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Time Development of Scour around a Cylinder in Simulated Tidal Currents.

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42 Abstract

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44 A laboratory flume experiment was performed to investigate the time-development of scour around a  
45 vertical cylinder acting as a scaled model of an offshore wind turbine monopile in tidal currents. The tidal  
46 current was simulated by resolving each half cycle into three time-steps, between which flow velocity and  
47 depth were varied. Flow direction was reversed between half-cycles, which were otherwise identical.

48 Between them, the three time-steps exhibited clear-water, transitional and live-bed conditions. The  
49 experiment was run over two full simulated tidal cycles. The scour hole formed tended to a symmetrical  
50 shape after two half-cycles and was both shallower and slower-developing than the scour hole in a  
51 unidirectional current test carried out in the same flume. This was due mainly to the variable rates of scour  
52 caused by the variable flow conditions within each half cycle, and to a lesser extent to the infilling of the  
53 scour hole when the current direction reversed. The lower scour depth recorded in tidal conditions implies  
54 that the amount of scour protection required may be less than previous studies suggest.

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57 Subject Headings: Hydraulic models, Scour, Cylinders, Wind power, Sediment transport

## 58 Introduction

59

60 Offshore wind energy generation is a rapidly expanding sector of the renewable energy market, particularly  
61 in the UK (e.g. Wilson et al. 2010). Offshore wind turbine farms are popular because they are larger, have  
62 lower visual impact and are situated in higher wind speed environments than their onshore counterparts. A  
63 significant problem associated with their deployment is bed scour at the base of their monopile foundation  
64 structures. Flow modification by the monopile increases velocity and turbulence. The resulting  
65 amplification of bed shear stress can induce scour, causing large, steep-sided holes around the monopiles.  
66 This can reduce their stability and longevity (e.g. Breusers and Raudkivi 1991; Melville and Coleman  
67 2000). It can also cause ‘free-spanning’ of cables attached to the monopile, i.e. exposure from their original  
68 buried positions (e.g. Zaijjer and Van Der Tempel 2004; De Vos 2008).

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70 There are numerous studies of scour around bridge piers in steady, unidirectional flow (e.g. Shen et al.  
71 1969; Melville 1975; Ettema 1980; Raudkivi and Sutherland 1981; Melville and Sutherland 1988;  
72 Sheppard et al. 2004), because of its importance in rivers. These have often aimed to define empirical  
73 equations for predicting equilibrium scour depth ( $d_{sce}$ ), the depth of the scour hole when flow modification  
74 by the structure no longer changes it significantly. Comprehensive reviews of this research can be found in  
75 Breusers et al. (1977), Hoffmans and Verheij (1997) and Melville and Coleman (2000).

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77 Predicting scour in marine environments has the added complexity of unsteady flow. The action of waves,  
78 which generate short-lived currents, is reasonably well understood (e.g. Sumer et al. 1992; Sumer et al.  
79 1992a; Sumer et al. 1997; Whitehouse 1998; Sumer and Fredsøe 1999; Sumer and Fredsøe 2001; Jensen et  
80 al. 2006; and De Vos 2008), but the effects of tidal flow are less understood. While the instantaneous  
81 structure of tidally-induced flow fields around a cylindrical obstacle is broadly analogous to that of  
82 unidirectional currents (Whitehouse 1998), variations in velocity and water depth during a tidal cycle may  
83 cause significant differences in scour patterns. An important parameter for quantifying these scour effects  
84 is the flow intensity  $U/U_c$ , where  $U$  is flow speed, and  $U_c$  is the critical flow speed for sediment motion.  
85 Flow intensity values can be used to distinguish between live-bed regimes ( $U/U_c > 1$ ), where the flow is  
86 strong enough to move sediment regardless of the presence of the obstacle, and clear-water regimes ( $U/U_c$   
87  $< 1$ ), where only its interaction with the obstacle causes sediment movement. These two regimes generate  
88 different scour hole time-developments and equilibrium depths (Figure 1). While uni-directional flow  
89 environments generally remain in one or other regime, tidal flows may pass between them within each tidal  
90 period. Thus, a different pattern of scour development from that of a steady unidirectional current may be  
91 expected.

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93 Escarameia and May (1999) conducted a laboratory study of the time-development of scour depth around  
94 various structures including a vertical cylinder under reversing flow conditions. For a square, vertical  
95 cylinder flow speed and depth were varied independently. For a circular cylinder, a single test was  
96 performed in reversing currents of constant depth and speed. The results demonstrated a smaller  
97 equilibrium depth for scour than found under unidirectional flows due to infilling of the scour hole during  
98 flow reversal. It was also found that the maximum scour depth was reached for a live-bed state ( $U/U_c > 1$ ),  
99 rather than a transitional state ( $U/U_c = 1$ ) as is observed in unidirectional currents. In unidirectional  
100 currents, clear-water scour generates the greatest equilibrium scour depths, because there are no migrating  
101 bedforms which change the scour depth during live-bed conditions. During the reversing current  
102 experiments, Escarameia and May (1999) observed that live-bed flow generated the greatest scour depths  
103 because it nullified the effect of infilling of the scour hole when the current reversed direction. Their study  
104 also suggests that the generation of bedforms alters the velocity field when the current reverses. Jensen et  
105 al. (2006) and Margheritini et al. (2006) also investigated tidal scour around a vertical cylinder.  
106 Margheritini et al. (2006) reported a series of experiments to investigate tidal scour at a single vertical  
107 circular cylinder (a scaled offshore wind turbine monopile). They approximated tidal flow to a ‘square’ tide  
108 (i.e. alternating equal and opposite constant velocity and depth flows, simplifying the typically sinusoidal  
109 nature of tidal variations, Figure 2), which resulted in permanently live-bed conditions. Jensen et al. (2006)  
110 found that the scour hole formed was symmetrical and had a larger eroded volume than the equivalent,  
111 asymmetrical unidirectional scour hole, although scour depth was found to be similar to the unidirectional  
112 case. These results are at odds with those of Escarameia and May (1999) who reported shallower scour  
113 holes in tidal currents.

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Time development of scour in uni-directional flow conditions has been well studied (e.g. Hoffmans and Verheij, 1997). Sumer et al. (1992) and Melville and Chiew (1999) both derived empirical predictions of the time-scale for equilibrium depth in unidirectional flow conditions. Melville and Chiew (1999), working in purely clear-water conditions, defined this as the time after which scour depth increases by less than 5% in 24 hours. They found this to be

$$121 \quad t_{e(\text{days})} 30.89 \frac{D}{U} \left( \frac{U}{U_c} - 0.4 \right) \left( \frac{h}{D} \right)^{0.25} \quad \text{for } h/D \leq 6 \quad (1)$$

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where  $U/U_c$  is the flow intensity,  $D$  is cylinder diameter, and  $h$  is water depth. They also provided a prediction of the time evolution of scour depth:

$$126 \quad d_{sc} = \exp \left( -0.03 \left| \frac{U_c}{U} \ln \left( \frac{t}{t_e} \right) \right|^{1.6} \right) d_{sce} \quad (2)$$

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where  $d_{sce}$  is the equilibrium scour depth. The development of scour for live-bed conditions may be predicted using the method of Sumer et al. (1992):

$$131 \quad d_{sc} = d_{sce} \left( 1 - \exp \left( \frac{-t}{t_e} \right) \right) \quad (3)$$

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The term  $t_e$  was determined empirically as

$$135 \quad t_e = \frac{D^2}{(g(s-1)d^3)^{\frac{1}{2}}} \frac{1}{2000} \frac{h}{D} \left( \frac{u_*^2}{g(s-1)d} \right)^{-2.2} \quad (4)$$

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where  $s$  is the specific gravity of the sediment and  $u_* = \sqrt{(\tau_b/\rho_w)}$  the shear velocity,  $d$  = mean sediment particle diameter, where  $\tau_b$  is the bed shear stress - calculated using the TKE method (e.g. Kim et al. 2000) and  $\rho_w$  is the density of water.

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However, there remains significant uncertainty regarding the development and equilibrium depth of scour holes around cylindrical obstacles, such as wind turbine monopiles, in tidal flows. The study reported here was carried out to address this. In particular, it explores the effects on scour hole development of simultaneous changes in flow depth and speed through the tidal cycle, thereby expanding on previous studies which have separated out speed and depth effects (Escarameia and May 1999) or idealized tidal flow using a square-wave pattern (Jensen et al. 2006).

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## Methods

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A series of laboratory flume experiments was conducted in The Total Environment Simulator Tank at The Deep, Hull, U.K. Within the 16 m long, 6 m wide, re-circulating tank, a 1.2 m wide by 11 m long channel was constructed (Figures 3 and 4). Flow was driven in one direction by an electric pump housed under the flume, and in the other by nine submersible pumps. Control tests in undisturbed (no cylinder) conditions were taken to ensure that the opposing flows exhibited the same velocity profiles. A lattice screen conditioned the flow at the inlet to the flume. The monopile was simulated using a 0.2 m diameter PVC cylinder positioned with its centre at the flume mid-point (Figures 3 and 4). The blockage ratio of 1:6 was within the limits advised by Whitehouse, (1998) and therefore blockage effects were assumed insignificant. The influence of the side walls is also considered negligible, since the lateral limits of the scour holes formed remained > 20 cm away from both side walls. The flume bed was composed of sand with a median diameter  $d_{50} = 0.135\text{mm}$   $d_{10} = 0.088\text{mm}$  and  $d_{90} = 0.211\text{mm}$  and density  $\rho = 2.65 \text{ g/cm}^3$ . Its natural angle of repose was  $\approx 45^\circ$ , and it was of uniform grading according to the manufacturers specifications. The

163 flume was filled with fresh water of density = 1000 kg/m<sup>3</sup> and salinity < 0.1 ‰. No direct temperature  
 164 measurements were taken but, as this was mains water, the temperature was likely in the range of 5 – 15°C,  
 165 depending on ambient temperatures at the time. It was assumed that using freshwater would have negligible  
 166 effect on density and viscosity of the water in comparison with sea water as long as the flow conditions  
 167 were turbulent (see discussion of scaling below). The flume bed was built-up using bricks to give a  
 168 sediment depth of 0.1 m except in the central section of the flume channel (1 m up and downstream of the  
 169 cylinder) which was filled with sediment to a thickness of 0.4 m.

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 171 Runs of the experiment were carried out under both unidirectional and reversing flow conditions. The  
 172 reversing current was designed to approximate a sinusoidal, non-progressive (standing wave) tide, each  
 173 tidal half cycle being approximated in three time-steps, as illustrated in Figure 5. The flow speed and depth  
 174 in each time step were derived from a prototype tide, based on measurements from the British  
 175 Oceanographic Data Centre taken in Liverpool Bay, UK, the location of several existing and proposed  
 176 offshore wind farms. A sample of this data is shown in Figure 6. The choice of water depth is based on  
 177 field data from the Rhyl Flats wind farm of recorded lowest annual tide water depths around individual  
 178 monopiles. Reversing pump capacity limits necessitated a reduction of flow depth to achieve the desired  
 179 flow speeds. Therefore, it is noted that the water depths used in this study are lower than would generally  
 180 be found in the field, though not implausible. A detailed discussion of the scaling from this prototype data  
 181 to the model, including the choice of water depth is given by McGovern (2011). The first prototype tidal  
 182 half-cycle was constructed by taking mean values of flow velocity for each third of the corresponding half-  
 183 cycle in the Liverpool Bay data. The subsequent half-cycle was constructed by assuming tidal symmetry,  
 184 and the flow depth calculated for each time-step from the mean of the measured tidal ranges associated  
 185 with the velocity data. The length scale  $l$  of the experimental model ( $m$ ) was 1/20<sup>th</sup> that of the prototype ( $p$ )  
 186 data. The velocity and time scaling between the prototype and model was determined by requiring Froude  
 187 number  $F = U/(gh)^{1/2}$  similitude. The changes in the free surface and resulting flow in the vicinity of the  
 188 cylinder can be characterised by  $F$ . Larger values of  $F$  are associated with a larger difference between the  
 189 surface elevation in front and side edge of the cylinder resulting the induced pressure gradient driving a  
 190 strong down flow with a very strong component of flow velocity in the radial direction (Roulund et al.  
 191 2005). Smaller  $F$  is associated with flow conditions for which the ‘head’ difference is too small to cause  
 192 any significant flow in the radial direction.  $F$  similarity, therefore, ensures similitude of flow conditions  
 193 around the cylinder. The scale relationships are given in Equations 5, 6 and 7 where  $L$ ,  $V$  and  $T$  are the  
 194 length, velocity and time scales respectively. The ratio of prototype to model time scale is  $\sqrt{20} = 4.47$ . This  
 195 gives a model half-cycle of 81 minutes, therefore each model time step is 27 minutes. Reynolds number  
 196  $R = Uh/\nu$  was greater than  $10^4$ , and thus fully turbulent, in both model and prototype (Hughes, 1993).

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 198  $L_p = lL_m$  (5)

199  $V_p = \sqrt{l}V_m$  (6)

200  $T_p = \sqrt{l}T_m$  (7)

201  
 202 Due to the well-known difficulty of geometrically scaling sediment particle size (e.g. Ettema et al. 1998),  
 203 the flow speeds used were raised above those given by Froude scaling to attain similitude in the flow  
 204 intensity ( $U/U_c$ ), resulting in the flow speeds given in Table 1. Such values lead to relatively large current  
 205 speeds when scaled up to the prototype.  $U_c$  was calculated following Melville (1997). There remains a scale  
 206 effect in the cylinder boundary layer, which is laminar in the model but turbulent in the prototype. The  
 207 nature of the boundary layer is related to the cylinder Reynolds number ( $R_D = UD/\nu$ ) which is  
 208 approximately  $10^4$  in the model but  $10^6$  in the prototype. The main effect of this is to alter the lateral  
 209 location of boundary layer separation on the cylinder. However, it is noted that the vortex shedding this  
 210 separation causes is not a primary mechanism of sediment entrainment. Rather, its main effect on the  
 211 sediment is to transport it downstream (for example see Melville 1977 and Breusers et al. 1977). Therefore,  
 212  $R$  dissimilitude is not likely to have a significant effect on the local scouring process. Moreover, from  
 213 Figure 1.9 of Sumer and Fredsøe (1997) which shows the Strouhal number ( $St = f_v/D$ , where  $f_v$  = the  
 214 frequency of vortex shedding) as a function of  $R_D$ , the rate of vortex shedding at prototype  $R_D$  ( $\sim 0.2$  for the  
 215 transition and live-bed conditions, and  $\sim 0.1$  for the clear-water test) is similar to rate for the model (in  
 216 which  $R_D \sim 0.2$  throughout). Therefore, the separation regimes of both the model and prototype exhibit  
 217 similar  $St$  values, suggesting a similar rate of sediment transport out of the system. Hence, it is assumed

218 that the scale effect in the cylinder boundary layer will be minimal.  
219

220 The reversing current test was simulated for two full tidal cycles, a total of 12 time steps, referred to as  
221 TS1-TS12 (so the first half cycle is made up of TS 1-3 etc.). The ‘upstream’ and ‘downstream’ sides of the  
222 cylinder change with flow direction. During ‘positive’ flow, the ‘A’ side is upstream of the cylinder and the  
223 ‘B’ side downstream, and *vice versa* during ‘negative’ flow. A rectilinear coordinate system is used with  $x$   
224 denoting longitudinal position (positive on the B side,  $x=0$  at the cylinder centre) and  $y$  denoting lateral  
225 position (positive to the right when looking towards the A side,  $y=0$  at the cylinder centre). The  $x$  and  $y$   
226 positions are normalised by the cylinder diameter  $D$ , such that  $x' = x/D$  and  $y' = y/D$ . The plane  $y' = 0$  is  
227 referred to as the ‘centre-plane’. The parts of the centre-plane on the ‘A’ and ‘B’ sides are referred to as the  
228 ‘A plane’ and ‘B plane’ respectively.  
229

230 The unidirectional test was run as a control. This was performed under live-bed conditions, because they  
231 result in the fastest rate of scour, and thus are hypothesized to be the flow conditions that cause most  
232 scouring in the reversing current situation (Escarameia and May 1999). While the velocity  $U = 0.31\text{m/s}$  was  
233 kept the same as in the reversing live-bed time-step, due to logistical difficulties, water depth was 5cm  
234 greater ( $h = 0.25\text{m}$ ). Despite this, the use of this unidirectional data for comparison is valid, within certain  
235 limits. Firstly, at low  $F$  numbers such as those in this experiment ( $F = 0.22$  for the unidirectional and live  
236 bed tests), the flow around the cylinder is not significantly influenced by  $h/D$  (Roulund et al 2005).  
237 Furthermore, Hoffmans and Verheij (1997) argue that flow depth only has a direct effect on scour when  
238  $h/D < 1$ . In the present experiments,  $h/D = 1.25$  in the unidirectional test and  $h/D = 1$  in the live-bed time-  
239 steps of the reversing flow tests, thus in both conditions, water depth was expected to have little effect on  
240 scour development. These  $h/D$  values lie in an ‘intermediate’ range where the influence of flow depth on  
241 scour depth is only felt when the surface roller interacts with the horseshoe vortex (Melville 1997). Hence,  
242 the decreased flow depth in the reversing current tests may reduce the scour depth slightly. To quantify the  
243 potential difference in scour depths, maximum scour depths were calculated using a scour prediction  
244 equation. Following Johnson (1995), the most suitable such equation for transition, live-bed and clear-  
245 water conditions is the CSU equation (HEC-18 1993)  
246

$$247 \quad d_{sce} = 2K_1K_2K_3hF^{0.43} \left(\frac{D}{h}\right)^{0.65} \quad (8)$$

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249 where  $K_1$ - $K_3$  are correction factors for, respectively, cylinder nose shape (1 for circular cylinders), angle of  
250 attack of flow (1 for circular cylinders), and bed condition (1.1 for these tests). The maximum predicted  
251 scour depths are 0.23m for  $h = 0.2\text{m}$ , and 0.25m for  $h = 0.25\text{m}$ . Thus, the effect of the different water  
252 depths on the scour depth is <10%. Therefore, comparison between the uni-directional and reversing  
253 current test scour depths is made within these limits.  
254

255 Velocity profiles were measured 3 m away from the cylinder in both longitudinal directions, using Acoustic  
256 Doppler Velocimeters (ADV), to ensure that velocity profiles were well-developed at both ends of the  
257 experiment (McGovern, 2011). Time-series of bed elevation around the cylinder were collected with a  
258 Seatek Ultrasonic Ranging System (URS). The URS derives bed elevation from measurements of the  
259 travel time of acoustic ‘pings’ from transducers to the bed and back. In this deployment, 12 transducers  
260 were positioned around the circumference of the pile at  $0^\circ$ ,  $90^\circ$ ,  $180^\circ$  and  $270^\circ$  from the centre-plane, and at  
261 radial intervals of 10 cm, beginning at 6.5 cm from the pile’s surface (Figure 8). Each recorded bed  
262 elevation measurement was the average of measurements from 20 ‘pings’ made over 1 second, with the  
263 highest and lowest three readings removed. Time-series records were collected at all positions except on  
264 the downstream side (either the  $0^\circ$  or  $180^\circ$  position, Figure 8) due to the large amount of suspended  
265 sediment present in this region during tests, which interfered with the acoustic signal. Only measurements  
266 from the start and end of each element of the tidal cycle are presented in the downstream planes, taken in  
267 still-water conditions.  
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269 Full bed profiles on either side of the cylinder were made at the end of each full test using a Leica Disto  
270 laser distance measurer. This was mounted on a rig that allowed sampling from  $x' = 6.75$  to  $-6.75$  and  $y' =$   
271 2 to  $-2$  on both sides of the cylinder.

## Results and Discussion

### *Smooth Cylinder, Reversing Current Test*

Figure 8a-c shows the time development of scour in the first half cycle, TS1-TS3. Scour begins first at the sides of the cylinder, eventually attaining depths of 0.12D and 0.165D in the 90° and 270° planes respectively. This is consistent with the location of greatest bed shear stress amplification around the cylinder's circumference recorded in rigid bed tests (McGovern et al. 2009). In these tests, bed shear stress was calculated from velocity profiles using the TKE method:

$$\tau_b = C_1[0.5\rho(\overline{u'^2} + \overline{v'^2} + \overline{w'^2})] \quad (9)$$

where  $C_1$  is a constant of proportionality, which is given the value 0.19, following Soulsby, (1986) and Kim et al. (2000).

In the centre-plane on the A side, scour is recorded after approximately 20 minutes at  $x' = 0.325$ , as the hole gradually expands upstream, to a depth of 0.04D. Downstream from the pile (B), there is sediment deposition, which is greatest near the cylinder ( $x' = 0.095D$ ).

The rate of scour near the cylinder ( $x' \approx 0.325$ ) increases significantly during live-bed conditions (TS2, figure 8b) remaining greatest in the lateral planes. There is evidence of deposition in the 270° plane further away from the cylinder ( $y' = 1.325$ ). This may be attributed to the passage of ripples which were observed forming all around the cylinder, and were present throughout the remainder of the test (Figure 9). Along the centre-plane, scour is confined to  $0.825 < x' < 0$  upstream from the cylinder and reaches a maximum depth of 0.195D. Downstream from the cylinder there is scour present for  $x' < 0.825$  and reaches a maximum of 0.26D at  $x' \approx 0.325$ .

During TS3, the changes in scour depth were negligible. Scour in the lateral planes developed asymmetrically, which was unexpected. There are several possible reasons for this: heterogeneity in the approaching flow, non-uniform sediment distribution, asymmetry in bed-form development, or natural asymmetry in scour hole development.

Figure 10a-c shows scour hole development during TS4-6 in which the current direction is reversed, so the A and B sides become downstream and upstream respectively. As in TS3, TS4 shows negligible change in scour depth in the centre-plane.

During TS5, the rate of scour is similar on both sides of the cylinder. Scour in the A plane is delayed particularly at  $x' = 0.325$  where, after five minutes, the scour depth has *decreased* by  $\sim 0.025D$  (Figure 10b), before increasing to 0.375D. Deposition in the B plane at  $x' = 1.325$  increases to 0.09D. This is due to the large increase in scouring on the upstream side resulting in significantly more suspended sediment in the wake for TS5 which is deposited at this location.

The downstream (A) side scour depth increases significantly to 0.08 m, and extends beyond  $x' = 1.325$ . During the sixth time step (TS6) the scour hole exhibits the same asymmetrical, elongated shape, with a shallower slope downstream as at the end of time step 3 (TS3), though elongation develops in the opposite direction. This is in agreement with Margheritini et al. (2006), who observed the scour hole changing alignment in response to different flow directions. The end of TS6 is the end of the first tidal cycle and maximum scour depth is approximately equal in both along- and across-flow directions (0.48D and 0.455D in the 90° and 270° planes, 0.41D and 0.385D on the A and B sides of the centre-plane, respectively).

Figure 11a-c presents results from the third half-cycle where flow direction is positive. Most of the scouring in this half cycle occurs during TS8. Maximum scour depth at the end of TS9 and TS10 is 0.535D in the lateral planes and 0.46D in the centre-plane. The depositional mound in the B plane is reduced as the scour hole widens, most significantly during transitional (TS7) and live-bed conditions (TS8). By the end

328 of the clear-water condition in TS9, scour has extended to  $x' = 1.325$  in the B plane, meaning less  
329 deposition than scour here. In the A plane, the slope of the scour hole remains approximately constant  
330 during TS7, but in TS8 there is a steepening of the slope between  $x' = 0.325$  and  $0.825$ , indicating a greater  
331 rate of scour closer to the cylinder than further out. By the end of this half-cycle, the scour has become  
332 more symmetrical.

333  
334 During TS10-12, the scour depth increases to  $0.505D$ ,  $0.555D$ ,  $0.495D$  and  $0.52D$  in the  $90^\circ$ ,  $270^\circ$ , A and  
335 B planes, respectively (Figure 12a-c). Relative to the previous half-cycles, the changes are small, indicating  
336 that scour depth is approaching equilibrium. The majority of scouring again occurs during the mid-tide live  
337 bed condition.

#### 338 339 *Time-Development of Scour in Reversing Flow*

340  
341 Figure 13 shows the time development of scour in the variable, reversing flow test at the probes closest to  
342 the cylinder in each plane (probes 1, 4, 7 and 10). The changes in  $h$  and  $U/U_c$  due to the different flow  
343 conditions of each time-step appear to be the main factors influencing the scour development with the  
344 clear-water, live-bed and transitional time steps exhibiting different rates of scour. It is often stated that the  
345 scour depth will reduce under reversed flow (e.g. Hoffmans and Verheij 1997; Escarameia and May 1999),  
346 due to infilling. Figure 13 shows that infilling does take place during some periods of flow reversal (e.g.  
347 TS4 and TS10). Observations during the experiments indicated that infilling occurred through slumping of  
348 sediment from the scour hole edge to the middle, and via small vertical vortices forming on the leading  
349 edge of the scour hole carrying small amounts of sediment into it. Infilling is clear at the start of live-bed  
350 conditions in TS5 (shown as a decrease in scour depth for the 5 minute measurement) and transitional  
351 conditions in TS7. The flow during clear-water time-steps (TS4 and 10) is too weak to generate significant  
352 scour or infilling. Infilling also occurs long after flow reversal in the  $90^\circ$  plane throughout TS9-12.  
353 However, infilling is quickly replaced by scouring during these time-steps, resulting in a net increase in  
354 scour depth. These observations imply that the effect of infilling on scour time-development is both a delay  
355 to the onset of scour and a reduction in scour depth.

356  
357 The rate of measured scour due to the variable reversing flow decreases with time (Figure 13). The average  
358 scour depth at all four probes increased by approximately 26% between the end of the first and second half  
359 cycles. This reduced to approximately 9% between the second and third half-cycles, and approximately 5%  
360 between the third and fourth half-cycles. Equilibrium, as defined by Melville and Chiew (1999), is  
361 achieved when there is <5% increase in scour depth over 24 hours. Although this is not achieved by the end  
362 of the test, the reduction in scour rate indicated approaching equilibrium. The second cycle is a stabilisation  
363 stage, where the rate of scour decreases and the depth nears equilibrium (e.g. Hoffmans and Verheij 1997).

364  
365 The best-fit exponential curve to the observed data is shown in Figure 14a, and extrapolated to equilibrium  
366 (equilibrium as defined by Melville and Chiew 1999, see above), which is reached at  $\approx 5400$  minutes (i.e.  
367 90 hours), in Figure 14b. Clearly this extrapolation is only approximate due to the lack of data beyond 5.5  
368 hours (the two full tidal cycles tested).

#### 369 370 *Comparison of Time-Development of Scour with Predictions and Unidirectional Data*

371  
372 The predictions of the time evolution of scour using (2) for the transition and clear-water time development  
373 and (3) for live-bed time development were compared with the experimental data. The predictions are  
374 based on the  $d_{sce}$  which, estimated by (8) was for the transition, live-bed and clear-water conditions of  $0.9D$ ,  
375  $0.95D$  and  $1.15D$  respectively. The prediction method of Escarameia and May (1999) is not used here as it  
376 is not developed for the live-bed flow conditions or  $h/D$  ratios ( $> 1$  in the high-tide condition) used in this  
377 test.

378  
379 The time-development of scour at Probes 1, 4, 7 and 10 is plotted in Figure 15a together with these  
380 predictions. Figure 15b shows the curves predicted using same equations, but using the final measured  
381 depth ( $0.59D$ ) as the equilibrium scour depth.

382  
383 Figure 15a shows that the changes in current velocity, depth and direction influence the rate of scour. The



384 development of scour in the variable reversing test is less smooth than in the case of the unidirectional  
385 flow, and as predicted by (2) and (3), which do not capture the recorded unidirectional scour very well  
386 either. The maximum scour depth at the end of the variable reversing test was 0.59D (Figure 15a). This is  
387 well below the predicted equilibrium depths of 0.9D, 0.95D and 1.15D for the transition, clear-water and  
388 live-bed conditions respectively. The recorded maximum scour depth for the unidirectional test was 0.8D (  
389 Figure 15a) which is 25% greater than for the variable reversing current test (significantly more than the  
390  $\approx 10\%$  effect of the deeper water). The unidirectional test was conducted for 2.7 hours, equivalent to half of  
391 the variable reversing test period (i.e. one full tidal cycle). These observations confirm previous findings  
392 that both a faster rate of scour (hence a faster time to equilibrium) and greater scour depth occurs in the  
393 live-bed unidirectional current than in the variable reversing current. This observation conflicts with the  
394 results Jensen et al. (2006) but is in general agreement with Escarameia and May (1999). These differences  
395 can be explained when the nature of the tidal simulations are considered. Jensen et al. (2006) employed a  
396 'square tide' (Figure 2), which gave live-bed conditions with no changes in depth and velocity. As a result,  
397 their scour hole developed much faster than in our experiment. The present experiments employ a closer  
398 approximation to a sinusoidal tide (Figure 5) and are closer to Escarameia and May's (1999) experiment,  
399 which investigates the independent influence of changes in flow speed, direction and depth. This implies  
400 that the variability of tidal flow depth and velocity needs to be taken into account when predicting scour  
401 depth in tidal conditions. Furthermore, the significant underestimation of the scour development by (2) and  
402 (3) of the recorded unidirectional scour indicates that these equations which ought to be conservative for  
403 design purposes, require greater accuracy.

404  
405 In Figure 15a, the scour depth for the transition flow regime (low-tide) predicted by (2) appears to  
406 overestimate the measured scour rate initially, while the measured depth remains significantly lower  
407 throughout. This is probably due to a combination of the probe location being 6.5 cm from the cylinder, a  
408 slower rate of scour, and perhaps a lower  $d_{sce}$  (as will be discussed in greater detail below). The predicted  
409 rate of scour using (2) and (3) matches the measured data in the first tidal cycle, though the individual  
410 measured rates during live-bed stages (TS2 and TS5) are larger. Overall, (2), which is for clear-water  
411 conditions, gives the best prediction of the measured time development of scour. The slower-than-predicted  
412 rate of scour development during the second tidal cycle indicates that the equilibrium depth may be smaller  
413 than those predicted and used in the models (see also below). While the clear-water curve provides the best  
414 prediction of the time-development, this does not necessarily indicate that the equilibrium scour depth is  
415 closer to the predicted clear-water value of 0.95D.

416  
417 Figure 15b compares the measured and predicted time-development curves calculated using the measured  
418 maximum scour depth (0.59D). The clear-water, transition and live-bed time-development curves all  
419 underestimate the measured rate of scour. It is difficult to tell whether this is because the measured  $d_{sc}$  is  
420 not the equilibrium depth, but it clearly indicates that in order for these equations to predict the measured  
421 data well, the equilibrium depths used need to be larger. The poor fit of the predictions to the measured data  
422 also indicate that such equations, which are intended for unidirectional flow conditions, are inappropriate  
423 for tidal flow scour prediction.

#### 424 425 *Equilibrium Scour Depth under Variable Reversing Currents*

426  
427 The equilibrium scour depth in the variable reversing current test is lower than that in the unidirectional  
428 test, and those predicted by the models. The CSU equation (8) predicts an equilibrium scour depth of  
429 1.15D. The extrapolation of the exponential curve fitted to the data in Figure 14 gives  $d_{sce} < 0.6D$ ,  
430 indicating that equilibrium scour depth in these experimental conditions is significantly over-estimated by  
431 the predictions. The scour depth recorded by each probe may not be representative of the maximum scour  
432 depth, as this will likely occur closer to the cylinder than the location of the probes. Assuming that the  
433 slope angle remains constant to the edge of the cylinder, the maximum depths reached in each plane are  
434 given in Table 2. This assumption is conservative as the scour depth decreases very slightly closer to the  
435 cylinder's edge, due to the weaker turbulence and velocity in this region. This does not change the main  
436 observation that the calculated maximum depths in Table 2 are only slightly larger than the measured  
437 depths, and still significantly less than the predicted values. Thus, the measurements indicate that the  
438 equilibrium depth is significantly lower under a variable reversing current than a square tide current or a  
439 unidirectional current. This appears to be a combination of the different scour rate and maximum scour

440 potential associated with each time-step as well as the infilling that occurs during reversed flow, rather than  
441 infilling alone of scour under the reversed currents, as is often proposed (e.g. Hoffmans and Verheij 1997;  
442 Escarameia and May 1999). Consider the fact that in the unidirectional current, scoured sediment is being  
443 permanently removed downstream from the region around the monopile. There is a permanent loss of  
444 sediment from the monopile vicinity, whereas in the reversing flow more sediment is kept in the vicinity of  
445 the monopile, mainly in the form of a depositional mound and is thus available for infilling during reversed  
446 flow. This is particularly true when the reversed flow is of variable intensity as in tidal flow which,  
447 therefore, reduces the amount of time in which the most energetic flows such as live bed / transitional  
448 conditions can remove sediment completely from the monopile vicinity. Furthermore, the scouring  
449 potential during each half-cycle of the tide is significantly less than in the unidirectional flow over the same  
450 time period due to the inclusion of the clear-water regime that generates far less scour. This experiment  
451 also shows that, comparatively, the development of the scour hole in variable reversing currents is slower  
452 than in unidirectional currents. This reasoning, however, may only be valid for relatively low values of  
453 Shields parameter such as in these tests ( $\theta = 0.044 - 0.11$ ). In cases where Shields parameter is relatively  
454 large, the amount of sediment transport taking place in a single tidal half-cycle may become large enough  
455 to remove significantly more sediment from the monopile region. This would potentially decrease the  
456 amount of sediment available for back filling when the flow reverses. In such cases the scour depth may be  
457 influenced more by the Shields parameter rather than the duration of the half-cycle.

458  
459 Of the two differences between the tidal and unidirectional flow conditions - changes in flow velocity and  
460 water depth – the latter appears less important here, as  $h/D$  falls below unity only in the transition (low-  
461 tide), therefore, there is little interaction between the surface roller and the downflow which causes scour  
462 (see above). Any such interaction will reduce as the scour depth increases and with it the value of  $h/D$ . The  
463 main parameter influencing variable-reversing scour appears to be  $U/U_c$ , as the amount of scour that occurs  
464 during the live-bed time-steps is greater than that during the transitional flow time-steps, which is much  
465 greater than that during the clear-water time-steps. This is not observed in the unidirectional test, where the  
466 constant  $U/U_c$  leads to the scour development exhibiting the typical curve observed in previous work (for  
467 example Melville and Coleman 2000). Here, when  $U/U_c$  is held constant, the time development is a smooth,  
468 asymptotic curve.

#### 469 *Scour Hole Shape*

470  
471  
472 Figure 16 shows the final URS readings for the unidirectional test. The difference in scour hole shape is  
473 noticeable compared to Figure 12c; the downstream (B) side has a shallower slope than the upstream (A)  
474 side, indicating that the scour hole is elongated downstream. The scour hole is deeper in all measured  
475 directions as well as wider in the downstream (B) and lateral planes compared to Figure 12c. The mean  
476 final slope angles for each measurement plane for the unidirectional test are given in Table 3. For example,  
477 the mean slope of the  $90^\circ$  plane is the mean of the slope angles between transducers 4 - 5, and 5 - 6.  
478 Clearly, the tidal scour hole is significantly shallower than the unidirectional scour hole.

479  
480 After one full cycle of variable reversing flows, the scour hole has developed sufficient depth for it to retain  
481 symmetry regardless of flow direction. This is contrary to Margheritini et al. (2006) who found that the  
482 scour hole continues to adjust in response to a reverse in current direction during the third and fourth half-  
483 cycles. The more realistic representation of tidal flow in the present experiments suggests that this  
484 asymmetry may not actually occur. These experiments include the transition and clear-water time-steps  
485 which both generate significantly less scour than the live-bed time-steps. This means that the scouring  
486 potential during each half-cycle of the tide is significantly less than it is in Margheritini et al. (2006), hence  
487 any change in scour hole morphology in response to the reversed flow will take longer. In these  
488 experiments, such changes take longer than a half-cycle. However, some of the experiments conducted by  
489 Margheritini et al. (2006) (tests 2.10 - 2.18) have similar flow conditions to the current tests. The velocity  
490 used was similar ( $U = 0.3\text{m/s}$ ), water depth varied from 0.1 to 0.29m, median sediment grain size was  $d_{50} =$   
491 0.00015m and cylinder diameter was  $D = 0.2\text{m}$ . The length of a half tidal cycle was 30 minutes. This  
492 suggests that the incorporation of tidally-based variations in flow velocity and depth in the present  
493 experiments result in symmetrical scour hole development since neither flow direction dominates the  
494 morphological development of the scour.

495

496 Figure 10a shows that when the flow reverses, clear-water conditions in TS4 cause negligible further scour  
497 to occur. In itself, the clear-water flow intensity should be large enough to generate scour (as  $U/U_c > 0.5$ ,  
498 Hoffmans and Verheij 1997). There are three possible reasons for no scour occurring here: 1) the scour  
499 hole generated by the previous transition and live-bed time-steps is already greater than the equilibrium  
500 scour depth for clear-water conditions; 2) the morphology of the scour hole has altered the flow near the  
501 cylinder, reducing its scouring potential; or 3) the rate of scour is slow in comparison to the length of the  
502 time-step. Considering (8), which predicts a scour depth of  $0.95D$  for the clear-water conditions, and the  
503 fact that the previous clear-water time step did generate scour, the second and third points above give the  
504 most likely explanation for negligible scour during TS4.  
505

506 While there is minimal change in the depth and scour hole orientation during TS4, once TS5 begins, the  
507 scour hole orientation adjusts to the new flow direction. The upstream side becomes deeper and the  
508 downstream side, due to the low intensity of the wake, is filled in close to the cylinder before scour  
509 continues and the depth increases (Figure 10a and b). Deposition does not occur during the reversal in TS7,  
510 likely because the transitional flow is turbulent enough to keep sediment in suspension for longer, allowing  
511 it to be transported out of the scour hole. The adjustment of the scour hole to the new flow direction occurs  
512 relatively quickly, after a delay of approximately 5 minutes (Figure 11a).  
513

514 The scour hole at the end of the two full tidal cycles is more symmetrical than was found under  
515 unidirectional flow conditions. The finding that scour development in the variable reversing test take longer  
516 needs validation through further tests. Such tests should be run to equilibrium. This would allow more  
517 accurate extrapolation to prototype conditions.  
518

519 The rates of scour predicted by some of the widely-used equations for unidirectional flow are different  
520 from those measured here, mainly due to problems of estimation of the time-scale needed for the  
521 development of the equilibrium depth. As the flow conditions change over each tidal cycle, so does the rate  
522 of scour (or infilling), and this is not accounted for in the equations considered above.  
523

## 524 **Conclusions**

525  
526  
527 This paper presents results of an experimental investigation into the development of scour under variable  
528 reversing currents. The scaled tide was divided into half-cycles, each of which was resolved into three  
529 time-steps in which flow speed and depth were constant. At the end of each half-cycle the flow direction  
530 was reversed and a symmetric second half-cycle began. The test ran for a total of four half-cycles.  
531

532 The rate of scour was found to change over each half cycle, as the flow regime varied from live-bed to  
533 transitional to clear-water regimes and *vice versa* under the reversed flow condition. During the first half-  
534 cycle, the scour hole shape was analogous to that generated by a unidirectional current. In the second half  
535 cycle, the reversal of current direction both delayed the continuation of scour and caused the scour hole to  
536 become more symmetrical. This symmetry persisted throughout the remainder of the test. Changes in scour  
537 depth and shape in the third half-cycle were significantly smaller. The fourth half-cycle had little effect,  
538 with the hole maintaining a symmetrical shape and the scour depth stabilising.  
539

540 Overall, the equilibrium scour depth found in the variable reversing current conditions used in this test was  
541 lower than that predicted by existing equations (which are derived from unidirectional current  
542 measurements) or measured in 'square-tide' experiments. Thus, extrapolating these findings to prototype  
543 scale suggests that the amount of scour protection required and therefore the costs of scour protection could  
544 be reduced. Despite the special care taken in design of the experiment to present plausible field conditions  
545 and fulfil the scaling laws for flow properties and sediment transport, the simplifications made in the  
546 experiment as well as laboratory effects would affect the scour hole shape, depth and time development.  
547 Hence it would not be appropriate to derive practical guidelines solely on the data of this experiment. The  
548 key finding from these experiments is that they demonstrate that changing flow direction and intensity will  
549 affect the final scour hole depth and its time-development. Furthermore, these data can be used for  
550 validation of the numerical models which can then be applied to test different prototype flow conditions.  
551 Future experiments should consider a constantly changing tidal current depth, speed and direction as well

552 as the case of combined wave and current action on the scour development.

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554

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Time Step	Flow Direction	Upstream Plane	Test Condition	Tidal Stage	Tidal Half-Cycle	Duration [mins]	U [m s <sup>-1</sup> ]	h [m]	U/U <sub>c</sub>	θ	h/D	608 <sub>Fr</sub>
Unidirectional Scour Test												
-	Unidirectional	A	Live-bed	mid-tide	-	162	0.31	0.25	1.24	0.1	1.25	7.9 x 10 <sup>-4</sup> 0.22
Variable Reversing Current Scour test												
1	Positive	A	Transition	low-tide	1st	27	0.23	0.1	1.02	0.044	0.5	2.3 x 10 <sup>-4</sup> 0.23
2	Positive	A	Live-bed	mid-tide	1st	27	0.31	0.2	1.24	0.11	1	6.3 x 10 <sup>-4</sup> 0.22
3	Positive	A	Clear-water	high-tide	1st	27	0.15	0.4	0.54	0.041	2	6.1 x 10 <sup>-4</sup> 0.08
4	Negative	B	Clear-water	high-tide	2nd	27	0.15	0.4	0.54	0.041	2	6.1 x 10 <sup>-4</sup> 0.08
5	Negative	B	Live-bed	mid-tide	2nd	27	0.31	0.2	1.24	0.11	1	6.3 x 10 <sup>-4</sup> 0.22
6	Negative	B	Transition	low-tide	2nd	27	0.23	0.1	1.02	0.044	0.5	2.3 x 10 <sup>-4</sup> 0.23
7	Positive	A	Transition	low-tide	3rd	27	0.23	0.1	1.02	0.044	0.5	2.3 x 10 <sup>-4</sup> 0.23
8	Positive	A	Live-bed	mid-tide	3rd	27	0.31	0.2	1.24	0.11	1	6.3 x 10 <sup>-4</sup> 0.22
9	Positive	A	Clear-water	high-tide	3rd	27	0.15	0.4	0.54	0.041	2	6.1 x 10 <sup>-4</sup> 0.08
10	Negative	B	Clear-water	high-tide	4th	27	0.15	0.4	0.54	0.041	2	6.1 x 10 <sup>-4</sup> 0.08
11	Negative	B	Live-bed	mid-tide	4th	27	0.31	0.2	1.24	0.11	1	6.3 x 10 <sup>-4</sup> 0.22
12	Negative	B	Transition	low-tide	4th	27	0.23	0.1	1.02	0.044	0.5	2.3 x 10 <sup>-4</sup> 0.23

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Table 1

Probe	Plane	Variable Reversing Test end of first cycle (t = 162 min). $d_{sc}/D$	End of Variable Reversing Test. $d_{sc}/D$	Unidirectional Test. $d_{sc}/D$
1	A	0.405	0.495	0.6
4	B	0.48	0.5	0.7
7	90	0.38	0.5	0.6
10	270	0.45	0.55	0.65

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Table 2

Measurement Plane	Unidirectional Mean Slope Angle [degrees]	Tidal Mean Slope Angle [degrees]
A	28.9	11
B	25.5	11.2
90	29.7	11.4
270	28.2	11.8

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Table 3

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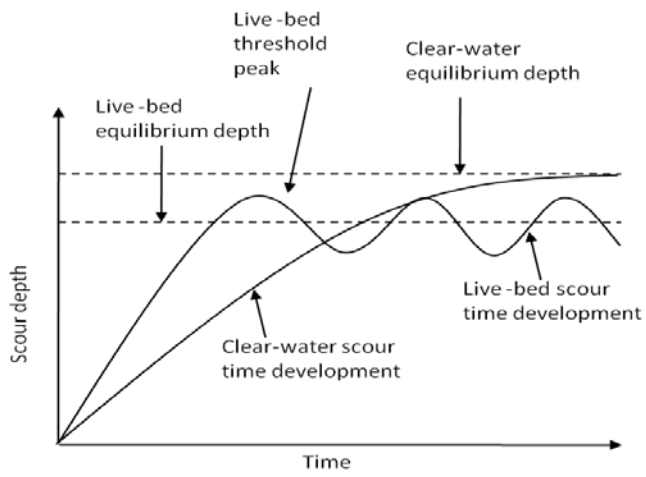


Figure 1

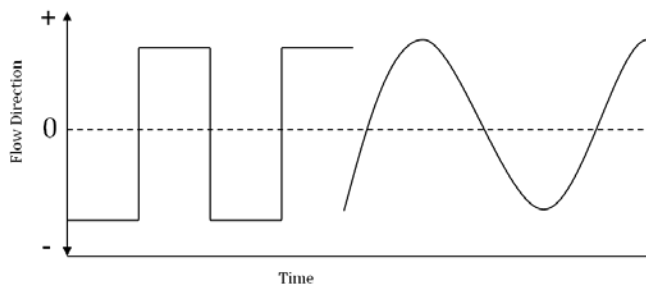


Figure 2



Figure 3

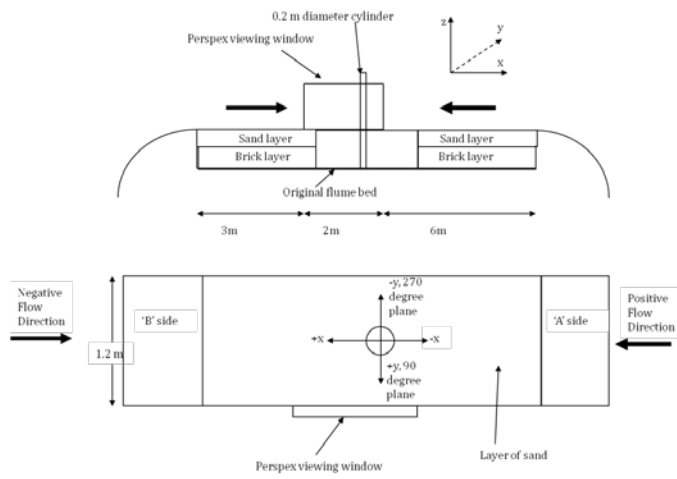


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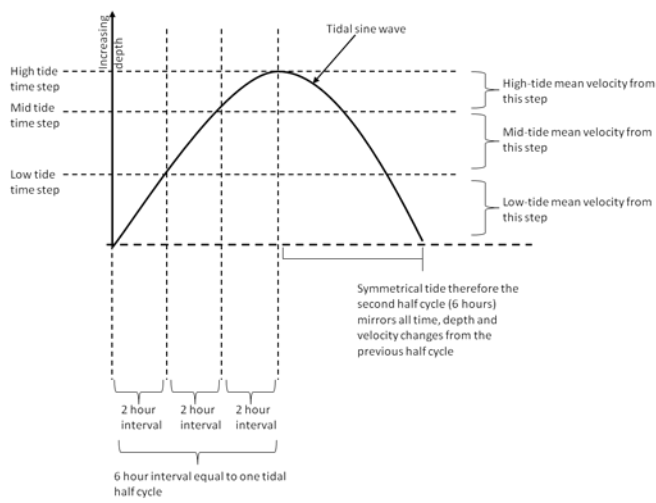


Figure 5

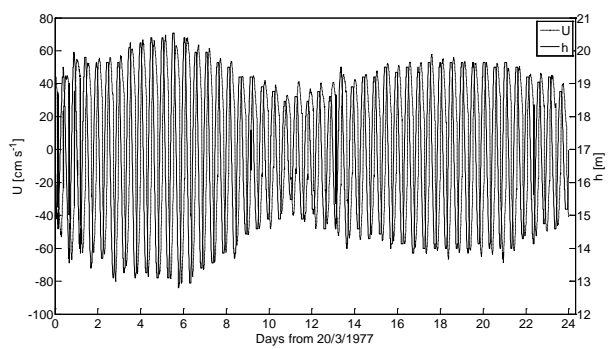


Figure 6

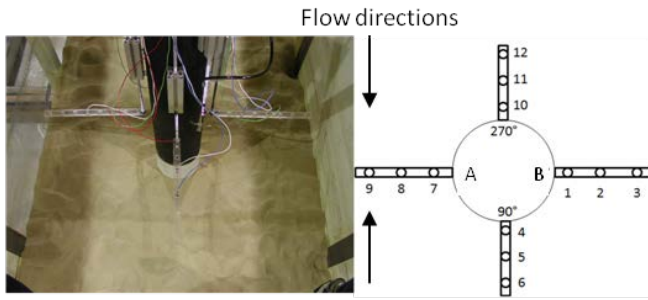


Figure 7

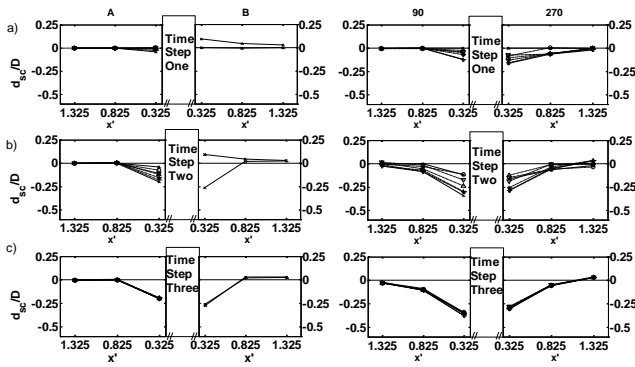


Figure 8

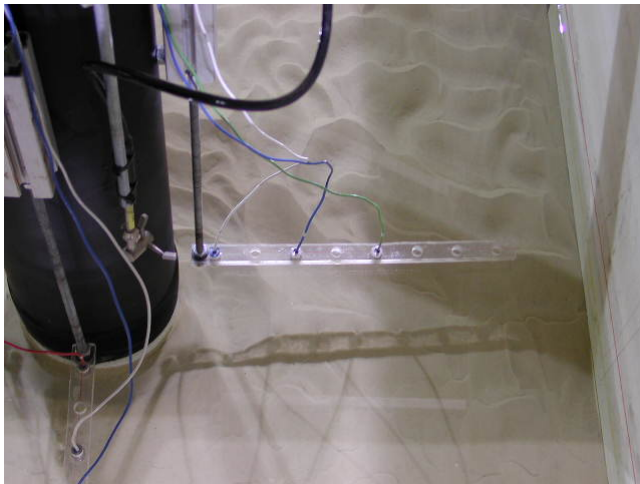


Figure 9

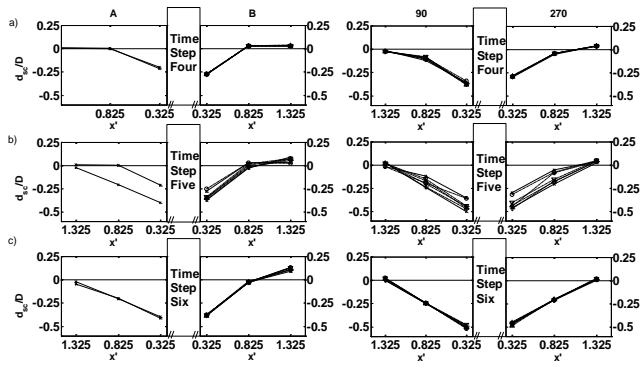


Figure 10

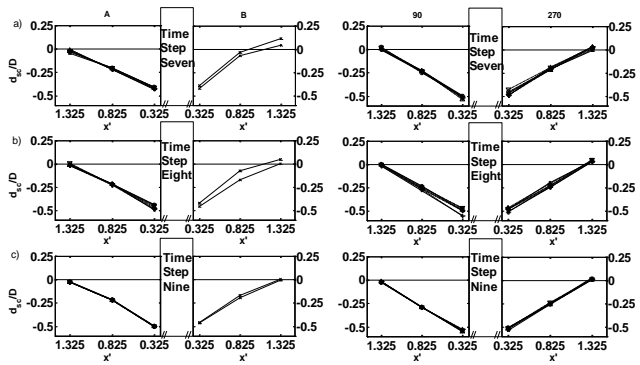


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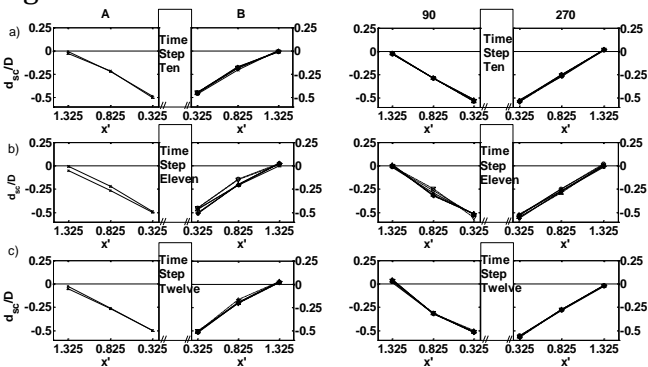


Figure 12

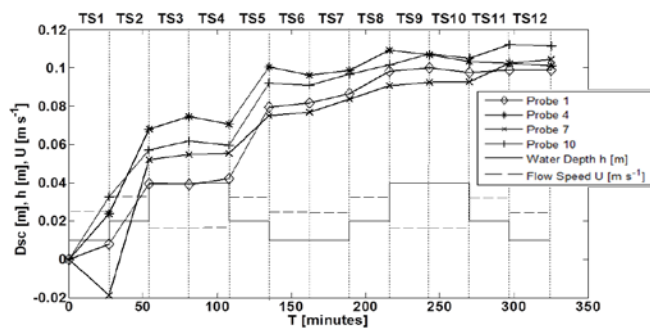


Figure 13

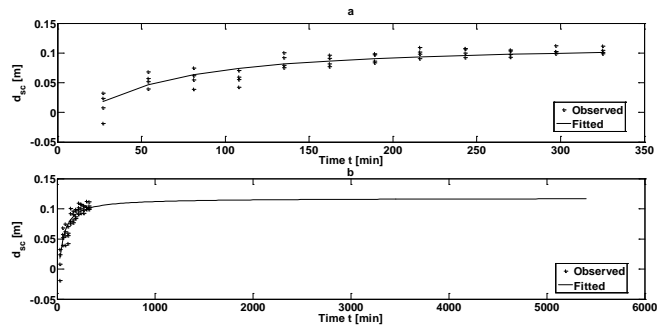


Figure 14

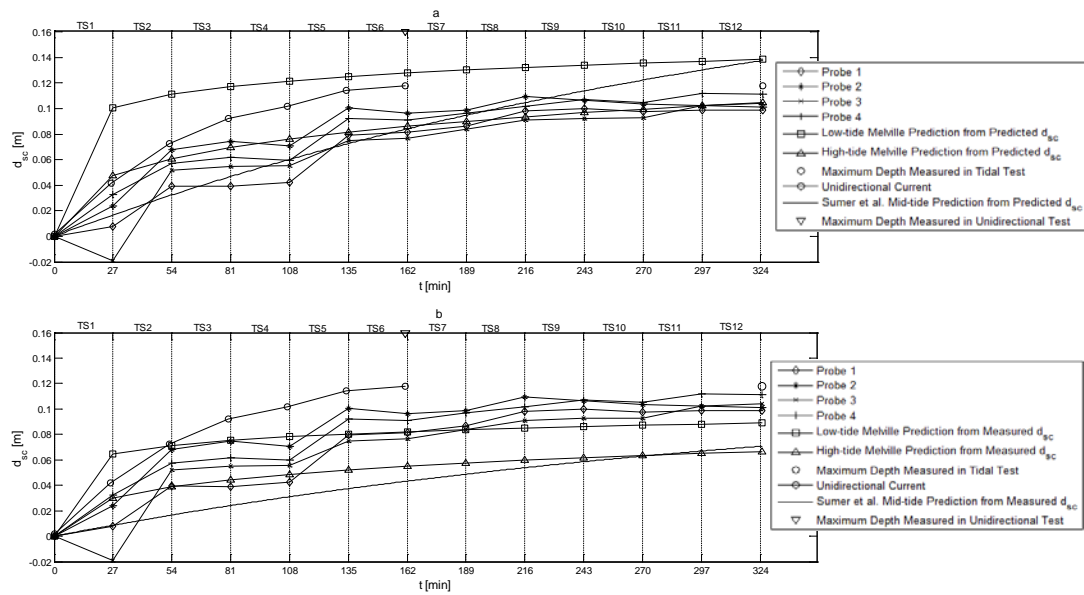


Figure 15

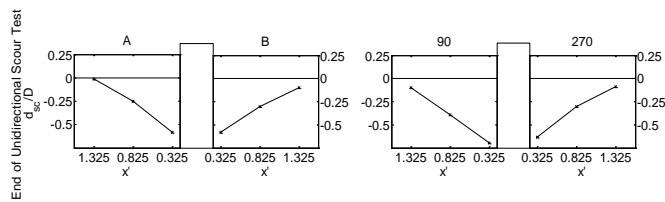


Figure 16

## Figure Captions

Figure 1. Comparison of the time development of clear-water and live-bed scour, after Breusers and Raudkivi (1991).

Figure 2. Square tide where velocity is equal and opposite for each half-cycle (left), and a sinusoidal tide (right).

Figure 3. Image of the flume constructed within the tank with the test cylinder positioned at the midpoint of the flume.

Figure 4. A schematic diagram of the flume set-up.

Figure 5. Schematic diagram showing the construction of the test time-step from the sinusoidal non-progressive tide.

Figure 6. Sample flow speed and depth time series from a tidal gauge and current meter in Liverpool Bay, U.K. Data name b0015569, and collection date 1977.

Figure 7a-b. An image of the URS deployment around the cylinder, (7a) a schematic diagram of the URS positions with the origin is set at the cylinder centre (7b).

Figure 8a-c. URS time series scour development between TS1 (8a), TS2 (8b), and TS3 (8c). Depth at the start of each time-step is denoted by crosses on a medium weight black line, and at the end of the time-step by crosses on a heavy black line. Time-series depth readings at 5, 10, 15, 20 and 25 minutes are represented by the circles, down-triangles, up-triangles, stars, and plus signs respectively on dashed lines for each plane except the downstream (B) plane, which shows only the start and end readings. The edges of the cylinder are located at their true positions along the adjacent x axes; that is, at  $x'=0$ . However, the cylinder diameter is not scaled to the adjacent x axes (as denoted by axis break symbols).

Figure 9. Rippling of the bed after time-step two.

Figure 10a-c. URS time series scour development between TS4-6. Symbols as in Figure 7a-c.

Figure 11a-c. URS time series scour development between TS7 to 9. Symbols as in Figure 7a-c.

Figure 12a-c. URS time series scour development between TS10-12. Symbols as in Figure 7a-c.

Figure 13. Variable reversing scour time-development for the closest probes to the cylinder at each radial position (top), water depth and current speed (bottom).

Figure 14. Exponential curve fitted to the data from probes 1, 4, 7 and 10 (top), and the extrapolation of the curve to 90 hours (bottom). The fit is strongly statistically significant ( $r^2 = 0.7$ ;  $df = 46$ ;  $p < 0.001$ ).

Figure 15a-b. a) Time-development of scour at URS probes 1, 4, 7 and 10 with the curve for the

transition and clear-water time-step predicted using the Melville and Chiew (1999) method and the live-bed time-step predicted using the Sumer et al. (1992a) curve (1-2 and 3-4 respectively).  $d_{sc}$  is calculated from Equation (5). Also plot is the maximum depth measured in the unidirectional test (down triangle) and variable reversing test (circle); both measured using the laser profiler at  $x' = 0.75$  and  $y' = 0.5$ . b) As in Figure 13a except  $d_{sc}$  is taken as from the measured variable reversing maximum (Table 3). Note the less-smooth development of scour recorded by the URS probes in comparison to all prediction curves.

Figure 16. Final URS scour depth reading for the unidirectional scour hole. Symbols as in Figure 8a-c.

### **Table Captions**

Table 1. Test conditions.

Table 2. The final measured values of  $d_{sc}/D$  at probes 1, 4, 7 and 10 for the variable reversing and unidirectional tests.

Table 3. The mean slope angles for each measurement plane at the end of the unidirectional and tidal tests.