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Physical Model of wave-induced seabed response around trenched pipeline in sandy seabed

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ABSTRACT

The phenomenon of wave-seabed-pipeline interactions is one of the primary concerns of coastal engineers and researchers, as it could greatly affect the seabed instability and pipeline safety. Numerous researchers have expended great effort in studying wave-seabed-pipeline interactions in the past. However, the majority of them focussed on the wave-induced response around a submarine pipeline, in buried conditions, by numerical models and laboratory experiments. Unlike the previous studies, a series of regular wave experiments and numerical model analyses were conducted to investigate the wave-induced pore pressure in the sandy seabed, around a pipeline with different backfilled depths. The model pipeline with three diameters ($D = 6$ cm, 8 cm, and 10 cm) is buried in three sizes of sand, $d_{50} = 0.15$ mm, $d_{50} = 0.3$ mm, and $d_{50} = 0.5$ mm, with different backfilled depths. The results show that the pore pressure amplitude in the seabed is a minimum with a backfilled depth D, and a maximum with full backfill or a backfilled depth of zero. The pore-pressure amplitude increases as the backfill sand median diameter increases. The effects of the pipeline diameter on pore-water pressure are also analysed and discussed.

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1. Introduction

Submarine pipelines play an extremely important role in offshore engineering for the transportation of offshore oil and gas. One of the critical problems in the design of a pipeline, that is laid on or partly buried in the porous seabed, is to assess whether the pipeline will remain stable with the strong action of ocean waves. Clearly, the wave-induced seabed interaction around the pipeline is of particular importance in the design of offshore pipeline installations, and has attracted considerable attention among coastal and geotechnical engineers. In the past years, numerous offshore pipelines have been reported damaged from wave-induced seabed instability [1–4], as opposed to construction or material breakdowns. When a pipeline is placed in a trench with different backfilled depths, it could significantly disturb the wave motion and wave pressure around the pipeline, and consequently lead to changes in the effective stress in the seabed. Therefore, the evaluation of the wave-induced seabed response is of particular importance when designing protection of offshore pipelines.

Because of its practical importance, and potential engineering applications, extensive investigations on the interaction between waves, seabed, and pipelines have been conducted in recent years, using both theoretical and experimental approaches [5,6]. However, understanding the results of studies on wave-seabed-trenched pipelines, with different backfilled depths, remains incomplete. For example, MacPherson [7] studied the wave-induced pore pressure in a permeable seabed around a pipeline, and indicated that the seepage force should be considered. Cheng and Liu [8] used a boundary integral equation method to investigate the effects of wave and seabed parameters on the uplift seepage force and pore pressure around a pipeline, that was buried in a rectangular region with impermeable walls. There were a number of numerical analyses considering the effects of a cover layer with full backfilled conditions on the wave-induced seabed dynamic response around a buried pipeline [9–12]. However, these models may not be able to predict the seabed response in the neighbourhood of a pipeline when a wave is propagating over a partially backfilled pipeline, as opposed to fully backfilled. More recently, Zhao et al. [13] and Lin et al. [14] developed numerical models to

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investigate wave-induced soil responses around a buried pipeline, that was partially backfilled, and predicted the stability of a submarine pipeline. Their results showed that the pipeline backfilled up to a certain depth is better protected against wave-induced liquefaction.

In addition to the aforementioned theoretical methods mentioned above, some laboratory experiments have been conducted to investigate wave-induced soil dynamic responses, and the stability of offshore pipelines. Among these, Pan and Wang [15] carried out a series of large-scale laboratory experiments to study wave-induced pore pressures around shallowly embedded pipelines. Higher pore pressures were recorded at the top, and lower pore pressures at the bottom of a pipeline, for a sandy seabed. Sumer et al. [16,17] conducted a series of physical experiments to investigate the stability of pipelines on a liquefied sandy seabed, and the onset of scour below the pipeline in currents/waves. By analysing the pore-water pressures measured upstream and downstream of a partially buried pipeline, they reported that the excessive seepage flow and the resulting piping were two primary factors that caused the onset of scour below the pipeline. Sumer et al. [18] further extended the physical experiments to investigate the dynamic response around a pipeline buried in soil, and exposed to a progressive wave, by measuring pore pressures. The presence of the pipeline had no major influence on the build-up of pore pressure at the top of the pipe. The results further indicated that liquefaction initially occurred in the very top layer, and developed downwards, but was different in the vicinity of the pipe. Recently, Zhou et al. [19] experimentally studied the combined effects of waves and currents on the characteristics of soil responses around a marine pipeline. The results showed that the current intensifies the erosion process in all types of soils, and pore pressures in sandy soil decrease marginally over time. Yang et al. [20–22] presented results from a series of laboratory experimental models that studied the major safety issues of subsea pipelines induced by seabed scouring. A rubber plate was placed between the submarine pipeline and the bed, while a rigid spoiler was attached to the top of the pipe. The experiments showed that the rigid spoiler could increase the scour depth, thus greatly speeding up self-burying. In addition, they found that there existed a critical length of rubber plate, greater than which there was no scour around the pipeline and the pipeline was protected. If the rubber plate was shorter than the critical length, scour around the pipeline was significantly increased and self-burial of the pipe was accelerated. Recently, Fredsøe [23] reviewed the cause of pipeline-seabed interaction and the resulting consequences for pipeline stability in a natural environment.

The aforementioned studies focused on the wave-induced seabed response around a pipeline that is either fully buried, or resting on the seabed in different types of soil. However, in engineering practice, pipelines are occasionally placed in a trench that is partially backfilled with soil excavated from the seabed during trenching, or coarser materials, to reduce the possibility of instability/liquefaction. To date, only a few theoretical studies regarding the effects of partial backfill on the wave-induced seabed response around a buried pipeline are available in the literature, therefore, the actual mechanisms behind this marine process may not be fully captured or explained. Moreover, there is no physical modelling for the effects of a backfill layer on the dynamic soil response surrounding a trenched pipeline. Therefore, it is important to conduct such an experiment to properly and accurately predict wave-induced soil response around a pipeline, that is partially backfilled, in a porous seabed. The primary aim of this study is to present results from an experimental study of soil behaviour around a trenched pipeline, with different backfill depths in various types of soils, subject to regular wave action. To the best of the authors knowledge, the present study is the first set of wave experiments regarding a trench layer with a partially buried pipeline. At the same time, a numerical model is used to investigate the distribution of wave-induced pore-water pressure for different seabed conditions.

2. Experiment model

2.1. Experimental set-up

The experiments were conducted in a wave flume, 1.0 m wide, 1.3 m deep, and 50 m long. The experiment was performed at a 1:30 geometric scale, and at a 1 g condition (g is the gravational acceleration). Hettler [24] pointed out that, at 1 g, the soil in a field test can be used in model experiments without particle size scaling, although the geotechnical engineers argued about the stress level within the seabed. Fig. 1 shows the detailed setup of the experiment. The bottom of the flume was elevated 0.25 m by constructing plywood floors on both sides of the sediment basin. Two plywood ramps, with a 1:10 slope, were built at the end of the false floors to ensure smooth transformation of the waves before entering the measuring section. The flume comprised a piston-type wave generator and two porous, sloped wave absorbers at either end of the flume to minimise wave reflections. The wave maker could generate regular waves with periods 0.6–2.5 s, and wave heights up to 0.2 m. Four wave-height gauges were positioned along the central axis of the flume to measure the variation of wave height at the test section. The specific locations are depicted in Fig. 1. The water level on top of the mudline (i.e., water depth) in all tests was maintained at 0.40 m.

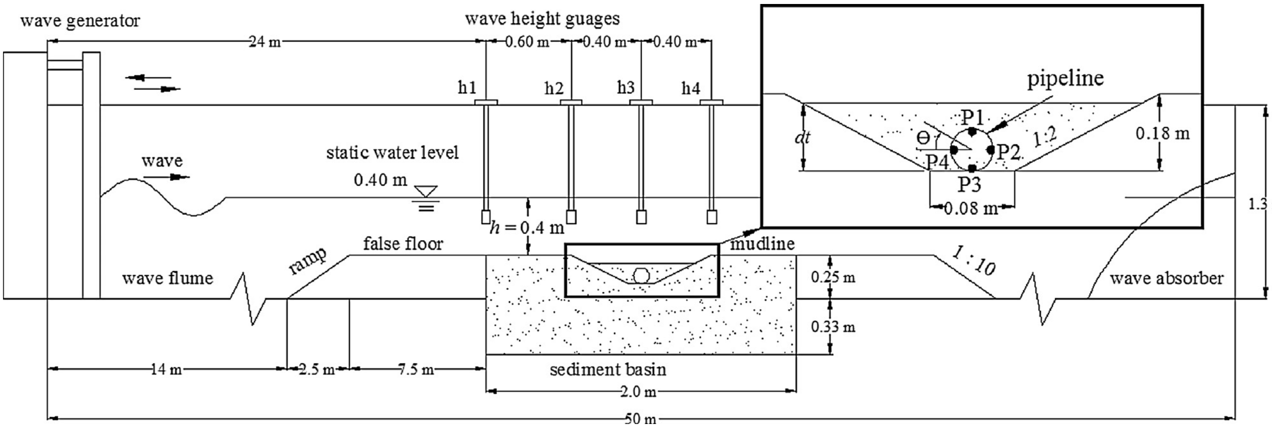

Fig. 1. Schematic of wave flume.

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