Local Scour and Pore-water Pressure around a Monopile Foundation under Combined Waves and Currents

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ABSTRACT
A series of experiments were conducted in a large flow-structure-soil interaction flume to analyze the scour development and pore-water pressure response around a monopile foundation under the action of combined waves and currents. In the experiments, the scour depth and pore pressure response around the pile were measured simultaneously. The experimental results indicate that the maximum equilibrium scour depth due to waves plus currents is greater than a linear sum of those caused by waves and currents respectively. This nonlinearity effect is particularly obvious when the sand-bed condition under currents or waves alone is in clear-water regime. The maximum equilibrium scour depth normalized with pile diameter is closely dependent on the Froude number with increasing the wave-induced water particle velocity meanwhile the current velocity keeping constant. The wave-induced pore pressure gradient around the monopile under the wave trough weakens the buoyant unit weight of the surrounding sand and induces the sand-bed more susceptible to scouring.

KEY WORDS: monopile; local scour; pore pressure; combined waves and currents

INTRODUCTION
In recent decades, quite a few monopile foundations have been utilized in shallow-water subsea locations for economically constructing fixed-bottom offshore structure systems, e.g. oil platforms, offshore wind farms and long-span cross-bay bridges. Local scour and soil liquefaction usually occurs around the pile due to various hydrodynamic loads, e.g. waves, unidirectional currents and tidal. As such, the bearing capacity of the monopile is reduced and the stability of coastal structures could be threatened. In most parts of coastal and shelf seas, scour process becomes more complex owing to the coexistence of waves and currents than those in the cases of waves or currents alone.

The local scour around a monopile or pile groups under steady flow or current alone was originally studied for the scour protection design of the bridge piers in the river. It has been investigated extensively from various aspects, e.g. scour mechanism, time scale, prediction of the maximum scour depth, and preventive measures for scour. e.g. Raudkivi and Ettema (1983), Chiiew and Melville (1987), Melville and Sutherland (1988), Breusers and Raudkivi (1991), Hoffmans and Verheij (1997), Ettema et al. (1998), Melville and Chiew(1999) and Whitehouse (1998). Many empirical formulas have been proposed to predict the depth, extent and rate of scour. Meanwhile, quite a substantial knowledge of scour around pile in waves has accumulated in the last decades. Sumer et al. (1992) and Kobayashi and Oda (1994) demonstrated that the Keulegan-Carpenter number ($KC$) is the main parameter governing the scour process on a live-bed. The relative density of the soil also has much influence on the scour depth in waves (Sumer et al., 2007).

Nevertheless, studies on scour under combined waves and currents are still rare. The studies by Wang and Herbich (1983, 1984) showed that the scour depth under waves plus currents is essentially not radically different from that in the case of the waves or currents alone, which has been proved not a general rule by Sumer and Fredsøe (2001), but mainly determined by the test parameter range in their experiments. The experimental results of Eadie and Herbich (1986) indicated that the scour development is faster and the equilibrium scour depth is greater under waves plus currents, compared with the case of currents alone. Kawata (1988) conducted tests to mainly examine the process of local scour around a pile under combined waves and currents in the regimes of clear water scour and live-bed scour and to study the effect of sand ripples on the scouring characteristics. Sumer and Fredsøe (2001) conducted a series of tests of waves propagating either with or against the currents, indicating that the scour depth for combined waves and currents is a function of the $KC$ number and the ratio of velocities ($U_c/(U_r + U_w)$), and the scour depth is not influenced by the direction of wave propagation. The aforementioned studies on the scour under combined waves and currents mainly focused on the effects of flow velocity, i.e. the effect of wave-induced pore pressure in the soil has been rarely taken into account in the previous studies. The wave-induced dynamic pore pressure may lead to liquefaction or partial liquefaction of the soil and finally affect the scour process. The scour around marine structures under waves or combined waves and currents is a complex coupling between the fluid, structure and soil.

In this study, a series of large flume tests were conducted to further reveal the wave/current-pile-sand coupling mechanism for the local scour around a monopile foundation under combined waves and currents. The scour depth, pore pressure, wave height and flow velocity were measured simultaneously. The effect of wave-current combination is examined by superimposing waves with various values of wave height on a certain current with constant velocity; meanwhile pore pressure response around the monopile and its effect on the scour development is discussed.