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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 decade years, 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 costal 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), Chiew 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 ($U_c/(U_c+U_w)$), and the scour depth is uninfluenced 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.

EXPERIMENTAL INVESTIGATION

Dimensionless analysis

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

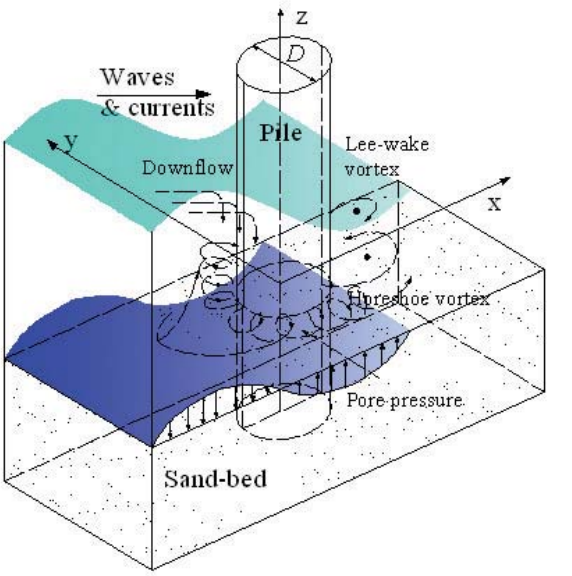


Fig. 1 Illustration of wave/current-pile-soil coupling process for the local scour around a monopile foundation

For the local scour around a monopile in combined waves and currents, there exists many pertinent parameters characterizing the pile, sand-bed and hydrodynamic loads. Following the dimensionless analyses, the maximum scour depth is mainly dependent on the following parameters

$$S/D = f\left(Fr, \theta, KC, \mathrm{Re}, U_{cw}, D_r, \dots\dots\right) \quad (1)$$

where the Froude number (Fr), the Shields parameter (θ), the Keulegan-Carpenter number (KC), the pile Reynolds number (Re), and the ratio of velocities U_{cw} are defined as follows, respectively:

$$Fr = U_m / \sqrt{gD} \quad (2)$$

$$\theta = \frac{U_f^2}{g(s-1)d_{50}} \quad (3)$$

$$KC = U_{wm} T / D \quad (4)$$

$$\mathrm{Re} = U_m D / \nu \quad (5)$$

$$U_{cw} = U_c / (U_c + U_{wm}) \quad (6)$$

in which U_m (= $U_c + U_{wm}$) is the maximum value of the combined waves and currents velocity at the level of 1.0*D* above the sand-bed; g = gravitational acceleration; D = pile diameter; U_f = the maximum value of the undisturbed friction velocity; s = specific gravity of soil grain; d_{50} = mean diameter of sand grains; U_{wm} = orbital velocity at the level of 1.0*D* above the sand-bed; T = wave period; ν =kinematic viscosity of water; and U_c = the velocity of the current component of the undisturbed combined flow, measured at the level of 1.0*D* above the sand-bed.

The parameter Fr represents the Froude number under combined waves and currents, which is slightly different from that under currents alone, replacing U_c with U_m. The Froude number has been proved a significant dimensionless parameter controlling the scouring mechanism for the case of only current loading (Ettema et al., 1998). It could be reasonably presumed from the definition and physical meaning of the Froude number under waves plus currents that, there exists certain dependence between S/D and Fr as current velocity component keeps constant and wave velocity component varies. Note that Fr has exactly the same meaning in the later contexts as Eq. (2) if no special definition is given. Nevertheless, the relationship between S/D and Fr under combined waves and currents has not been well established so far.

The Shields parameter (θ) is a nondimensionalization of the shear-stress at the surface of sediments in a fluid flow, whose physical meaning is the ratio of fluid force on the particle to the weight of the particle. The calculation of θ under combined waves and currents is complex and the detailed calculation procedure is given by Soulsby (1997). The variation of the scour depth at the bridge pier in a steady flow with θ has been given by Melville and Coleman (2000). Under combined waves and currents, the wave induced upward seepage force make the sand grains easier to be lifted, the bed more vulnerable to motion, i.e. decrease the critical Shields parameter (θ_{cr}) and make the bed surface more susceptible to the scour.

The Keulegan-Carpenter number (KC) is the controlling parameter for vortex generation and development around a cylindrical structure in waves, which was used for correlation with the scour depth around a pile under the action of only waves (Sumer and Fredsøe, 2001). In the present tests, the pile Reynolds number $\mathrm{Re} \sim O(10^4)$, so the flow around the test pile is turbulent. The pile Reynolds number is usually not a significant parameter if the flow is fully turbulent (Ettema et al., 1998).

Experimental set-up

The experiments were conducted in a flow-structure-soil interaction flume (52 m long, 1 m wide and 1.5 m high) at the Institute of mechanics, Chinese Academy of Sciences. The flume is capable of synchronously generating waves and currents. A piston-type wave generator is located at the upstream end and a porous plastic type sloped wave absorber at the downstream end to handle the wave reflection. While producing either regular waves or irregular waves, this flume is capable of generating reversible steady flow with velocity up to around 0.6 m/s at 0.5 m water depth meanwhile. A specially designed large soil-box (6.0 m in length, 1.8 m in depth and 1.0 m in width) is located in the middle section of the flume, and a segment of 2.0 m $\times$ 0.5 m $\times$ 1.0 m (length $\times$ depth $\times$ width) was employed in this series of experiments. The water depth was kept constant at 0.5 m and the period of regular waves generated in the tests kept 1.4 s, as illustrated in Fig. 2.

A saturated sand-bed was adopted to simulate a sandy seabed, whose main physical properties are listed in Table 1. Two perspex cylindrical model piles with diameters D =0.20 m and 0.08 m were used, respectively. The model pile was vertically installed at the central point of the soil box.

Far-field wave height was measured synchronously with two wave height gauges at two points with a 0.5 m gap along the central line at the distance 15 m apart from the pile. Thus the wave length could be calculated using the Goda's two-point method. Other two wave height gauges were located just above the pore pressure sensors with the distance of 30 cm and 50 cm apart from the pile centre along the central line, respectively. An Acoustic Doppler Velocimetry (ADV) was mounted to measure the undisturbed flow velocity at the level of 1.0 D above the sand-bed at the distance 20 m apart from the pile centre. Two ultrasonic distance sensors were fixed vertically in the water at the upstream-face and the side-face of the pile separately to measure the development of scour depths. Ten GE Druck miniature pore-pressure sensors were utilized to measure the wave-induced pore water pressure in the surrounding sands. The arrangement of the pore-pressure sensors is detailed in Fig. 2 (filled circles in the top right corner of Fig. 2). A topographic meter consisted of 15 ultrasonic distance sensors and a laser displacement transducer was designed and utilized to obtain the 3-D topographic details of the local scour around the model pile.

The signals of wave height gauges and pore pressure sensors were multichannel synchronous sampled via the NI USB-6255 Data Acquisition Card. Moreover, the phenomenon of the scour development was recorded with a camera through the transparent glass wall of the flume.

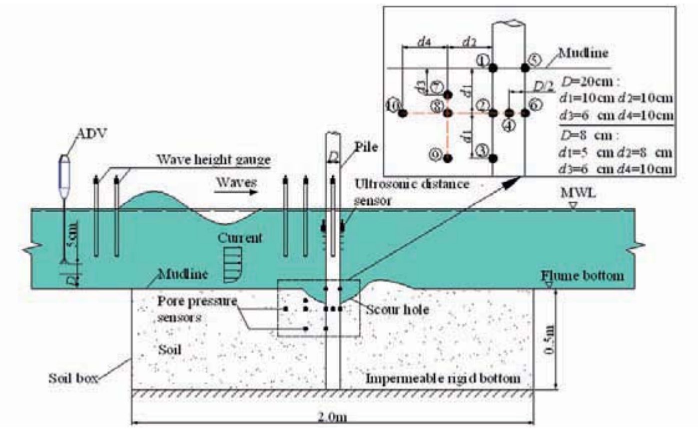


Fig. 2 Schematic diagram of the experimental system

Table 1. Index properties of test sands

Mean size of sand grains	Coefficient of permeability	Void ratio	Relative density	Buoyant unit weight of soil
d_{50} (mm)	k_s (m/s)	e	D_r	γ' (kN/m^3)
0.38	1.88×10^{-4}	0.771	0.352	9.03

Testing procedure

Two series of experiments were carried out: (I) pore pressure response experiments around a pile under combined waves and currents; and (II) scour experiments around a pile under combined waves and currents. The waves are propagating either with or against the currents in the two series of experiments.

In general, the testing procedure was adopted as follows:

(1) The flume including the soil box was firstly emptied and cleaned.
(2) The pore pressure sensors were soaked and deaired to ensure their argil-covers being free of air. They were then installed at the specific locations with the support of a rack, and the model pile was fixed in the middle of the soil box (see Fig. 2);
(3) The soil box was whereafter filled with clean water to a certain depth. The sand bed was carefully prepared by means of sand-raining technique. The surface of the sand bed was leveled off smoothly with a scraper.
(4) The flume was then filled slowly with water to a given depth (e.g. 0.5 m).
(5) Both the wave maker and the current generator were switched on to generate waves and currents concurrently.
(6) The multichannel synchronous sampling system was then started to measure the multi-physics parameters in the aforementioned two series of experiments, e.g. wave height, pore pressure, flow velocity, and scour depth.

RESULTS AND DISCUSSIONS

Time development of scour depth

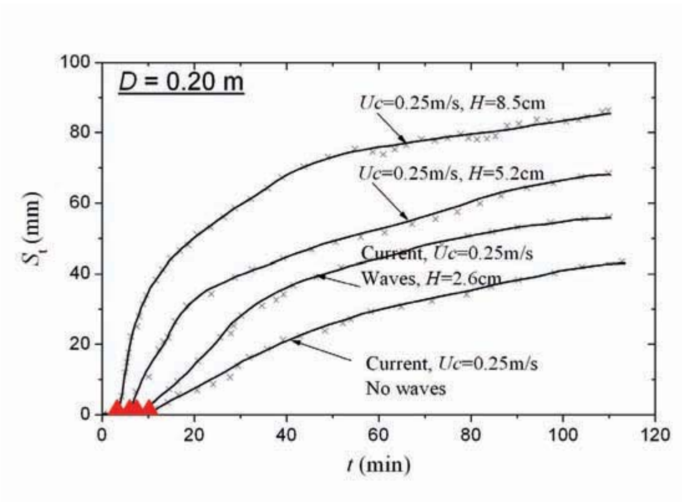
Case of regular waves plus currents: Clear-water scour regime (U_c = 0.25 m/s)

Fig. 3 (a) and (b) give a series of time evolution of scour depth at the upstream edge of the model pile for D = 0.20m and 0.08m, respectively. As shown in this figure, a rapid development of the local scour depth occurs at the initial scouring stage. Then the scouring rate decreases more tardily until the equilibrium state is reached. Note that the solid lines in Fig. 3 are the smooth approaches to the original data marked with crosses. Experimental observation also shows that, sand ripples were formed while the waves with relatively greater wave height (e.g. H = 8.5 cm in Fig. 3 (a) and H = 10.3 cm in Fig. 3 (b)) were superimposed on the current (U_c = 0.25 m/s), which resulted in a fluctuation of the scour depth as the sand waves propagating through the local scour zone around the model pile.

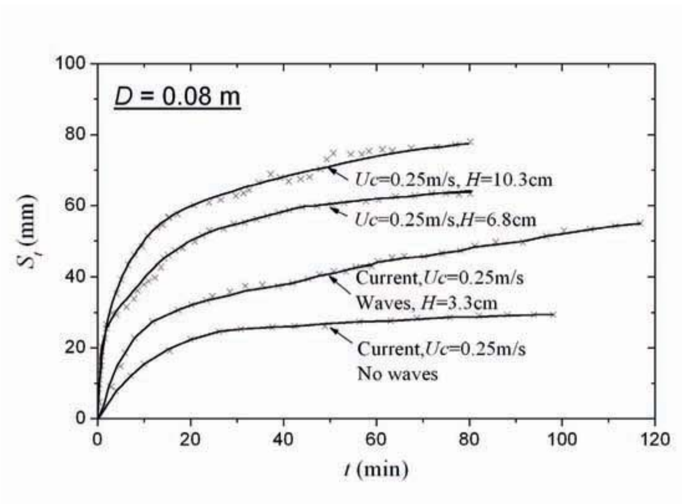
Comparison between these series of the time development of scour depth indicates that, the rate of scour depth development under waves plus currents is remarkably faster than that under currents alone, and the equilibrium scour depth is greater than a linear superposition of those under waves and currents separately (e.g. approximately 3 times of that under current alone, see Fig. 3).

The nonlinear increment of equilibrium scour depth and scouring rate resulted from the involvement of waves can be explained as follows. Wave owns a higher capacity of lifting sands than current, while current owns a higher capacity of carrying sands than waves. For the coexistence of waves and currents, the enhancement of both steady and oscillatory components of the bed shear-stress was observed due to the nonlinear interaction of the wave and current boundary layers (Soulsby, 1997). Meanwhile, the mean-velocity profiles were found obviously different from those suggested by a linear superposition of wave and current velocities (Kemp and Simons, 1982; 1983). Introducing a current in the waves increases the size and lifespan of the horseshoe vortex, and lowers the critical KC number for the threshold of vortex shedding and horseshoe vortex (Sumer et al., 1997). In addition, the transient liquefaction due to upward seepage under the wave-trough or the residual liquefaction may occur, especially for the silty sand (Li et al., 2011), which makes the sand-bed more vulnerable to scour. These effects amplify the bed shear-stress greatly and decrease the critical velocity for transporting sand particles, resulting in an intensification of the scour process.

Comparing Fig. 3 (a) with Fig. 3 (b), it can be seen that the rate of scour depth development with pile diameter D = 0.20 m is smaller than that with pile diameter D = 0.08 m, i.e. more time is needed to reach the final equilibrium state in the case of pile diameter D = 0.20 m than the case of D = 0.08 m. It is indicated in Fig 3(a) that, the commencement time for local scour at the upstream side of the pile ($t_s > 0$; filled triangle in Fig. 3 (a)) doesn't coincide with the test starting time (i.e. t = 0). Test observation shows that, the local scour around the large-diameter model pile (e.g. D = 0.20 m) was triggered firstly from the lateral sides of the pile with two small scour holes, which then extended towards the upstream and downstream sides of the pile. A similar phenomenon of local scour development around the pile with large diameter was also observed by Dargahi (1990). Nevertheless, for the model pile with relatively smaller diameter (e.g. D = 0.08 m), the local scour triggered from the lateral sides of the pile extended rapidly to the upstream and downstream sides of the pile (usually 5~20 s in the tests, see Fig 3(b)). Thus, the commencement time for local scour at the upstream side of the pile ($t_s \approx 0$) coincide with the test starting time, i.e. the time effect of local scour extending along the circumference of the pile is ignorable for the small-diameter piles.



(a)



(b)

Fig. 3 Time development of scour depth measured at upstream edge of pile under the waves with various wave heights plus a current with a constant velocity U_c =0.25 m/s (clear-water regime): (a) D = 0.20 m; (b) D = 0.08 m.

Case of regular waves plus currents: Live-bed scour regime (U_c =0.34 m/s)

It would be interesting to examine the effects of superimposing waves onto a current with a higher velocity, under which condition the sand-bed is in the live-bed scour regime.

A series of time evolution of scour depth at upstream edge of the pile with D =0.20 m and 0.08 m is given in Fig. 4. The rate of scour depth development under waves plus currents is slight faster and the equilibrium scour depth gets a little bigger than that under a current alone. The critical Shields parameter for this examined medium sand-bed $\theta_{cr} \sim O(0.05)$. In Fig. 3, while the current velocity was kept constant U_c = 0.25 m/s and no waves were imposed, the sand-bed was in clear-water regime ($\theta_c \sim O(0.02)$). In Fig. 4, while the current velocity U_c = 0.34 m/s and no waves were imposed, the sand-bed was in the live-bed regime ($\theta_c \sim O(0.05)$). A comparison between Fig. 3 and Fig. 4 indicates that, the effect of superimposing waves onto a current under the live-bed condition (see Fig. 4) is not as obvious as that under the clear-water condition (see Fig. 3). The cyclic loading by the waves has much less influence on the scour depth under live-bed conditions than that under clear-water conditions.

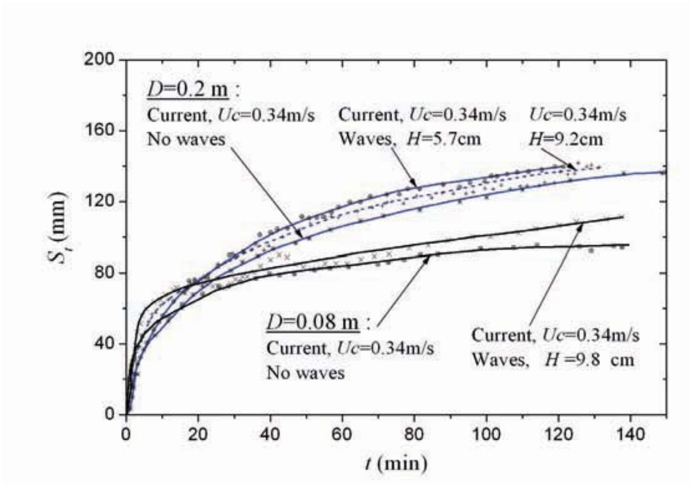


Fig. 4 Time development of scour depth measured at upstream edge of pile under waves with various wave heights plus a current with a constant velocity U_c =0.34 m/s (live-bed regime).

Variation of wave-height and pore-pressure with current velocity

While waves and currents coexist, the existence of the currents would change the wave height and wave length, which may have some effects on the pore-pressure response, and further affect the bed conditions and the corresponding scouring process. Fig. 5 shows the variation of the far-field wave height (H) and the average pore-pressure gradient at the upstream face section of the pile ($\Delta p_{13}/\Delta z_{13}$) with the velocity of the current component (U_c). A theoretical variation of wave height with current speed is also given in Fig. 6, which is calculated with

$$H/H_0 = 2\left[1+4U_c/c_0+\left(1+4U_c/c_0\right)^{1/2}\right]^{-1/2}\left[1+\left(1+4U_c/c_0\right)^{1/2}\right]^{-1/2} \quad (7)$$

in which $c_0 = L_0/T$ is the wave velocity without a current, and L_0 is the wave length without a current. The experimental results and the theoretical results are in good agreement.

It is seen that, H decreases with increasing the value of U_c while the waves propagating with the currents and H increases with increasing the absolute value of U_c while the waves propagating against the currents. Nevertheless, whether the waves propagate with or against the currents, $\Delta p_{13}/\Delta z_{13}$ always increases with increasing the absolute value of U_c. The amplitude increment of $\Delta p_{13}/\Delta z_{13}$ for the waves propagating against the currents is relatively larger than that as waves propagating with the currents. Experiments by Zhou at al. (2011) have also indicated a difference of pore pressure gradient as waves and currents coexist. No pore pressure accumulation is found due to the large grain diameters ($d_{50} = 0.38$ mm) and a high permeability of the soil ($k_s = 1.88\times10^{-4}$ m/s) in the tests.

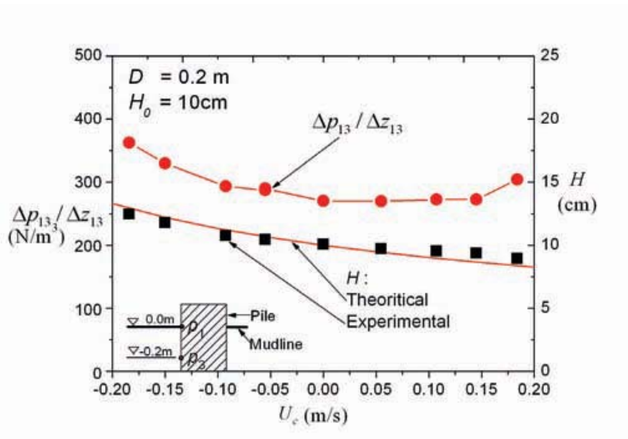


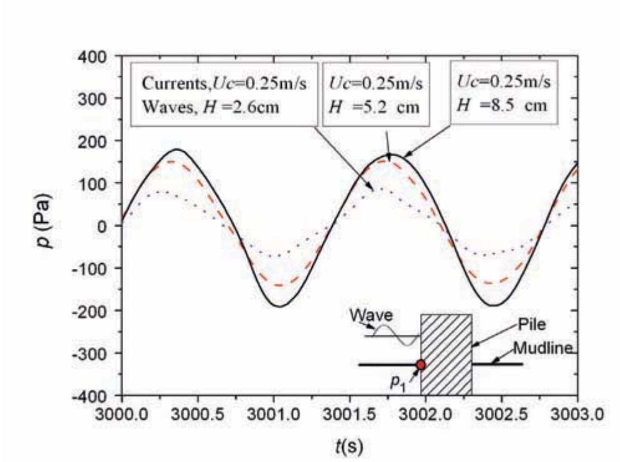
Fig. 5 Effects of a current on the pore pressure gradient at the upstream face section of the pile ($\Delta p_{13}/\Delta z_{13}$) and the far-field wave height (H). (Wave height without a current H_0 = 10 cm, T = 1.4 s, D = 0.20 m, D_r = 0.352).

Correlation between pore-pressure and scour development

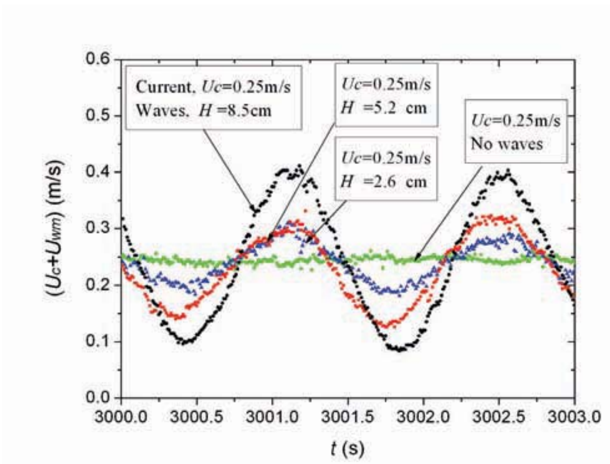
As waves are superimposed onto a current, this has two main effects: one is to enlarge the flow velocity periodically, so as to increase the shear-stress on the surface of the sand-bed, which make the grains more vulnerable to the motion initiation; the other is to exert upward seepage force onto the sand grains under the series of wave troughs, which is also beneficial to the bed mobility.

Fig. 6 (a) gives a comparison of different time series of pore-pressure p_1 for various values of wave height. It is indicated that the regular wave-induced instantaneous pore pressure at the interfacial of the pile and the sand-bed (p_1) presents a sinusoidal variation.

Fig. 6 (b) gives a comparison of different time series of flow velocity at the level of 1.0D above the sand-bed under various values of wave height. As aforementioned, the velocity variation due to superimposing waves has much effect on the scour depth development when the sand-bed under currents is in the clear-water regime. As shown in Fig. 6(b), the flow velocity is changing periodically and the maximum value of the periodic velocity reaches $U_c + U_{wm}$ = 0.4m/s for the superimposed waves with H =8.5cm. The periodic variation of flow velocity also enhances the vortex-shedding at the downstream side of the pile, which accelerates the sand grains transporting around the pile and makes a difference of the scour profile between under waves plus currents and under currents alone.



(a)



(b)

Fig. 6 Comparisons between (a) pore-pressure measured with sensor-1 (p_1) and (b) measured velocity at the level of 1.0D above the sand-bed for various values of wave height (U_c =0.25 m/s, T =1.4 s, D = 0.20 m, D_r = 0.352).

Fig. 7 gives the variations of time-dependent scour depth S_t and the amplitudes of p_2 , p_3 and $(p_2 - p_3)$ with the loading time t . Note that the pore-pressure sensor-2 and sensor-3 were beneath the sand-bed surface as S_t was less than 10 cm during the scouring process. The amplitudes of p_2 , p_3 and $(p_2 - p_3)$ scatter within a pressure range of about 25Pa, which may result from the vortex-induced pressure pulsation around the local scour hole. The approach lines of p_2 , p_3 and $(p_2 - p_3)$ using linear fitting method are also given in this figure. With increasing scour depth (S_t), the amplitudes of p_2 and p_3 tend to increase slowly; Meanwhile, the corresponding amplitude of $(p_2 - p_3)$ also increases. This might be due to that, the positions for the pore-pressure sensors were getting closer to the sand-bed surface with the development of the sand scouring.

As the coefficient of permeability k_s is somewhat large for the examined sand-bed, the attenuation rate of the wave-induced pore-pressure with soil depth is small, and the amplitude of $(p_2 - p_3)$ is less than 50 Pa. The upward seepage (pore pressure gradient) is about 3% of the buoyant unit weight of soil in the tests, so its effect on the scour development is not quite obvious in the present experiments. It might be inferred that for the case of silty sands, larger pore pressure gradients and even soil liquefaction (see Sumer & Fredsøe, 2002) could be observed, which may have much influence on the local scouring process.

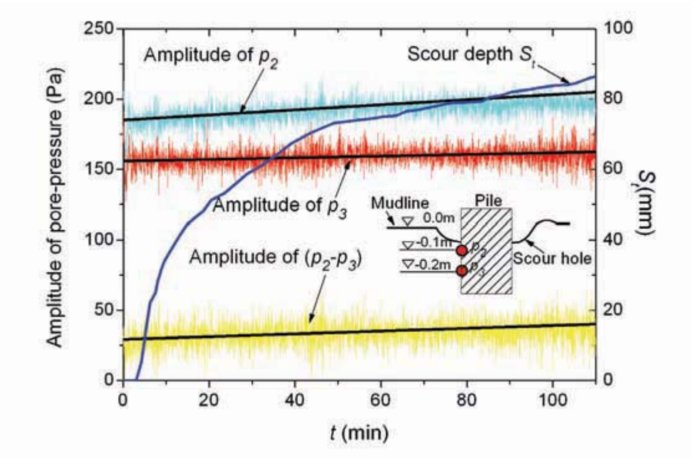


Fig. 7 Correlation between the wave-induced pore-pressure and the local scour development (U_c =0.25 m/s, H =8.5 cm, T =1.4 s, D =0.20 m, D_r = 0.352).

Fr dependence

In the previous studies, the KC number was ever adopted as the main dimensionless parameter for the correlation with the maximum scour depth. Fig. 8 gives the variation of the dimensionless maximum scour depth (S/D) with the KC number in combined waves and currents for the two values of the pile diameter, i.e. D = 0.2 m and 0.08 m, with the flow velocity of the current kept constant (U_c =0.25 m/s). It is indicated that, the relationships between S/D and KC are different for various pile diameters. This implies that when using KC number for the correlation, the pile-diameter effect (size effects) is significant.

The relationships between the dimensionless maximum scour depth (S/D) and the Froude number (Fr) for two constants of current velocity, i.e. U_c = 0.15 m/s and 0.25 m/s, are shown in Fig. 9, respectively. Note that the Froude number is defined as $Fr = (U_c + U_{wm})/\sqrt{gD}$. As such, when the value of U_c is fixed, the increase of Fr in Fig. 9 represents the increase of wave-induced water particle velocity U_{wm} . For a given value of current velocity (U_c = 0.15m/s or 0.25m/s, see Fig. 8), S/D increases linearly with increasing Fr . The size effect from the pile diameter on the correlation between Fr and S/D seems slight for the examined two values of pile diameter (D = 0.08m and 0.20m, see Fig. 9). Note that for the U_c = 0.15 □ 0.25m/s without waves superimposed, the sand-bed is in the clear-water regime ($\theta_c < \theta_{cr}$). In the case of U_c =0.15 m/s, the increasing rate of S/D with Fr is relatively small. In the case of U_c =0.25 m/s, the increasing rate of S/D is much more remarkable than the case of U_c =0.15 m/s. However, in the case of U_c =0.34 m/s (live-bed regime without waves: $\theta_c > \theta_{cr}$, see Fig 4), the effect of Fr on S/D becomes weaker. Under combined waves and currents, the sand-bed conditions (clear-water or live-bed) have much effects on the variations of S/D with Fr . Froude number basically represents the flow gradients around the pile and is responsible for the formation of the horseshoe vortex and the downflow (Ettema et al., 1998). The experiments by Roulund et al. (2005) showed that, the Froude number takes effects when it is larger than $O(0.2)$ for the steady current loading. Note that for the definition of Froude number in Roulund et al. (2005), the characteristic length is water depth, which is different from the present definition (Eq.(2)). Furthermore, Froude number also has much effect on the intension of the lee wake (Ozturk et al., 2008). These aforementioned flow structures make the shear-stress on the bed surface amplified and the flow capacity of transporting sand grains increased.

In addition, the two dash lines in Fig. 9 represent the linear sum of scour depths under waves and currents, respectively. In the present tests, no scour hole was formed for the cases of waves alone, i.e. $S/D = 0$ for only waves. So the sums of scour depths are practically equal to those under the action of only currents. The scour depth under combined waves and currents is much greater than the linear sum of those caused by waves and currents separately. This nonlinearity effect is particularly obvious when the sand-bed condition under currents or waves is in clear-water regime.

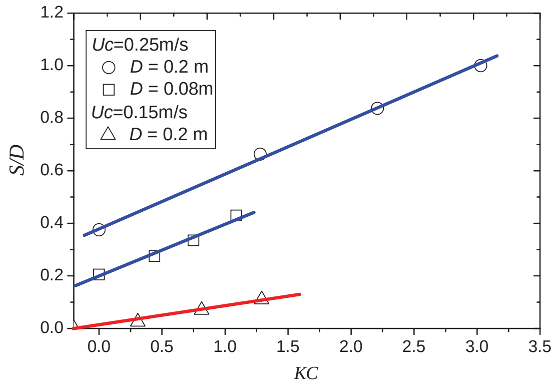


Fig. 8. Maximum scour depth normalized with pile diameter (S/D) vs. KC number for combined waves and currents.

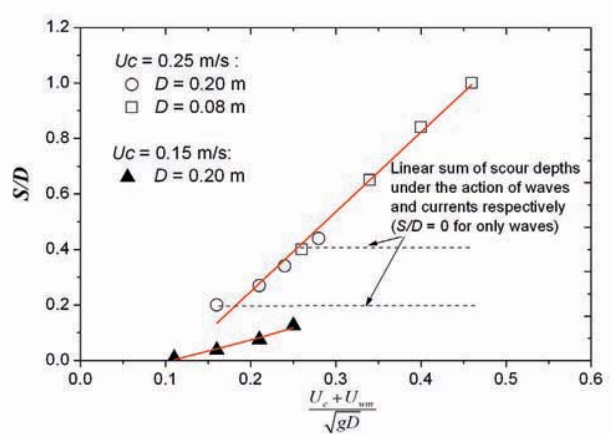


Fig. 9. Maximum scour depth normalized with pile diameter (S/D) vs. the Froude number (Fr) for combined waves and currents.

CONCLUDING REMARKS

Monopile foundations are being widely utilized for economically constructing offshore structures, e.g. offshore wind farms, oil platforms, etc. The local scour around the monopile involves a complex coupling between wave/current, pile and its surrounding seabed. In this study, the local scour and the pore-pressure response around the pile under combined waves and currents is investigated experimentally.

Based on the results of a series of tests in a large flow-structure-soil interaction flume, the following conclusions are drawn:

(1) The equilibrium scour depth caused by combined waves and currents is greater than a linear sum of those caused by waves and currents separately. This nonlinearity effect is particularly obvious when the sand-bed condition under currents or waves alone is in clear-water regime. Moreover, the time evaluation of local scour at a pile under combined waves and currents is much faster than that under the currents alone.

(2) For a given value of current velocity (e.g. U_c = 0.15m/s or 0.25m/s), the dimensionless maximum scour depth (*S/D*) increases linearly with increasing Froude number ($Fr = (U_c + U_{wm})\big/\sqrt{gD}$).

(3) Under combined waves and currents, the wave-induced pore-pressure is always accompanying the process of local scouring at the monopile. Wave-induced upward seepage force under the wave troughs weakens the buoyant unit weight of the surrounding sand and causes the sand-bed more susceptible to scouring.

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