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MARINE SCOUR AT LARGE FOUNDATIONS

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This paper presents the results from a study into the scour development around a monopile and three different large (20m diameter) marine foundations in currents and waves. The relevant hydraulic processes are discussed and the results from a mobile bed physical model investigating the scour process presented.

1 Introduction

In pursuit of renewable energy targets there is presently interest in alternative foundation options for windfarm turbines placed in shallow coastal waters where tidal currents and wave activity produce a mobile seabed. When a foundation is installed on the seabed the local marine velocity field is disrupted, additional turbulence is generated and the potential for sediment transport near the foundation is increased leading to local scouring [1,2,3,4].

The "live-bed" situation where sediment is just mobilised everywhere is considered to be the regime for which the scour depth is deepest around a slender cylinder diameter Dm. The largest scour depth S occurs in wave-current conditions with a current dominated "live-bed" condition [4], up to S/Dm = 2.

From a review of available predictors it became clear that there were presently no accepted equations for the scour depth around composite monopile-caisson structures in waves and/or currents. It was proposed that the most productive way to proceed was to undertake laboratory testing to determine how the scour behaviour differed between different foundation types in current, waves, and current and waves conditions.

Three factors need to be considered for a scour assessment:

- What are the key external features of the structure and what are its dimensions above the seabed level and below the soil surface, e.g. presence of skirts?
- What are the environmental conditions – metocean and soils?
- What are the implications of scouring taking place?

In the present study the structure is a monopile tower with outside diameter Dm 4.6m joined to a circular suction foundation caisson with an outside diameter Dc of 19m. The height of the top of the caisson above seabed level is 2m and the skirt tip depth is 9.5m. Penetration of the skirt to this depth around a "plug" of soil and maintenance of the seabed level is one of the requirements for foundation stability. Three different monopile-caisson connection geometries were proposed including a girder top with radial fins, a concrete slab top, and a conical top (Figure 1). For comparison the situation with a 4.6m monopile directly placed in sand bed was also considered.

The water depth was selected as 10m as this represents typical water depths at a number of potential UK windfarm sites. Borehole records showed that the surficial layer is typically fine to medium sand, up to 20m thick with an average median grain size d_{50}=0.338mm. A flow velocity of approximately 0.4ms^{-1} is required to mobilise this sediment and expected peak tidal currents up to 1.5ms^{-1} are well in excess of the threshold of motion for the sediment. A typical nearshore wave condition typical of 1-year return period was selected with H_s = 4.5m and T_m =7s which produces bottom orbital velocities well in excess of threshold. Thus a vigorous scour environment is expected.

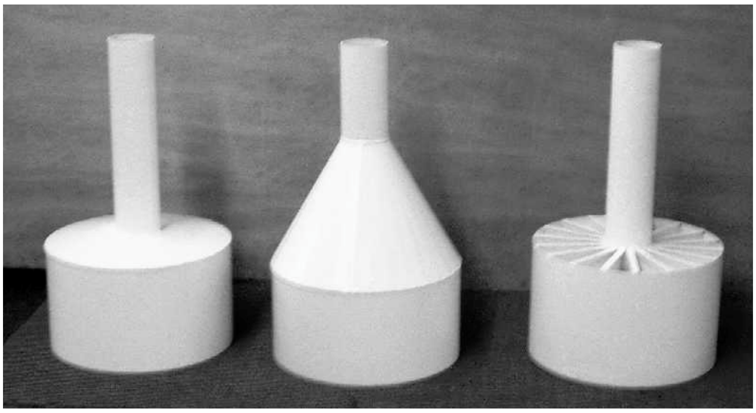

Figure 1 Foundation models used in testing – L-R: concrete-conical-girder

The implications of scour taking place around the foundations are a loss of skirt depth. Thus it was important to understand how scour might develop around the foundation. The paper discusses the flow-structure interaction for the foundations, the test methodology and an inter-comparison of the results from the tests, before drawing conclusions.

2 Flow structure interaction

The variation of velocity with height in seabed boundary layer approaching a monopile structure drives a flow down the face of the monopile. A recirculating vortex forms as the flow impinges on the seabed which wraps around the monopile and trails off in a downstream direction creating a “horseshoe” vortex. These mechanisms and the link to the mechanics of the scour are dealt with in detail by Sumer and Fredsøe [4, 5].

The flow-structure interaction of the composite monopile-caisson foundation is depicted in Figure 2. The main effect is that the caisson foundation actually protects the seabed from the intense flow field around the base of the monopile. However, flow acceleration and vortex action and hence scour occurs directly around the wall of the foundation. The flow over the top of the caisson will generate a recirculating zone downstream akin to flow separation over a rearward facing step and the associated reattachment point downstream will be a point of high turbulent shear stress. In addition the turbulent wake from the monopile will extend downstream and also interact with the bed increasing the potential for scour in that region.

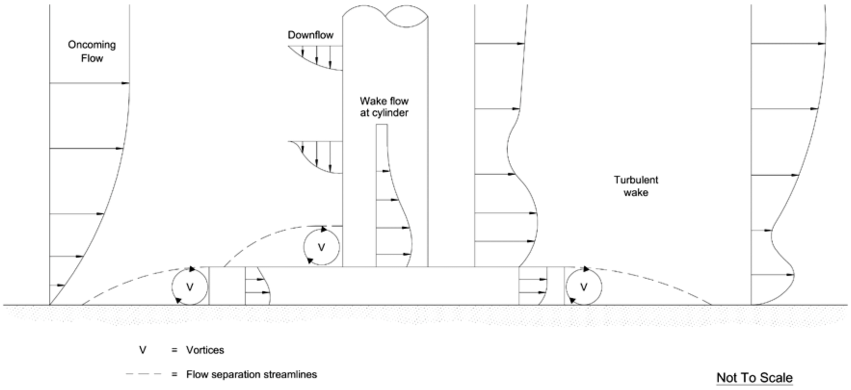

Figure 2 Schematic flow-structure interaction for foundation

The different connection details between the base foundation and the monopile will produce different hydraulic interactions. Geotechnical aspects of foundations have been covered by Byrne and Houlsby [6].

3 Methodology

Tests were undertaken with constant wave and/or current forcing to provide comparative data on scour at the different foundation types. The modelling was done in a large test basin at HR Wallingford with waves generated at 90º to the current.

The main features of the test basin were a re-circulating uni-directional current system with control structures to widen and steady the flow and produce a smooth transition onto the sand bed, plus sump and sediment trap at downstream end. The wave paddle generated irregular period long-crested waves to the required wave spectrum (JONSWAP) and conditions were calibrated from wave-probe measurements taken at the test section.

The foundation models were built at a geometric length scale of 1:40 and the corresponding model velocity and time-scales were 1:6.3. These were selected as appropriate for simulation of bed scour. The monopile and foundation models were fixed in position to prevent settlement or displacement once scour had occurred. The sediment used in the model was a fine quartz density sand of a median diameter of d_{50}=0.111mm and the model sand bed was 0.24m deep, 5.0m long and 3.0m wide. The wave-alone and current-alone conditions were capable of mobilising the bed sediment, i.e. “live bed” conditions, which was confirmed by observations of the bed during testing and the sediment was also transported in suspension in the water column. These two factors were important to reproduce process similitude.

The depth of the scour hole at eight radial locations (A-H – see Figure 4) adjacent to the foundation wall was measured during every test to determine the time development.

4 Results

The test conditions are presented in Table 1 and the results (e.g. Figure 3) are summarised in Table 2. The results are scaled to prototype/field-scale using the scale factors stated earlier.

Table 1 Measured conditions during tests (scaled up). *assumed – same flow boundary conditions as Test 5

Test nr - Structure	$H_{1/3}$ (m)	T_m (s)	Current speed (ms^{-1})
1 - 4.6m OD Monopile	0	0	1.7
2 - Girder top	0	0	1.7
3 - Girder top	3.9	7.1	1.5
4 - Girder top	3.9	6.9	0
5 - Concrete top	3.8	6.9	1.7
6 - Conical top	4.1	6.9	1.7*

Table 2 Summary of measured scour depths.

Test	Structure	Condition	Maximum scour depth @ end of test duration @ radial location(s)	Maximum scour depth after 10 hours @ radial location(s)
1	Monopile	Current	4.3m @ 36.1 hrs @ D	3.4m @ G
2	Girder top	Current	3.5m @ 28.6 hrs @ C	1.5m @ C
3	Girder top	W+C	9.3m @ 44.4 hrs @ G	3.0m @ G
4	Girder top	Waves	0.8m @ 18 hrs @ C	0.6m @ B/C
5	Concrete top	W+C	7.5m @ 38.1 hrs @ F&G	2.9m @ F
6	Conical top	W+C	8.5m @ 27.5 hrs @ G	4.9m @ F

Comparison of scouring at monopile and foundation in current (Tests 1 and 2)

In Test 1 a local scour hole formed around the monopile and in the early stage of development the majority of the eroded sediment was transported into suspension and carried downstream by the current, with some of it depositing to form a lenticular shaped accumulation of sediment behind the structure. The time development curve was the characteristic exponential decay experienced for a cylindrical pile [3]; i.e. fast rates initially slowing down with time to a reasonably stable maximum equilibrium depth in this test of around 4.3m or 0.94Dm (Figure 3).

In Test 2 the scour development was nearly linear with time. The maximum scour depth was 3.5m which is 0.18Dc, 0.37 times the skirt depth or 0.30 times the total foundation height. As expected from the assessment of the flow-structure interaction scouring was intense on the seabed adjacent to the foundation and the turbulent wake produced scour pits that trailed away from foundation. The rate of scour depth development up to 10 hours was slower for the foundation than the monopile due to persistent vortex and eddy shedding around the monopile (Figure 5).

Figure 3 Result of scour test with current (Test 2)

Foundation scour with waves and current (Test 3)

In Test 3 sediment was suspended to the height of the upstand on the footing and then transported by the current between positions A and B. The deepest scour followed a linear development in time and took place faster than under the current only condition. The deepest scour did not reach an equilibrium situation as observed with the monopile during the test. The reason for the change in shape is due to the fact that as the scour depth grows, so too does the degree of flow disturbance. Initially, there was only 2m of the foundation above the bed level and hence the flow disturbance was low. However, as the scour hole grew, so too did the length of skirt that is exposed to the flow. The maximum scour depth was 9.3m which is 0.49Dc or 0.8 times the foundation height. There was a radial variation in scour development with the sheltered down-current side at location B where sediment erosion was counter balanced to some extent by accretion, yielding a smaller scour depth of just over 3m.

Foundation test with waves (Test 4)

In Test 4 the time development was linear and then constant, but the overall scour depths were much smaller with waves only. The maximum scour depth was 0.8m which is 0.04Dc or 0.07 times the foundation height. The ratio S/Dc is similar to the situation experienced with full water depth cylinders of the same diameter [4,7].

Different foundation connections with waves and currents (Tests 5 and 6)

In Test 5 the results showed that the time development in this test was relatively linear, with some small step-like variations. The steps in the time development are due to periods of time when the sediment transport out of the scour hole is counterbalanced by occasional inputs of sediment avalanching into the scour hole. It is quite similar to the scour produced with the girder top (Test 3) after an equivalent length of time. This indicates that the caisson top detail does not appear to have a significant influence on the scour development. The maximum scour depth was 7.5m which is 0.39Dc or 0.65 times the foundation height. In the first 5 hours of the test it was noted that the scour depth at the down-current locations A and H are deepest and that whilst the bed at location H continued to deepen the bed level at location A increased by a smaller amount due to the influence of sediment deposition.

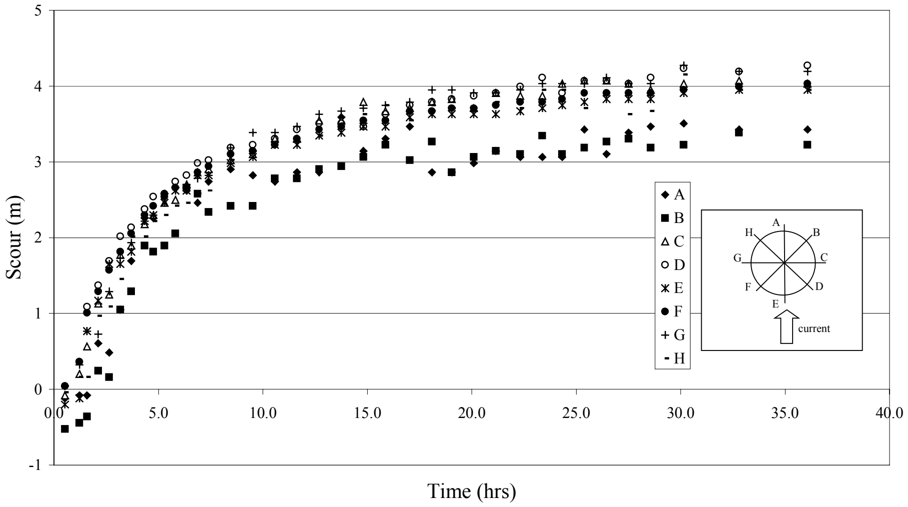

Figure 4 Scour depth time development at monopile in live-bed current – Test 1

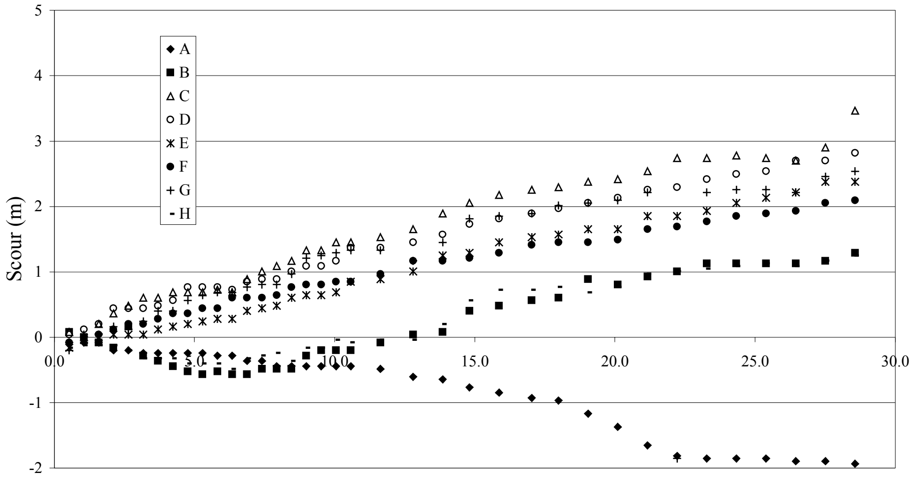

Figure 5 Scour depth time development at structure in live-bed current –Test 2

In Test 6 scour was observed to develop quickly around the conical caisson. The time development data showed that overall the scour develops quicker with this kind of foundation compared with the girder top or concrete top; in the phase of scour development to 5m the scour around the conical foundation was roughly a factor of 1.8 faster than with the girder or concrete top. The scour around the foundation after 20 hours was generally deeper than with either the girder top or concrete top. The maximum scour depth was 8.5m which is 0.45Dc or 0.73 times the total foundation height.

5 Discussion

The results for the current-alone scour around the foundation (Test 2) can be compared with the situation with a full-water depth cylinder of the same diameter as the base. The maximum scour depth in the "live-bed" regime could be of the same order as the cylinder diameter. Clearly the limited height of the foundation leads to an expected reduction in the scour depth which is confirmed by the present tests.

The results from the 1:50 scale laboratory tests of Wilson and Abel [8] are relevant to the present study. They examined scour around three-circular pontoon footings of a jack-up rig in a steady current under live-bed conditions representing 25m of water. The foundations were 24.5m diameter and 8m high and the scour depth with all units scaled to full size was 6.5m. Settlement of the model to 2 to 4m took place during the testing. The modelled scour depth to foundation diameter ratio equates to 0.27Dc or 0.8 times the foundation height. The scour depth is controlled by the height and diameter of the foundation and by the settlement which promotes scour as the blockage caused by the foundation moves down into the bed. The initial above-bed blockage is higher in this case and combined with the settlement promotes deeper scour than for the current-only scour test for the present foundation.

6 Concluding Remarks

The results obtained in the physical model tests provide a clear insight into the potential scour development around suction caisson foundations in (long-crested, random) waves and/or a steady current. The scour development around the 19m diameter skirted caisson foundations supporting the 4.6m diameter monopile showed an approximately linear increase in scour depth with time. This is because the flow contraction against the 2m upstand on the skirt initiates the scour process which is then reinforced as more of the skirt becomes exposed. The deepest potential scour depth with the caisson was 9.3m in Test 3 with waves and currents and corresponds closely to the 9.5m skirt initially embedded in the bed. It is interesting to note that Test 2 with only the current produced a much lower scour depth than at comparable times in Test 3. In both cases the current was running at about threshold of motion for the sand in the model for which it is commonly accepted that the deepest scour occurs [3,4]. The scour development around the girder top and concrete top models was similar. The scour development with the conical top was approximately 1.8 times faster (Test 6) than the girder top (Test 3).

The results provide good indications of the potential scour that can develop in "live - bed" current and wave conditions, or current dominated regimes. The foundations are less susceptible to scouring in wave dominated regimes. With currents and waves scour protection will be required to prevent scour from causing a drop in the seabed level adjacent to the footing and can be expected to be successful if appropriately designed. In a site assessment the local scour and regional scale erosion and accretion patterns of sediment need to be considered. General changes in seabed level can take place due to storm events, the changes in the profile and position of marine dunes, subtidal channels and shoal areas or sandbanks will need to be considered. All these factors need to be considered in site selection and in designing scour protection measures.

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