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Physical modeling of local scour development around a large-diameter monopile in combined waves and current

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ABSTRACT

In most of the previous studies on local scour around pile foundations, wave-induced pore pressure response has not been taken into account. The local-scour and pore-pressure responses around a large-diameter monopile in combined waves and current have been physically modeled with a specially-designed flow–structure–soil interaction flume. In the series of experiments, the time developments of the scour-depth and the pore-pressure in the proximity of the model pile were measured simultaneously. Experimental results indicate that the wave-induced upward seepage under the wave troughs may weaken the buoyant unit weight of the surrounding sand, which brings the sand-bed more susceptible to scouring. The superimposition of the waves on a current has much effect on the time-development of local scour and the resulting equilibrium scour-depth, which is particularly obvious when the sand-bed is in the clear-water regime under the current or waves alone respectively. It is observed that the maximum flow velocity at the boundary layer for the following-current case is larger than that for the opposing-current case, which further results in faster time development of scour depth and greater equilibrium scour depth for the following-current case.

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1. Introduction

In the coastal and offshore engineering, piled foundations have been widely used for supporting various structures, e.g. fixed-type platforms, cross-bay bridges, and near-shore wind turbines. In the recent decades, quite a few monopiles with large diameters up to 6 m were constructed in the near-shore wind farms. Due to the large slenderness ratios (i.e. the ratio of pile diameter to pile embedded length) typically employed for the existing monopile foundations, the scour depth could be up to 25% of the embedded pile length (Sørensen et al., 2011).

In the severe shallow water environments, ocean waves and current are usually coexisting, which may bring the soil responses around marine structures more complicated than that due to wave or current alone. The sediment movement at the soil surface in the local scour process is often accompanied with cyclic pore pressures generated in the soil around the monopile. A better understanding of the fluid–pile–soil coupling mechanism would be crucial for proper prediction of the maximum scour depth of a large-diameter monopile in combined waves and current.

1.1. Scour at pile foundation in current-alone

Local sediment scour at circular piles has been studied by many researchers over the last 4 decades. In the river hydraulics, the local scour at the bridge piers has proven to be one of main causes for the structure failure (Melville and Coleman, 2000). The phenomenon of scouring at bridge piers has been studied extensively from various aspects, including flow characteristics & local scour mechanism and prediction of maximum scour depth. Comprehensive descriptions of scour around the pile or bridge pier in a steady current have been given by Hoffmans and Verheij (1997), Whitehouse (1998), and Sumer and Fredsøe (2002).

The dominant feature of the flow near a pile is the large-scale eddy structure, or the system of vortices including the horseshoe vortex, the wake vortex, and/or the trailing-vortex system. If the scouring potential created by those vortices is strong enough to overcome the particles' resistance to motion, local scour will be initiated around the pier. The existing test observations indicated that the horseshoe vortex (including the down-flow) has a dominant effect on the local scour in currents alone. With the development of the scour hole, the vortex rapidly grows in size and strength as additional fluid attains a downwards component and the strength of the down flow increases (see Breusers et al., 1977). Based on the flow measurements by the ADV within the intermediate and equilibrium scour holes, the characteristics of horseshoe vortex at circular and square piers have been further investigated (Dey and Raikar, 2007).

The equilibrium scour depth prediction is a key concern in the geotechnical design for the coastal and offshore foundations. Experimental results of Raudkivi and Ettema (1983) indicate that the equilibrium scour depth under clear-water condition is related to the particle size distribution and the mean particle size of bed sediment, flow depth relative to both the pier diameter and the particle size of the sediments, etc. The equilibrium scour depth was ever taken as

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lower values (e.g., $S/D = 1.3$) for the live-bed scour condition by many researchers (see Whitehouse, 1998). Melville and Sutherland (1988) proposed a conservative design method for local scour depth around piers based on envelope curves to experimental data. Their method is basically a systematic reduction of the potential largest possible local scour depth, according to the scour regime, flow depth, sediment size, and shape of pier. As the effect of moving ripples on the equilibrium scour depth is not fully understood, which may bring a discrepancy in prediction of scour depth, it is recommended to use the deeper scour for design purposes (Zanke et al., 2011).

1.2. Scour at pile foundation in wave-alone

For scour around the pile under the action of waves alone, Keulegan–Carpenter number is one of the main parameters governing the scouring process for the live-bed scour regime (see Kobayashi and Oda, 1994; Sumer et al., 1992). Keulegan–Carpenter number (KC) is defined as

$$KC = U_{wm}T/D \tag{1}$$

where U_{wm} is the maximum velocity of the undisturbed wave-induced oscillatory flow at the sea bottom above the wave boundary layer; D is the pile diameter; T is the wave period. However, for small values of KC (such as $KC \approx O(10)$), the presence of the horseshoe vortex is quite limited in both space and time domains, and its influence on the scour is much less than that in steady currents ($KC \approx \infty$). That is, with decreasing KC, the effect of horseshoe vortex decreases and that of the vortex shedding increases accordingly. An empirical expression for scour depth at a circular slender pile exposed to regular waves was established by Sumer et al. (1992):

$$S/D \approx 1.3[1-\exp(-0.03(KC-6))] \quad \text{for} \quad KC \geq 6. \tag{2}$$

Note that the expression of Eq. (2) is valid for the live-bed conditions, which was confirmed by Kobayashi and Oda (1994).

Sumer et al. (2007) further investigated the effect of the soil density on the scour depth and the time scale of scour at a pile in waves. Sumer and Fredsøe (2001b) also made an experimental study on the steady-streaming flow and the scour process around a large vertical circular cylinder under waves. The flow is in the unseparated flow regime ($KC < O(1)$). The scour is found to depend mainly on KC and the diffraction parameter (D/L). The scour depth generally increases with these parameters.

Zanke et al. (2011) proposed a unifying formula by introducing a transition function ($x_{\text{rel}} = x_{\text{eff}} / (1 + x_{\text{eff}})$) into Eq. (2), for the prediction of equilibrium scour depth around a pile under the action of waves, tidal or steady currents, i.e. $S/D = 2.5(1\text{–}0.5U_{cr} / U)\, x_{\text{rel}}$, where S is the equilibrium scour depth at the pile, $x_{\text{eff}} = 0.03(1\text{–}0.35U_{cr} / U)(KC\text{-}6)$, U is the mean velocity in case of steady currents, and U_{cr} is the critical velocity for initiation of sediment motion, which can be calculated with $U_{cr} = 1.4\left(2\sqrt{\frac{\rho_s-\rho_w}{\rho_w}gd} + 10.5\nu/d\right)$, in which ρ_s is the sediment grain density, ρ_w is the water density, g is the gravitational acceleration, d is the grain diameter, and ν is the kinematic viscosity of water.

For the scour region around a pile in waves, Umeda (2011) identified a variety of scour regimes according to the shape of the scour hole and ripple pattern. It was also noticed that, there exists substantial discrepancy among KC data, even when the data were obtained in the same series of laboratory experiments.

1.3. Scour at pile foundation under combined waves and current

As illustrated in Fig. 1, the local scour around a pile under combined waves and current involves a complex interaction between waves, current, pile and its neighboring soil.

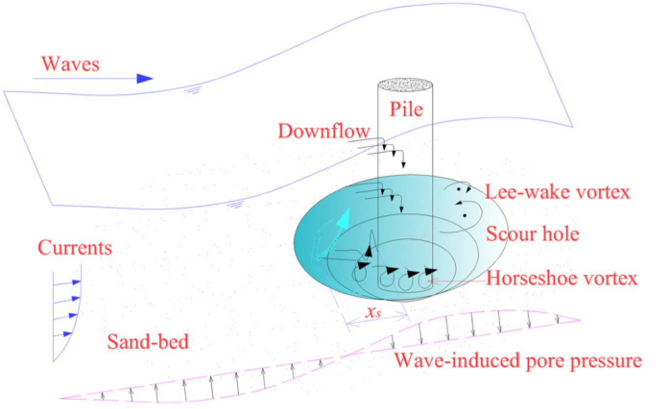

Fig. 1. Illustration of wave/current–pile–soil coupling process for the local scour around a monopile foundation.

When the waves and current coexist, the sediment is normally picked up by the waves due to its higher capacity of lifting sands and transported by the current due to its higher capacity of carrying sands. Nevertheless, the effect of waves and current's coexistence is more than just a superimposition of their capacities of initiating and carrying sediment due to a nonlinear interaction between waves and current within and outside the bottom boundary layer (Grant and Madsen, 1979; Kemp and Simons, 1982, 1983; Klopman, 1994; Olabarrieta et al., 2010). Furthermore, if a circular cylinder was mounted vertically on the flat wall in the combined current–wave flow, a three-dimensional separation of the wave–current boundary layer flow will produce a complex time-dependent three-dimensional flow field around the base of a vertical monopile (Sumer et al., 1997), which controls the scouring process at the pile under combined waves and current.

When the combined current–wave flow is obstructed by a circular cylinder mounted vertically on the flat wall, the characteristics of the horseshoe vortex and wake vortex around the pile can be very different according to different current conditions and wave conditions compared with those under current-alone or wave-alone condition. To the author's knowledge, the only experimental investigation so far on the flow pattern around a vertical pile in a combined current–wave flow is made by Sumer et al. (1997). Their results showed that introducing a following current in the waves increases the size and lifespan of the horseshoe vortex, and lowers the critical KC number for the threshold of horseshoe vortex. The horseshoe vortex exists for smaller KC with increasing current-to-wave velocity ratio. This result is related to the increase in the adverse pressure gradient in front of the pile caused by the superimposed current.

Scouring at the pile foundation in combined waves and current is a complicated coupling process between fluid, structure and soil. The experimental results of Eadie and Herbich (1986) indicated that the scour development is faster and the equilibrium scour depth is greater under combined waves and current, compared with the case of current-alone. The scale and shape of the scour hole depend on the relative magnitude of the current velocity and the oscillatory flow velocities. Sumer and Fredsøe (2001a) conducted a series of tests of irregular waves propagating either with or perpendicular to the currents, indicating that the scour depth for combined waves and current is influenced by KC and the ratio of velocities ($U_{cw} = U_c / (U_c + U_{wm})$, in which U_c represents the undisturbed near-bed current velocity component of the combined flow). The scour depth approaches an asymptotic value called steady-current value as U_{cw} is larger than about 0.7. Rudolph and Bos (2006) carried out model tests on scour around a monopile under combined waves and current with oblique directions, focusing on the range $1 < KC < 10$. They proposed an improved scour depth prediction formula based on Sumer and Fredsøe (2002) by analyzing their new data and preceding data.

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