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# Oscillatory Seabed Responses Around Two Pipelines in Tandem Under Combined Wave and Current Loading

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**Seabed stability around submarine pipelines under wave-plus-current loading is one of the major issues in offshore projects. Unlike previous works that focused mainly on the evaluation of the seabed response around a single pipeline, in this study, two pipelines in tandem will be considered. The previous model (PORO-FSSI-FOAM) will be adopted to investigate the effect of the gap ratios ($G/D$) of twin pipes on the wave and current-induced oscillatory seabed response. The numerical model is validated with the previous experimental data for two pipelines in tandem. Based on numerical examples, the following conclusions were found: (i) when the gap ratio ($G/D$) is greater than 1.25, the soil response beneath both pipelines is more significant than in the condition of a single body; and (ii) the maximum liquefaction depth appears to increase as $k_s$ and $S_r$ decrease, and $k_s$ is more sensitive to the evolution of the liquefied zone.**

## INTRODUCTION

Pipelines have been one of the essential associated installations for the oil and gas industry, which have been used for the transportation of oil and gas from offshore to onshore. Since the first offshore pipeline was built by Brown Root to carry oil in 1954, submarine pipeline networks have been regarded across the globe as the “lifelines” of the oil industry (Sumer and Fredsøe, 2002). The existence of a submarine pipeline does not only alter the nearby flow morphology, but also enhances the surrounding seafloor instability (including soil liquefaction, scour, and shear failure) and ultimately causes damage or failure of the pipeline (Sumer, 2014).

In general, when the seabed is exposed to the wave, the dynamic pressures along the seafloor can induce pore pressures, effective stresses, and soil displacements within the seabed (Jeng, 2012). Then, the seabed in the vicinity of the pipeline could become unstable or even liquefied due to the increasing excess pore pressures and the reduced vertical effective stresses. Once the liquefaction occurs, the soil will behave like a kind of heavy fluid without any shear resistance, which greatly increases the risk for the pipeline to sag.

Two categories associated with the mechanisms of wave-induced seabed liquefaction have been identified (Nago et al., 1993; Zen and Yamazaki, 1990): oscillatory and residual liquefaction, depending on the pattern of variations of the excess pore pressure. Among these, oscillatory liquefaction normally appears instantaneously under wave troughs in very dense sand deposits with linear reversible soil characteristics, which is related to phase lag and amplitude decay in the oscillatory pore pressures (Madsen, 1978). Residual liquefaction is generally caused by the buildup of the excess pore pressure under the volumetric wave loading, which is usually observed within the fully saturated seabed (Seed and Rahman, 1978; Sumer, 2014). In this study, only the oscillatory liquefaction mechanism with transient pore pressure is examined.

Based on Biot’s poro-elastic theory (Biot, 1941), several numerical studies for the Wave-Seabed-Structure Interactions have been available in the literature. Among these, Jeng and Cheng (2000) proposed a Finite Difference Method model to discuss the possibility of wave-induced shear failure around a pipeline. They found that, as the burial depth and pipe radius increase, the potential shear failure around a pipeline rises in the seabed with a lower degree of saturation. A few Finite Element Method studies have been implemented to explore the wave-induced seabed responses around a buried or trenched pipeline (Gao et al., 2003; Gao and Wu, 2006; Zhang et al., 2011). However, the aforementioned investigations have not considered the combined loading of waves and currents. A more recent attempt related to the wave and current-induced liquefaction around a buried pipeline was numerically performed by Liang et al. (2020) in a 3D pattern. In their study, the design of a trench layer was also involved.

Extensive investigations only focused on a single pipeline, although it is common to have two tandem pipelines in engineering practice for transporting hydrocarbons. With the development of offshore oil and gas engineering, more than one pipe is required to be laid along the same path on the seabed. Regarding the arrangement of multiple pipes, the flow patterns and seabed response around them are difficult to estimate (Rados et al., 2000). Due to technical and economic factors, two identical pipelines are occasionally laid in tandem. For instance, the recent pipeline project, Nord Stream, consists of the construction of two parallel natural gas pipelines. The two 1,224-kilometre offshore pipelines are the most direct connection between the vast gas reserves in Russia and energy markets in the European Union. The pipeline system’s total capacity is set to double to 110 billion cubic metres following Nord Stream 2 (second pipeline)’s entering into operation. Nord Stream 2 could help Europe secure a relatively low-cost supply of gas (Hirschhausen et al., 2018). Therefore, two pipelines in tandem tend to play a key role in offshore oil-gas transportation.

In the existing design method, the two tandem pipelines were processed individually. However, Li et al. (2020) revealed the

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