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Experimental study of local scour around piles in tidal current

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Abstract

This paper presents an experimental study of local scour around a vertical circular pile subject to unidirectional flow, sinusoidal tidal current and a reversing current (i.e. a 'square' tide). The scour depth around the model pile was continuously measured using a pair of Contact Image Sensors (CIS) with high spacial resolution and sampling frequency. The test results show that the equilibrium scour depth induced by tidal current is slightly smaller than that induced by a unidirectional flow with a velocity equal to the peak velocity of the tidal current. Since backfilling occurs on the downstream side of the pile after flow reversal in tidal current tests, the measured scour depth fluctuates with the same frequency as the tidal current. The three-dimensional (3D) scour profiles were measured with an infrared 3D scanner, providing detailed information on the extent of scour around the pile. .

1 Introduction

Local scour is one of the main hazards to the stability of offshore structures built on erodible seabed. As a result, continuous efforts have been made in the past several decades to investigate the local scour processes subject to various flow conditions, focusing mostly on wave conditions with or without superimposed currents. More recently, a focus has also been placed on investigating scour in tidal currents which are often approximated as long period oscillatory flows. Since local scour can accumulate between storms, and has a direct effect on the long term integrity of those structures. Predicting scour under tidal current conditions is important for understanding the cumulative scour around offshore structures, for example, offshore wind turbine foundations, gravity based foundations and subsea pipelines. The Keulegan-Carpenter (KC) number is one of the governing parameters for scour induced by oscillatory flows, and is defined as:

$$KC = \frac{U_w T_w}{D} \tag{1}$$

Where U_w and T_w are the peak wave velocity near the seabed and wave period, respectively, D is the diameter of the representative dimension of the offshore structures. Sumer et al. [10] investigated scour around a circular pile subject to oscillatory flow and found that for $KC > 6$ the horseshoe vortex formed at the flow facing junction of the pile and the seabed leads to local shear stress amplification and triggers local scour. According to [10] the maximum (or equilibrium) scour depth S can be predicted by:

$$S/D = 1.3\{1 - exp[-0.03(KC - 6)]\} \tag{2}$$

This correlation was derived based on experiments with KC number up to 102. Extending to predicting scour under tidal currents (for which $KC \gg 100$), the general form of (2) suggests that the maximum scour depth approaches a constant value of $S/D \approx 1.3$, which is equal to that commonly report for unidirectional currents. However, compared to low KC experimental conditions, very few studies have actually been conducted to confirm this limiting depth for large KC number.

Of the studies that have been undertaken at large KC number, Escarameia and May[4] investigated scour around square, circular and compound pile structures subject to tidal current with KC = 7151 ~ 58453. The study covered the effects of the flow direction, variation of tidal shape, flow velocity, flow depth and sediment size under both clear water and live-bed scour conditions. It was found that the equilibrium scour depth subjects to constant current reversal (i.e. a 'square' tide) and sinusoidal flow was shallower than its counterpart under the unidirectional flow scenario. Jensen et al. [6] conducted a series of tests of local scour around a vertical circular pile subject to: tidal current; wave flow with and without superimposed current; and unidirectional current. In terms of scour depth, their results contradicted Escarameia and May[4] in which the scour depth subject to tidal current was marginally deeper than that in a unidirectional flow. However, the KC number for the tidal current test was not given.

More recently Simons et al. [9] investigated reversing flow induced scour around a truncated circular cylinder with a KC number of 26790. And the maximum scour depth around truncated cylinder in tidally reversing current was found to be less than 50% of equilibrium scour depth for an equivalent unidirectional flow. Porter et al. [8] compared the scour processes subject to a unidirectional flow, a square tide and a simplified asymmetrical spring-neap tidal current. The threshold for scour and the effect of flow intensity upon the scour process was presented. The scour depth subject to square tide was considerably less than in the unidirectional case. McGovern et al. [7] studied the scour development process subject to a scaled tidal process by varying the current velocity and water depth simultaneously at a KC number of 30132. It was found that the scour hole was shallower and formed more slowly than the scour hole in a unidirectional current.

Modelling a tidal current is a great challenge in traditional wave/current flumes. Long period waves are difficult to generate in wave flumes, and so as to stepping flow is often used to model tidal current in current flumes. The time step of the stepping flow is usually large. For example, McGovern et al. [7] used 6 time steps to simulate each cycle of a tidal current.

Motivated by the limited number of laboratory tests reporting on the scour processes subject to tidal flow, and especially tests with a true sinusoidal tidal current, this paper presents results from three experiments conducted in the O-tube facilities at UWA. In the experiments a circular pile is modelled and the scour development processes subject to a uniform current, a square tide and a sinusoidal tide are considered in detail.

2 Test setup

This investigation was conducted in the Large O-tube facility at the University of Western Australia. The Large O-tube is an enclosed recirculating water channel that can generate various flows including steady current, regular/irregular oscillatory flow and combined flow encountered in river and subsea environment [1,2]. The motor of the O-tube is controlled by a Variable Frequency Drive (VFD), which allows the motor speed to be controlled continuously. Therefore the flow velocity can also be adjusted precisely and allows for smooth generation of oscillatory flow with long periods. The O-tube is well-suited for modelling tidal currents.

A model pile with a diameter of 115 mm, equipped with two CIS sensors, was used for the model tests. Detailed information about the CIS sensors can be found in An et al. [3]. A sketch of the model pipe with two CIS sensors (named as A and B) is given in Figure 1.For steady current tests, the flow direction was from A to B. For tidal current tests, the initial flow direction was from A to B. The spatial resolution of the CIS sensor was 0.43 mm. The data logging frequency was 1 Hz. A siliceous non-cohesive sand was used as the model seabed. The median grain size (d_{50}) of this sand is 0.243 mm and the specific gravity of the sand particles is 2.65. The test conditions are listed in Table 1.

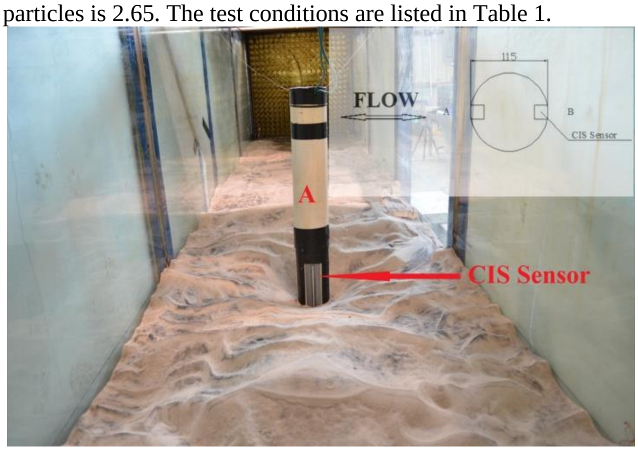


Figure 1. A sketch of the model pile with CIS sensors (unit: mm)

Test No.		Flow condition	KC	T_w (s)	$U_m/\bar{U}$ (m/s)	S/D	T^*
T1	Stage I	Unidirectional flow	∞	∞	0.48	1.37	1.19
	StageII	Square Tide	47182	3600	0.48	1.38	/
T2		Sinusoidal Tide	8961	2147	0.48	1.20	2.32

Table 1. A summary of the test conditions

3 Test results

3.1 Effect of flow reversal

Test T1 was designed to reveal the difference of the scour processes subject to square tide and unidirectional flow, since different conclusions about whether square tide can induce more or less scour than unidirectional flow have been reported [4, 6]. The velocity amplitude of the square tide in each half cycle was equal to the unidirectional flow. Test T1 was conducted in two stages (I and II). In stage I, unidirectional flow was generated until the equilibrium state was achieved (≈ 21 hours), then the square tide (reversing flow) with a period of T_w= 3600s was introduced and repeated for 7 cycles (see Figure 2).

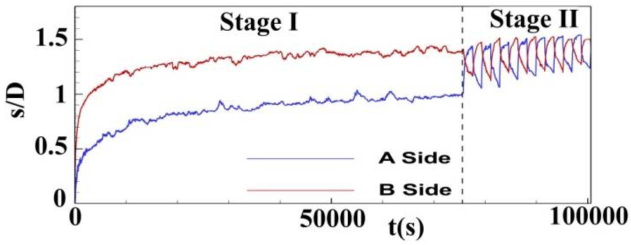
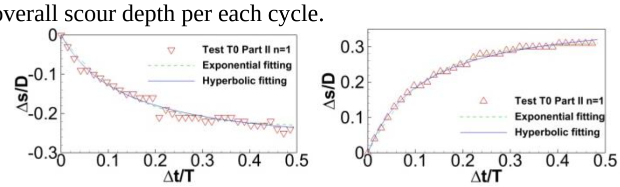


Figure 2. The scour development process of Test T1.

It can be seen that the scour depths measured by CIS A and B were close to equilibrium after 21 hours. The final scour depths at the end of stage I at A and B were 1.35D and 0.92D, respectively. It should be noted that most of the existing published data on scour depth corresponds to location A, where the scour is a maximum. At location B, the scour depth increased dramatically to 1.38D, which is similar to the scour depth at location A at the end of stage I. During the same time, location A experienced backfilling and the scour depth reduced to 1.15D. When flow reversed for the second time, scour depth at point A increased to about 1.41D and B point decreased to 1.03D. The scour depth increases and decreases periodically until the end of the test. The scour depths at A and B always changed in opposite directions during stage II of the test. The maximum scour depth increased slightly by 5% compared with that in stage I. This observation agrees with that presented by Jensen et al. [6]. However, further testing is needed to confirm and to understand the physical reason behind it.

Figure 2 also indicates that the fluctuation in scour depth at the two points (A and B) was about 0.35 D in general, indicating the extent of backfilling and re-scouring in each cycle. The backfilling on the downstream side after flow reversal is attributed to two mechanisms. One is the collapse of the side slope of the scour hole. More specifically it has been shown in unidirectional currents that a part of the slope on the upstream side collapses and induces backfilling after the flow is stopped ([3], [15]) due to the disappearing of the horseshoe vortex which provides shear stress on the slope of the scour hole in the upslope direction. A similar mechanism exists for flow reversal. After the flow reverses, the horseshoe vortex moves to the B side and the slope collapses on the A side. The second mechanism is the accumulation of sediment on the downstream side of the pile after flow reversal. In stage I the scour on the downstream side (side B) was smaller than that on the upstream side. Therefore, after the first flow reversal the excess sediment at side B (new upstream side) was deposited in the scour hole at A side, leading to backfilling. This second mechanism is consistent with the expectation that if the reversed flow was run for a sufficient long time in the same direction, the geometry of the equilibrium scour hole will approximately rotate 180 degrees with respect to the axis of the pile.

The scour and backfilling processes at Point B in the first period are plotted in Figure 3, in which Δs and Δt are the scour depth and time relative to their corresponding values when the flow reverses, respectively. The scouring and backfilling processes have been fitted with an exponential curve and a hyperbolic curve (Figure 3(a) and (b)) in a similar to that undertaken in unidirectional current by [14]. The net contribution of the scouring and backfilling processes determines the variation in the overall scour depth per each cycle.



(a) Fitted backfilling process (n=1)   (b) Fitted scouring process (n=1)

Figure 3. The scouring & backfilling process in the 1st cycle (B side,n for cycle number)

3.2 Sinusoidal tidal current

Due to the continuous change of flow velocity within on tidal cycle, Jensen et al. [6] proposed that a typical sinusoidal tidal flow induced scour process could be divided into three stages depending on the flow velocity:

- Phase 1: No scour development ($u < U_{cr1}$).
- Phase 2: Clearwater scouring ($\mathrm{U_{cr1}} < u < \mathrm{U_{cr2}}$).
- Phase 3: Live-bed scouring ($u \geq U_{cr2}$).

where U_{cr1} is the critical velocity for clear water scour and U_{cr2} is the critical velocity for live bed scour. $U_{cr2} = 0.3$m/s was measured in this work, and $U_{cr1} \approx 0.5U_{cr2}$. However it should be noted that the critical velocity for the above three phases are only applicable for an ideal testing condition, in which the test starts with a flat model seabed condition. The critical velocity for scour around a vertical pile is different from that for a flat seabed without a structure because of velocity amplification around the structure and the scour hole around the pile.

The detailed scour process of scour in tidal current has not been reported previously mainly due to two reasons. Firstly a long period sinusoidal flow is hard to model in traditional flumes. Secondly, it is a challenge to monitor scour continuously over a long time with high resolution. The large O-tube and the CIS used in this study can overcome these two challenges.

The features of the scour process subject to tidal current displayed in Figure 4 are very similar to those of the reversing flow induced scour as in Figure 2. The scour time histories at the two locations show opposite trends. The difference here is that two plateaus occur in each flow period at both location A and B. This is because the flow velocity was too low to make the sediment move during the plateau period. This is corresponding to the phase 1 (no scour) mentioned above. Detailed time histories of scour with the first and the sixth flow periods are given in Figure 4(a) and (b). It should be noted that the scour time history at location A and B could not be used to detect U_{cr1}. This is because the maximum stress happens at around $\mathrm{x/D} = -0.7$ for a vertical pile mounted on a flat surface (Sumer et al. [11]). $U_{cr1} \approx 0.15\mathrm{m/s}$ ($\approx 0.5U_{cr2}$) was visually observed in this work in the first flow period. In the first flow period, the onset velocity at point A was 0.24m/s. The majority of scour happened phase 3. Due to the sheltering effect, scour at location B initiated later (t = 432s) in the first flow period and it only reached about 50% the scour depth of location A. In the second half of the flow period, backfilling happened at location A side and scouring happened at location B. Similar to the scour process, the backfill at location A can also be divided into the same three phases.

The scour time histories for both location A and B fluctuation about 0.35D after reaching equilibrium, which is about 29% of the fitted equilibrium scour depth. It is suspected that this ratio is strongly dependent on the structure diameter and this ratio should decrease with the increase of the model diameter. However more model tests are required to confirm this.

The scour process in the 6th flow period is given in Figure 4 (b) as an example. The only difference is that the scour level at A and B always went in opposite direction.

3.3 Comparison on scour development process subject to different flow conditions

A comparison between the scour processes subject to sinusoidal tide and unidirectional current is given in Figure 5.Several observations may be made based on these figures. Firstly, the

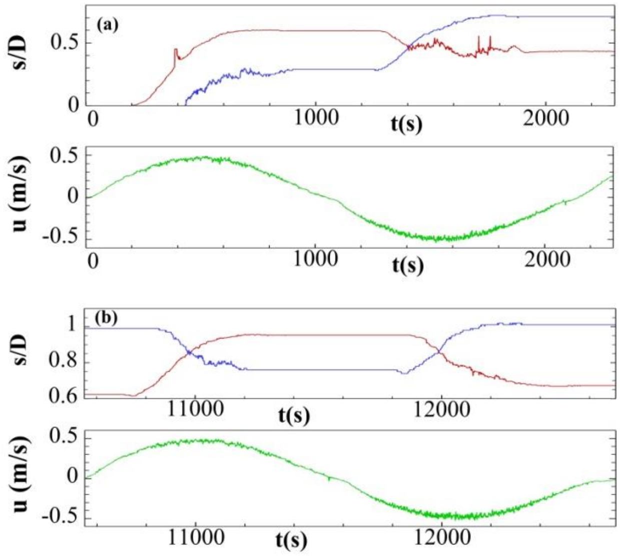


Figure 4. The scour time history and flow velocity, (a) first flow period, (b) 6th flow period.($T_w = 2147s$,$U_m = 0.48m/s$).

scour developed slower under the sinusoidal flow condition. This is because the effective scour time is shorter for the tidal current condition and the average flow velocity with $|u| > U_{cr1}$ for a tidal current is lower than $\bar{U}$ for the unidirectional flow condition. The second difference is the equilibrium scour depth. The equilibrium scour depth subject to unidirectional current is 1.37D. The fitted scour depth based on the maximum scour depth in each tidal period was 1.2*D*, as in Table 1. The latter one is slightly lower than its counterpart under unidirectional flow.

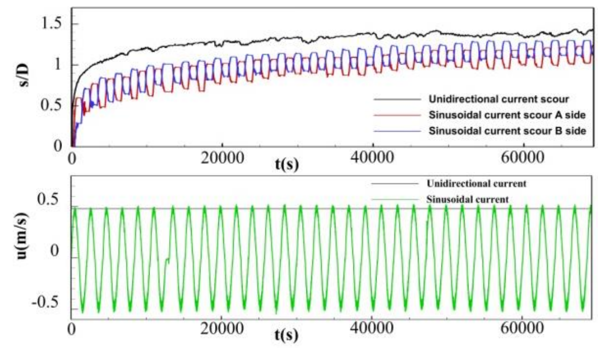


Figure 5. Comparison on the scour process subject to different current conditions ($\bar{U} = U_m = 0.48m/s$)

3.4 Three-dimensional scour hole profile

The three-dimensional scour profile was scanned with an infrared scanner at the end of each test. Each scan covered a horizontal range of 2m × 1m with a vertical resolution of 2 mm. Figure 6 displays the scour hole profiles subject to unidirectional flow and sinusoidal tide.

During each half cycle, the horseshoe vortex generates at the flow-facing side of the pile, and the Kármán vortex shedding appears at the lee side of the pile. Sumer et al.[12] stated that the equilibrium scour depth for large *KC* number is due predominantly to the horseshoe vortex. This may be verified with the scour hole 3D profiles of the present tests. For example, the deepest point of the scour hole coincides with the occurrence of the horseshoe vortex, as in Figure 6(b). By comparing the non-dimensional scour depth in Figure 6 (a) and Figure 6 (b), the scour depth subject to sinusoidal tide is shallower than its counterpart induced by unidirectional current. This is in line with the curve fitting results. Also, deposition zones exist on each side

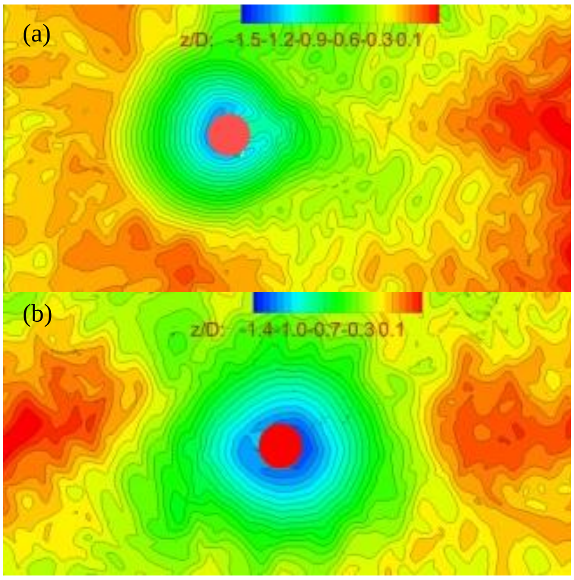


Figure 6. A comparison on 3D scour hole profile subject to unidirectional current and sinusoidal tide, (a) Unidirectional current, (b) Sinusoidal tide

of the model pile for the tidal flow. This is another significant difference to the unidirectional current.

Conclusions

The scour development process subject to unidirectional flow and tidal flow was studied experimentally. Comparison between the scour processes in unidirectional flow, square tide and sinusoidal tide induced scour process was made.

For periodic reversing flow (i.e. a square tide) backfilling occurs on the downstream side of the pile and scour takes place on the upstream side of the pile following the flow direction change. The scouring and backfilling processes within each half tidal cycle may be fitted either with an exponential equation or hyperbolic equation. The equilibrium scour depth induced by the reversing flow is marginally greater than that induced by the unidirectional flow. However, given long enough test duration, the former one approaches to the latter one and the net scour contribution trends to be zero.

For sinusoidal tides, the sediment transport on the upstream side can be divided into a no scour phase, clear water scour phase and live bed scour phase. Similarly on the downstream side, backfill happens according to the same three phases. At location A and B the scour depth fluctuates with an amplitude of 0.35D, which is about 29% of the fitted equilibrium scour depth.

The scour time scale for a sinusoidal tidal current is much greater than that in the unidirectional current condition due to less effective scour time and lower averaged effective scour velocity.

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