that the uplift force increases with increasing wavelength and degree of soil saturation. McDougal et al. (1988) proposed an analytical model for estimating the pore pressure in the soil and the resulting pressure force on buried pipelines in case of the rigid infinitely deep seabed. Zienkiewicz et al. (1980) proposed the \( u-p \) approximation to porous flow through one-dimensional analysis. This model has been first applied to the wave-induced soil response and clarified the range of its application (Jeng et al., 1999). Sumer and Fredsøe (1991) and Sumer et al. (2001) conducted a series of experiments focusing on the stability of pipelines on liquefied sandy seabed and the onset of scour around the pipeline. By analyzing the pore water pressures measured at the upstream and downstream of a slightly buried pipeline, they have shown that the excessive seepage flow due to pore pressure gradient in the soil and the resulting piping effect are the major cause of the onset of scour. Jeng and Cheng (2000) proposed a finite difference model in a curvilinear coordinate system to investigate the wave-induced soil response in the vicinity of a buried pipeline.

The main purpose in this paper is to investigate the wave-induced response of a multi-layered porous seabed. The partly dynamic \( (u-p) \) approximation method is used to characterize the layered poro-elastic seabed. Firstly, the finite element model is verified by a comparison between the present solution and the previous analytical solutions for a single layer seabed. Then, a series of parametric study is carried out to examine the effects of various soil and pipeline parameters on the wave-induced layered seabed response.