THE ROLE OF SEEPAGE RESPONSE IN TSUNAMI SCOUR

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INTRODUCTION

Tsunamis have distinctly different scour mechanisms compared with wind-generated waves or steady currents. Tonkin et al. (2003) showed that the shear stress measured on the sandy bed during the tsunami draw-down cannot qualitatively explain the rapid erosion around an monopile. They attributed this rapid erosion to the seepage response in the underlying soil induced by the rapidly decreasing water level. When the tsunami-induced upward pore-pressure gradient exceeds the buoyant weight of the sediment, the effective stress between sediment grains could vanish to form momentary liquefaction. Yeh and Mason (2014) reported the momentary liquefaction induced by the 1960 Chilean tsunami under no ground shaking and low flow velocity. These studies have identified that the seepage response can affect sediment transport and tsunami-induced scour, while the classic sediment transport model (e.g. used in Larsen et al. 2017) without considering seepage cannot well simulate the tsunami scour processes.

It is technically not possible to directly observe the seepage effects on tsunami scour in a laboratory experiment in a wave flume, as the wave-induced seepage within the surficial seabed is commonly very low compared with the buoyant weight of the sediment. This study aims to numerically quantify the contributions from the dynamic seepage response to tsunami-induced scour by a fully coupled hydrodynamic and morphological model. The role of seepage response in tsunami-induced sandy seabed scour beneath a submarine pipeline and around a monopile is discussed. This study will pave the way for better predictions of the tsunami scour.

HYDRODYNAMIC AND MORPHOLOGICAL MODELS

In this study, we further developed the fully coupled hydrodynamic and morphological computational fluid dynamics (CFD) models implemented by Jacobsen (2011) and Jacobsen et al. (2014) in the OpenFOAM framework. The hydrodynamic model solves the incompressible Reynolds-averaged Navier-Stokes (RANS) equations and closes it with the two-equation $k - \omega$ turbulence model (Wilcox 2006, 2008). The morphological model is based on a sediment continuity (Exner) equation considering the deposition and erosion stemming from the bed load transportation and sediment suspension. Li et al. (2020) for the first time coupled this sediment transport model with constant upward seepage effect. Considering the dynamic seepage forces induced by tsunami waves, we further develop this model by formulating the critical bed shear stress and bed load transportation. Moreover, the dynamic seepage velocities are imposed on the seabed according to Darcy's law.

TSUNAMI SIGNAL AND SEEPAGE RESPONSE

The signal from the 2004 Indian Ocean tsunami observed in the yacht Mercator at a water depth of 14 m is considered. Madsen et al. (2008) represented the leading wave of this signal as a sinusoidal wave with an amplitude of 2.5 m and a period of 780 s. The maximum velocity U_m can be estimated by the linear shallow water theory. The sandy seabed composed of cohesionless grains has a median diameter of 0.19 mm and a specific gravity of 2.65. The dynamic pore-pressure gradient i/i_c in the underlying permeable soil is obtained by Terzaghi's consolidation theory (Terzaghi 1943), where i_c is the critical pore-pressure gradient required to cause the momentary liquefaction. For scour simulations using the present advanced CFD models, we down-scaled the tsunami and structural parameters by maintaining the Froude number based on the pipeline/monopile diameter and the ratio of the boundary layer thickness to pipeline/monopile diameter with a scaling factor of 25 to reduce the computational cost, following Larsen et al. (2017).

Figure 1 shows the free-stream velocity U/U_m of the tsunami wave. The two half cycles represent the run-up and draw-down processes. The pore-pressure gradient response to the tsunami loading is sequentially suction (downward seepage) and injection (upward seepage) with a $0.125T$ phase advance compared to the free-stream velocity.

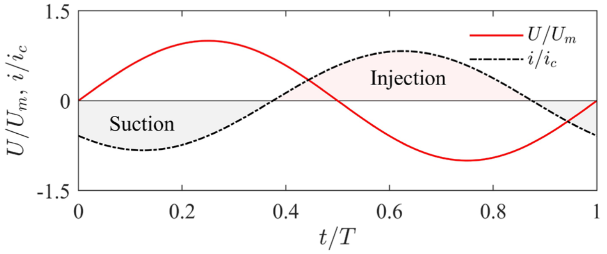

Figure 1 - Free-stream velocity and corresponding pore-pressure gradient at the seabed surface

TSUNAMI-INDUCED SCOUR BENEATH A PIPELINE

In the present simulations, the diameter D of the prototype pipeline is 0.75 m. An initial sinusoidal scour hole with $S/D = 0.15$ is prespecified to ensure the existence of computational cells below the pipeline, where S is the scour depth. To investigate the seepage effects on tsunami scour, we compare the scour depth beneath the center of the pipeline between the seabed with "seepage-on" and "seepage-off" cases, as shown in Figure 2. The "seepage-on" case considers the seepage response induced by the tsunami loading, while the "seepage-off" case serves as a control group without considering the seepage. After the tsunami run-up, the scour hole is approximately 20% deeper under the seabed suction than that of the "seepage-off" case. During the tsunami draw-down, the scour hole further deepens under the high injection intensity. The momentary liquefaction does not happen as the maximum $i/i_c < 1$. Afterward, the scour hole gradually backfills and approaches an equilibrium depth. For the "seepage-off" case, the scour hole rapidly backfills due to the erosion of the downstream shoulder. With the increasing backward flow velocity and the narrowing gap between the pipeline and the seabed, the scour depth gradually increases and arrives at a slightly higher equilibrium value than the "seepage-on" case.

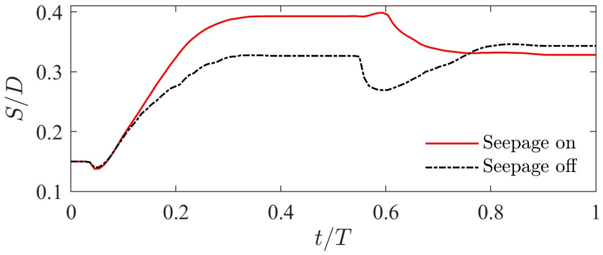

Figure 2 - Scour depth beneath the center of the pipeline

TSUNAMI-INDUCED SCOUR AROUND A MONOPILE

We further consider the tsunami scour around a prototype monopile with diameter D of 2.5 m. The present scaling approach ensures the similarity of the horseshoe vortex size in front of the monopile and the adverse pressure gradient induced by the structure between the field and model scale. Figure 3 compares the scour depth at the side of the monopile between the seabed with "seepage-on" and "seepage-off" cases. After the tsunami run-up, the scour depth under the seabed suction is generally lower than the "seepage-off" case, which differs from that beneath the pipeline. As the flow reverses, the scour hole backfills due to the erosion at the back of the monopile. Subsequently, more rapid scour with a gradient of 0.74 is observed with "seepage-on" compared to 0.52 with the "seepage-off" case, which is consistent with the results of Tonkin et al. (2003) and Yeh and Mason (2014). The upward seepage forces offset the part of the submerged weight of sediment particles and reduce the resisting frictional forces of sediment grains. Therefore, the sediment is easier to be transported away. Again, the equilibrium scour depth at the side of the monopile is higher for the "seepage-off" case after the tsunami propagation.

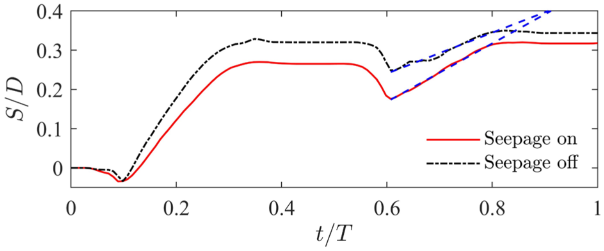

Figure 3 - Scour depth at the side of the monopile

CONCLUSION

In this study, we have investigated the effects of dynamic seepage response on tsunami-induced scour beneath a submarine pipeline and around a monopile by further developing the fully coupled hydrodynamic and morphological computational models. The seepage response leads to different trends of the scour hole development between the pipeline and monopile compared to the simulations without considering the seepage. Our results show that the seepage response plays a critical role in the tsunami-induced scour during both run-up and draw-down processes, which should be considered in the predictions of tsunami scour.

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