SPUDCAN PENETRATION DUE TO SCOUR: A COMBINED HYDRODYNAMIC AND GEOTECHNICAL STUDY

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ABSTRACT
The increasing use of jack-ups for wind farm construction exposes jack-up foundations to an increased risk of scour. This is because in commonly encountered sandy soil conditions, only a small amount of leg penetration occurs, and the water depth is relatively shallow so that near-seabed water velocities can be sufficient to scour the seabed. Scour around the spudcan foundations of a jack-up can lead to settlement that is dependent on the foundation preloading (or initial penetration), the applied leg loading, the geotechnical conditions and the scour processes. This paper presents reduced-scale flume experiments, which model the applied loading conditions on the spudcan as well as the hydrodynamic and sediment mobility processes. The model tests measure settlement rates of the spudcans during scour events and use image analysis to reveal two separate interaction mechanisms.

KEY WORDS: Local scour, spudcan penetration, sand, model tests.

INTRODUCTION
Offshore jack-up platforms are commonly used for drilling and construction operations in shallow to moderate water depths, including increasingly in the installation of renewable energy infrastructure. Many of the sites where they are being used have a sandy seabed and so foundation penetration, even after pre-loading, may be such that the widest part of the spudcan foundation remains above the level of the seabed (e.g. less than 3 m of penetration of a 16 m diameter spudcan). This, coupled with active near-seabed water movements in shallow water and potentially mobile sediments, means that spudcan foundations may be susceptible to scour.

Field evidence of scour around full-scale jack-up platforms has been reported by several authors including Sweeney et al. [1], Angus et al. [2] and Rudolph et al. [3]. These works report leg-lowering of up to several metres and the development of local areas of sediment removal around the foundations. Although these effects were tolerated during operations, there are conditions where such scour could threaten the stability of the jack-up. In particular, both Sweeney et al. [1] and Luger et al. [4] discuss conditions where local scour and leg penetration could lead to punch-through of foundations for sand over soft clay sites. Figure 1 shows the hypothesised conditions of scour for such a site reported by Luger et al. [4]. During installation of the jack-up, the foundation loading is taken to point ‘A’ (during preloading) and unloaded to point ‘B’ (the still water loading condition). Depending on the amount of scour that takes place, the foundation could be lowered to points C, C_1 or C_2 and this will then govern the available foundation resistance during a subsequent storm loading. As indicated by the still water penetration curve (black solid line) there is a reducing available resistance with increasing leg penetration and so a risk of punch-through (e.g. for the pink line, C_2, compared to the red line, C).

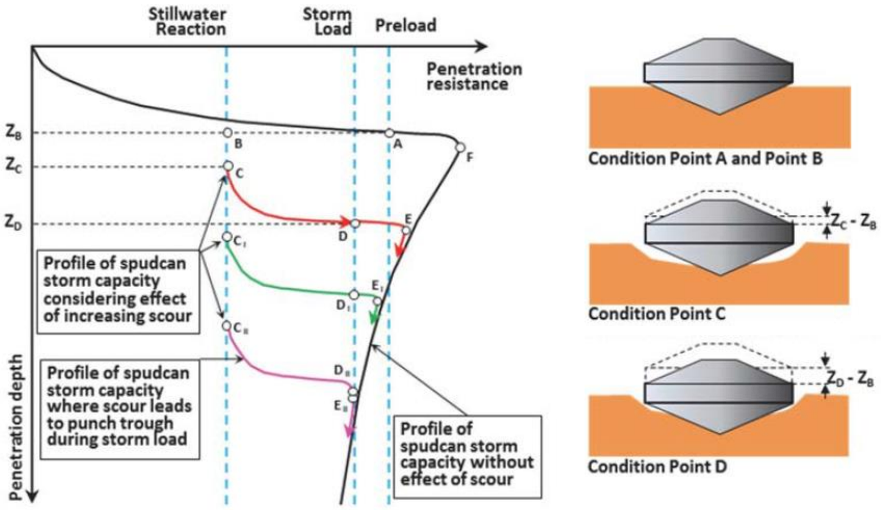


Figure 1. *Hypothesised spudcan response during local scour ([4])*

Local scour has been studied for a range of (mainly stationary) objects founded on the seafloor and on riverbeds. The majority of these studies have focused on objects that have been deeply embedded (e.g. piles and piers), for which scour can develop without settlement of the object. Comparatively less work has focused on shallowly embedded objects, such as spudcans, pipelines and sea mines, where local scour can result in undermining of the structure, leading to a reduction in bearing area and subsequent settlement of the structure (e.g. [5], [6], [7]). Friedrichs et al. [8] synthesised most of the available experimental observations concerning the self-burial of shallowly embedded horizontal cylinders, spheres and tapered cylinders in steady current conditions. Using regression analysis, they showed that the flow intensity (quantified in terms of the dimensionless seabed shear stress or Shields parameter) is the main factor that influences the burial depth; when the Shields parameter is increased (e.g. by increasing the current speed) the relative burial depth increases, presumably due to an increase in the potential for scour. Nevertheless, despite the dominance of the Shields parameter, the analysis undertaken by Friedrichs et al. [8] also indicated that the shape of the object and the density of the object appear to have an influence on burial depth - which hints at the complexity of the problem.

Scour around jack-up foundations has been investigated experimentally in several studies (e.g. [9], [10], [1], [11]). Sweeney et al. [1] tested a vertically loaded (but not pre-loaded) jack-up leg with a 30 cm diameter spudcan resting on sand in a unidirectional flow flume. Their experiments indicated gradual settlement at a rate that reduced as the test proceeded. However, only a small number of test results were presented and all tests started without a pre-loading phase. More recent testing by Raaijmakers et al. [11] investigated scour around fixed, approximately 50 cm diameter circular spudcans for a range of wave and current conditions. The experimental results were compared to a scour depth prediction equation with good agreement. However, the spudcan was not allowed to settle vertically during tests and so the interaction of the settling foundation and the scour process was not investigated.

The aim of the work reported in this paper is to investigate in more detail the interaction mechanisms between settlement and scour development for a jack-up on sandy seabed. Of particular interest is the effect of initial spudcan embedment (z_a in Figure 1) on the system response, investigated by introducing pre-load. The investigation focuses on scale model tests similar to those conducted by Sweeney et al. [1], in unidirectional flow. The remainder of the paper describes the experimental methodology used, presents preliminary results focussing mainly on the interaction mechanisms and briefly discusses the results and implications for jack-up design.

EXPERIMENTAL METHODOLOGY

Apparatus

Experiments were conducted to simulate a vertically loaded spudcan penetrating a silica sand sample in the UWA Small O-tube (see Figure 2). A range of different model scale experiments were undertaken, but this paper focuses on two specific scour tests, in which the initial spud can penetration and leg loading were different. These tests represent two different types of loading condition.

The Small O-tube used for the testing is a closed loop recirculating flume driven by an impeller and is capable of producing steady current, oscillatory flow, combined steady and oscillatory flow and other time varying flow conditions ([12]). It has a test section that is 300 mm wide and 450 mm high with a 150 mm deep sand bed.

Figure 2. *The small O-Tube facility used for the testing.*

For the present testing program the O-tube was filled with a uniformly graded sand having a median grain size of D_{50} = 0.19 mm and critical state angle of friction, ϕ_{crit} = 31.8°. This sand was chosen because its erosion properties had been measured previously ([13]) and remain relatively constant for varying sand densities (ensuring repeatable experiments). Mohr et al. [13] reported a threshold shear stress, τ_{cr} = 0.159 Pa.

The model spudcan used was based on the dimensions of a Keppel KFELS B-class Bigfoot Jack-up Rig spudcan (geometry obtained from [14]) at 1:161.5 scale (see Figure 3 (R)). This scale results in a spudcan diameter of 100 mm and ensures that it is far enough away from the walls of the flume to prevent an unrealistic flow field and scour profile. The spudcan was CNC machined from transparent acrylic to allow observation of the change in seabed contact area.

The model spudcan was connected to a vertical rod of diameter 16 mm (representing the jack-up leg), which was connected through a linear bearing (preventing lateral movement or rotation of the leg and foundation) to a loading plate. This cylindrical geometry is a simplification of a truss leg, which is not expected to not have an effect on the scour process if the scour is initiated from the upstream side of the spudcan. However, it may have an effect on scour initiated on the downstream side of the spudcan.

Vertical load was applied to the spudcan foundation by a combination of self-weight of the apparatus (i.e. the spudcan, rod and loading plate, which had a total mass of 1.3 kg) and additional loading to the loading plate. The leg assembly was built to be as light and compact as practical so that tests with different operating vertical loads could be conducted by applying different amounts of weight to the loading plate without potentially buckling the rod.

Two measuring devices were used and logged throughout the test: a load cell to measure the additional applied load during spudcan penetration events, and a string potentiometer to measure the vertical settlement of the spudcan during still water penetration events and during scour events. In addition, a digital camera was used to capture time-lapse images of the spudcan and surrounding soil surface through the O-tube sidewall, while a digital video camera was installed above the foundation to capture videos of contact condition changes under the spudcan. The experimental assembly is shown in Figure 4 (see also Figure 3 (L)).

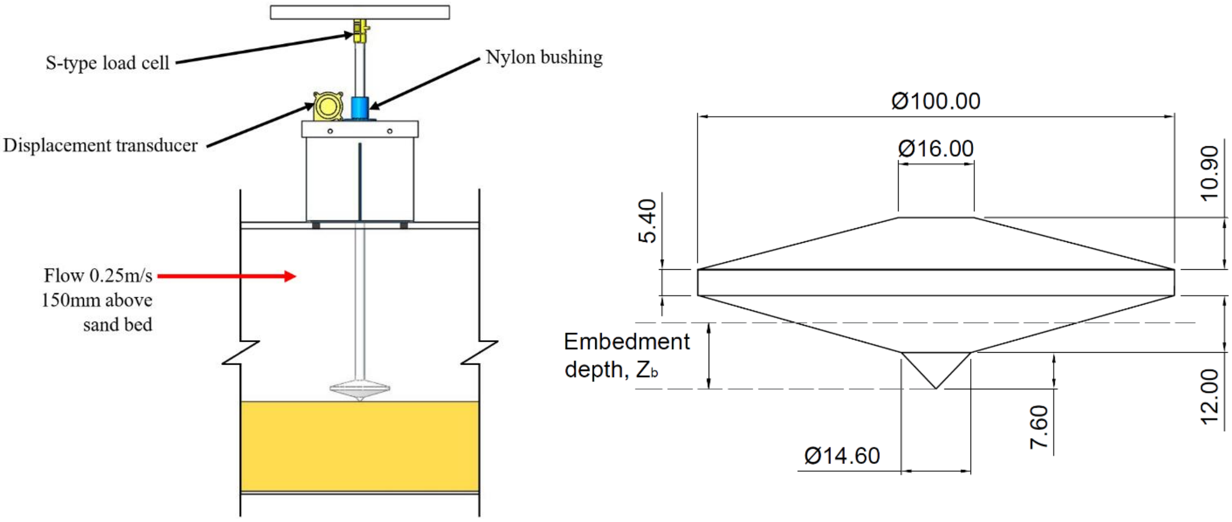


Figure 3. *Schematic of experimental apparatus (L) and scaled spudcan dimensions (R).*

Figure 4. *Test set-up, yellow arrow indicates location of the still water penetration test.*

Test procedure

For each test sand was placed in the base of the O-tube and stirred manually to create a relatively repeatable and loose density condition before each test. The soil surface was then levelled manually before introduction of the spudcan. The seabed had to be extremely flat upstream of the spudcan to prevent the formation of ripple-like features in clear water conditions. Ripples are undesirable as the size of the ripples trigged by unevenness in the model sand bed could be of the same order of magnitude as the scaled spudcan.

Following preparation of the seabed a penetration test on the flat sand surface was conducted as a reference downstream of the scour test location (yellow arrow in Figure 4). The pin holding the leg above the seabed was removed and the leg was gently lowered until the spigot (tip of the spudcan) touched the seabed. The displacement transducer and load cell were zeroed and the spudcan was gently lowered into the soil under its own weight. A still-water spudcan penetration test was then performed by progressively applying vertical load to the top of the ballast plate until the spudcan had reached a penetration depth of approximately half a diameter.

Next, the spudcan was moved to the scour test location (~0.5 m upstream of the still water penetration test location) to avoid resetting the model sand bed. The measuring devices were again zeroed and the spudcan lowered into the sand under its own weight. A ballast tank was placed on the ballast plate and filled with water until the target embedment depth was reached during a 'pre-loading' phase. A proportion of the water was then removed until the remaining vertical load on the foundation was half the value used in the pre-loading phase, thereby mimicking installation with a pre-load ratio of two. This vertical loading was maintained through the scour test by the dead-weight of the apparatus and the remaining water in the ballast tank.

Cameras were set up (with a shooting interval of 5 min) and the string potentiometer was set to log at a frequency of 10 Hz just prior to starting the O-Tube. A unidirectional flow velocity of 0.25 m/s at 150 mm above the seabed was then introduced, which was just below the critical clear-water scour flow velocity for the tested sand (Mohr et al., 2016). Clear-water conditions were adopted to avoid ripple-structure interaction. The flow velocity was maintained for approximately 48 hours or until equilibrium conditions were believed to be achieved (as described later in the results, testing may have accidently stopped prior to equilibrium in at least one of the tests reported herein).

After each scour test was completed the ballast tank was removed and the spud can was pushed vertically into the seabed at the scour location to measure the post-scour still water penetration curve.

Prior to any scour testing, six still water penetration tests were performed to investigate repeatability of the sample preparation and to quantify the spudcan penetration curve in the absence of scour. The median resistance curve for the tests is presented as the blue dashed line in Figure 5.

RESULTS: SCOUR TESTS

As noted earlier, two scour tests were performed for two initial tip embedment depths (z_b measured upwards from the tip of the spigot) representing partial spudcan penetrations in sands: z_b = 12 mm and 17 mm. The scour induced vertical motion is referred to as settlement (Δz).

Large initial penetration: Test with z_b =17 mm

The test started with z_b = 17 mm achieved by applying a vertical load of 170 N to the spudcan in the pre-loading phase (OA in Figure 5) and then unloading to a still water reaction load of 85 N (AB). The initial soil geometry following the penetration is shown in Figure 6(a). The scour test was started at point 'B' and the dead-weight applied load was kept constant while penetration occurred due to scour (to point C). Points CDEFG represent the post-test still water penetration event (to ascertain the capacity of the foundation after the scour event): the ballast tank was first removed (CD) and the foundation was then penetrated into the seabed to point F and unloaded (to G). The results confirm that significant (≈ 13 mm; 13% of diameter) foundation settlement occurred due to scour and that the post-scour capacity increased due to the scouring event because of the effect of foundation lowering (the plastic penetration curve is largely unaffected). Approximately 2 mm of foundation settlement (2% of diameter) was required to re-mobilise the pre-loading capacity (denoted by point 'E').

The solid blue line in Figure 7 presents the development of scour-induced foundation settlement against time during the 48-hour unidirectional current event. The time-lapse images on Figure 6 show the development of the scour hole around the spudcan at selected intervals during this process, as well as the settlement of the spudcan. To quantify the local scour development, the size of the scour hole immediately upstream of the spudcan was measured throughout the test by scaling from the still images. The definition of the front scour hole extent and its growth with time during the test are also shown in Figure 7.

For the first two hours of current flow, there is no scour-induced settlement. This is despite the fact that a scour hole develops both in front and behind the foundation (Figure 6 (a to d)): the front scour hole extent is approximately 50% of its final size (or 35% of the spudcan diameter) prior to any scour-induced foundation settlement. This time lag occurs because of the foundation pre-loading; significant undermining is required (hence contact area reduction) before any settlement occurs. Figure 9 presents images taken early in the scour process of the foundation and soil contact condition. Preloading has generated an initial contact condition whereby almost the whole base of the foundation is initially in contact with the seabed (Figure 9a). Following two hours of current flow the contact area, particularly on the upstream half of the spudcan, has been reduced to a value where it is just in equilibrium with the still water dead-weight load.

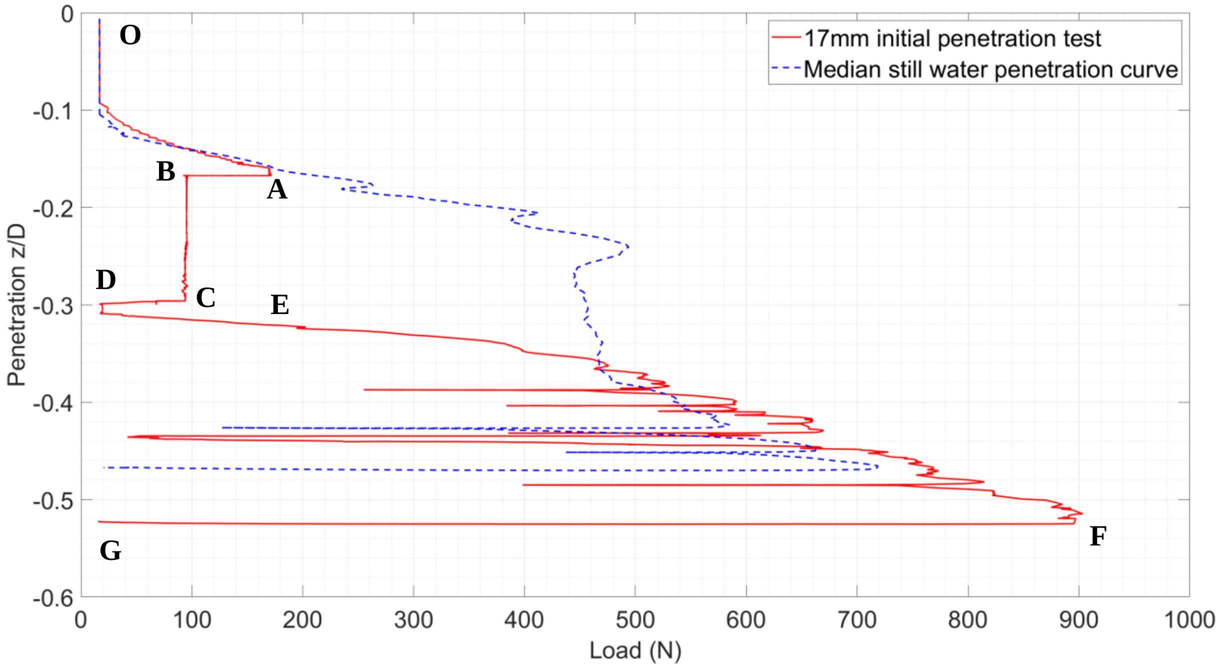


Figure 5. *Penetration vs Load for the whole duration of the test with* z_b *= 17 mm.*

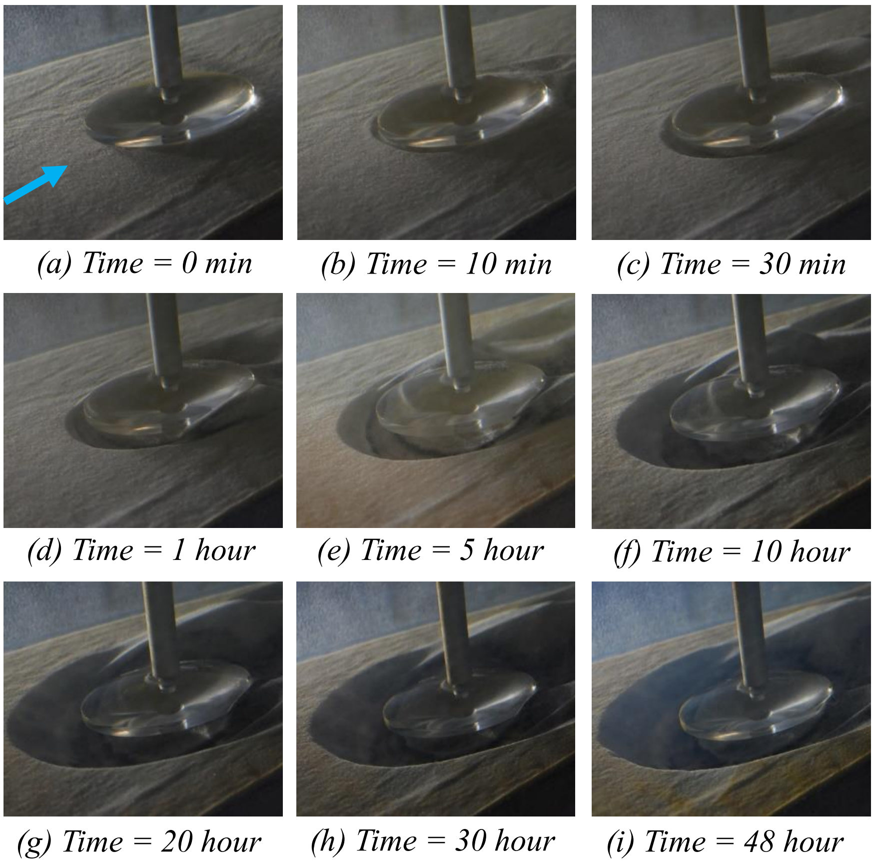


Figure 6. *Side view time-lapse images during 17 mm initial penetration test. Flow direction indicated by a blue arrow.*

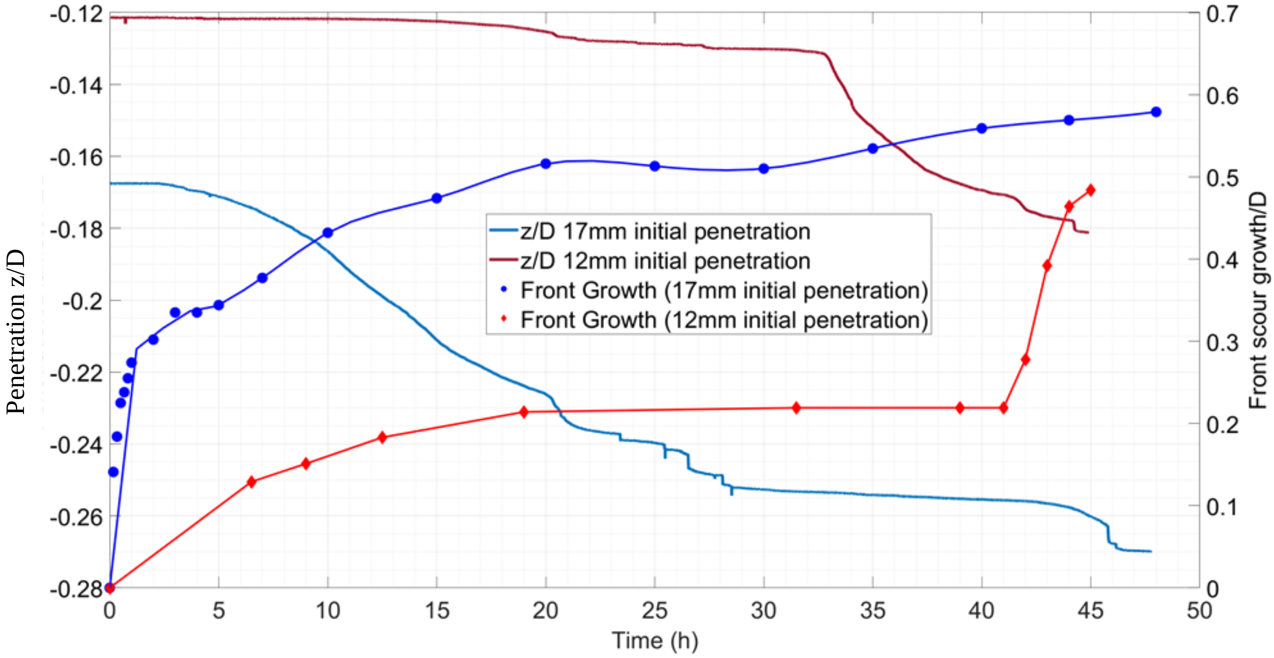


Figure 7. *Normalised scour-induced foundation settlement against time during the scour process, with the normalised front scour growth plotted on the secondary y axis.*

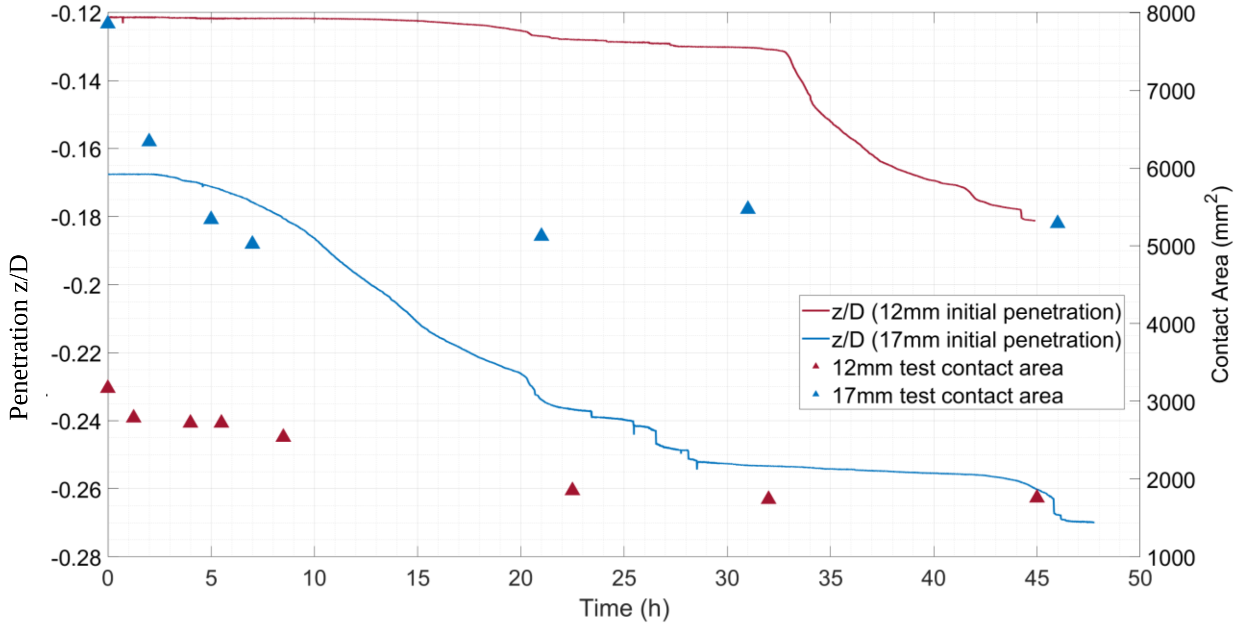


Figure 8. *Contact area and displacement z/D vs time*

Scour-induced foundation settlements start to occur after approximately two hours (Figure 7) and appears to reach a steady rate of approximately 0.4% of diameter per hour by about 10 hours into the test. During this stage, the front scour hole gradually increases in breadth but the contact condition (Figure 9) appears almost unchanged.

After about 20 hours of steady current flow the overall settlement rate starts to slow and the characteristics of the settlement appear to change, with abrupt settlement events occurring. It is not clear why this behaviour changes, nor whether a final equilibrium condition was approached. The final spudcan penetration at the end of the test, $z_c \approx 30$ mm, corresponds to a far-field soil level half way up the top inclined surface of the spudcan.

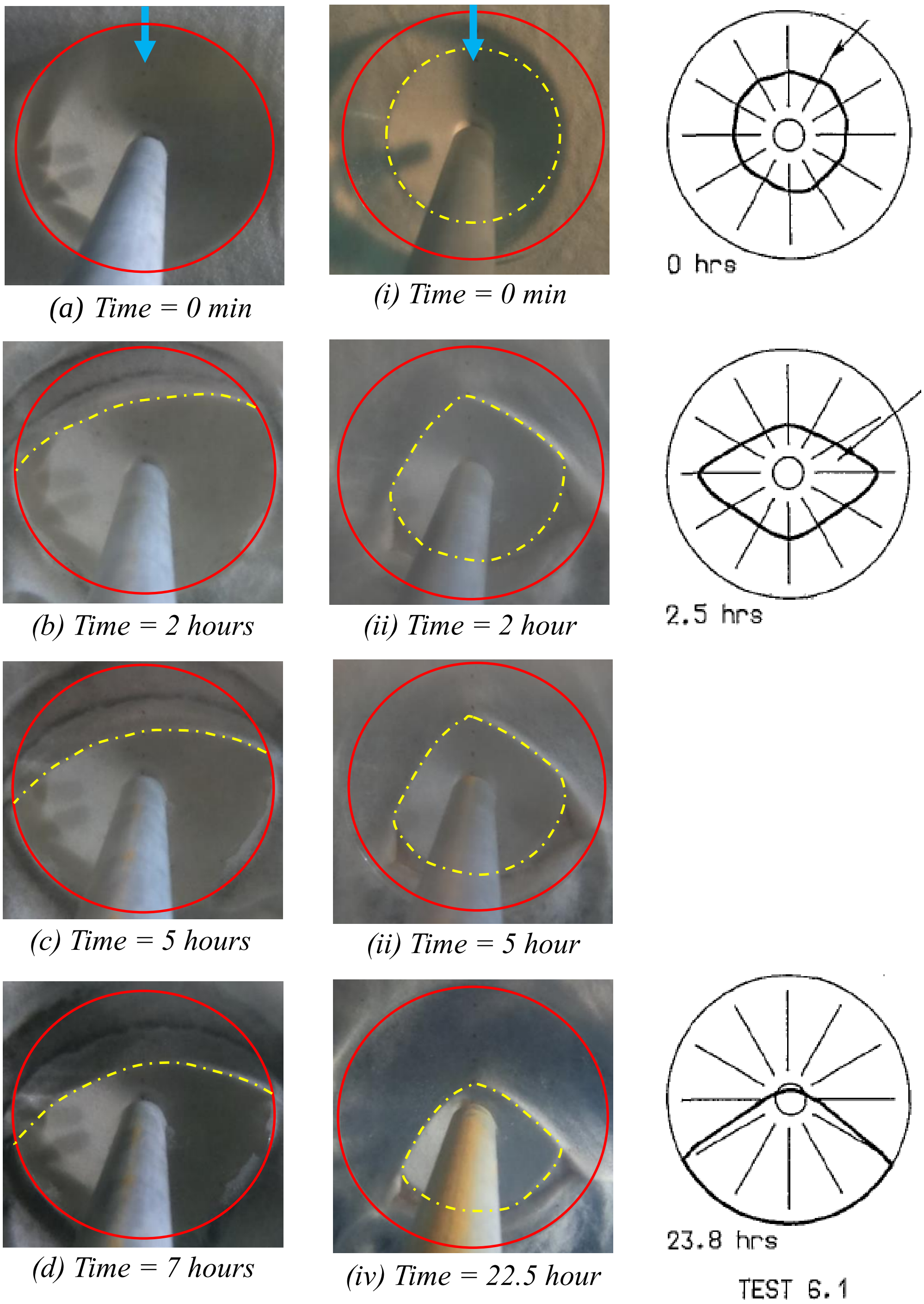
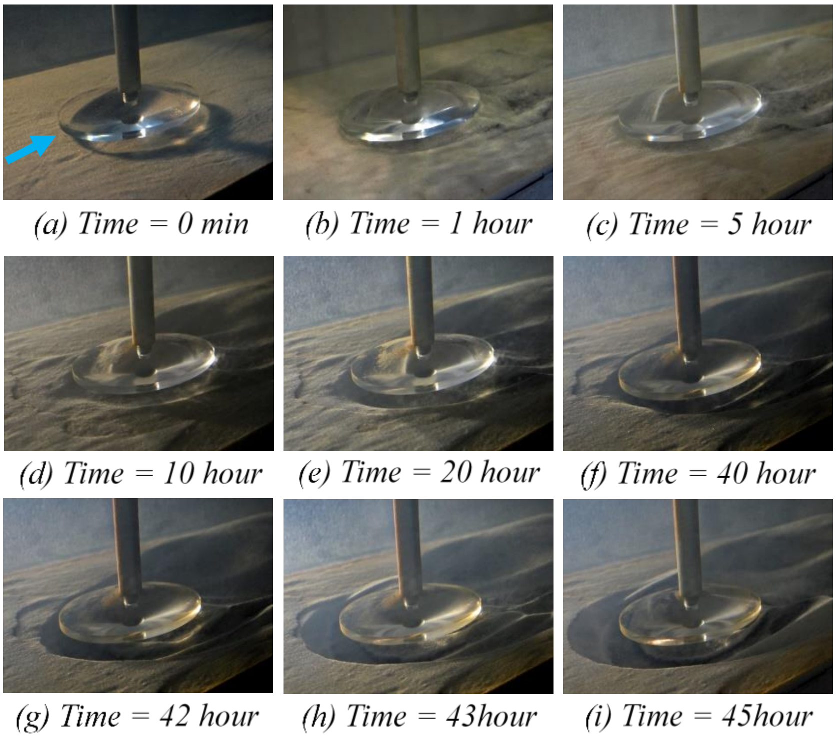


Figure 9. *Top view images for test with z_b = 17 mm (L), z_b = 12 mm (C) and the Sweeney et al [1] results (R) at selected times. The blue arrow indicates the flow direction. The red circles indicate the full spudcan footprint and the yellow dashed lines indicate the instantaneous extent of seabed contact.*

Small initial penetration: Test with z_b = 12 mm
The change of penetration and the growth of the front scour hole are shown for the tests with z_b = 12 mm and z_b = 17 mm in Figure 7. The images captured are shown in Figure 9 and Figure 10.

The response of the initially shallower embedded (and lower loaded) spudcan is quite different. It takes much longer for the foundation settlement to start (approximately 14 hours compared to 2 hours in the tests with z_b = 17 mm) and the scour hole upstream of the spudcan develops much more slowly. There is a step change in settlement rate after about 33 hours which may have generated a sudden change in scour hole growth rate after about 41 hours. Based on the images in Figure 10, initial scour happens downstream of the spudcan and the growth of this scour hole leads to growth of upstream scour. The difference in contact conditions is shown in Figure 9, with contact reducing to a much smaller bearing area because of the lower applied dead-weight load.



(a) Time = 0 min *(b) Time = 1 hour* *(c) Time = 5 hour*
(d) Time = 10 hour *(e) Time = 20 hour* *(f) Time = 40 hour*
(g) Time = 42 hour *(h) Time = 43hour* *(i) Time = 45hour*

Figure 10. *Side view time-lapse images (z_b = 12 mm). Flow direction indicated by a blue arrow.*

DISCUSSION
In summary, across the two tests presented herein, two separate scour-foundation initiation mechanisms were observed prior to the start of settlement:

- 'front scour' where scour started at the upstream side of the spudcan and settlement started soon after the onset of the current. This occurred for the test with z_b = 17 mm.
- 'back to front scour' where upstream scour was much slower and the main local scour occurred downstream of the spudcan. Initial scour-induced settlement took longer to start. However, once significant settlement occurred, upstream scour accelerated. This was observed in the test with z_b = 12 mm.

The difference in the scour behaviour for the two different initial spudcan penetrations is believed to be due to a difference in flow regime around the spudcan for shallow (z_b = 12 mm) and deeper (z_b = 17 mm) initial penetration. For shallow initial penetration (z_b = 12 mm), the flow blockage near the seabed is less significant. The shoulder of the spudcan (the widest part) is not touching the seabed in these two cases and so it is suspected that no horseshoe vortex is formed in front of the model. Therefore, the dominating scour process is initiated on the downstream side of the model due to turbulence from the spudcan and from the vertical rod. As the scour hole due to this turbulent flow gradually grows upstream, settlement happens and leads to scour from upstream. In contrast, for the case with relatively large initial penetration (z_b = 17 mm) the shoulder of the spudcan is very close or touching the sand surface and this leads to local flow contraction and strong local scour from the upstream side of the model. The settlement for the case with z_b = 12 mm (Figure 7) reached approximately 17 mm after 42 hours before increasing suddenly in size. Had this test been conducted for longer, scour-induced settlement may have continued.

In the two scour tests, the measured settlement due to scour reached 0.06D (z_b =12mm) and 0.1D (z_b = 17mm) at the end of the tests. It is interesting to consider how this settlement compares to the scour-induced settlement reported in the literature for other objects. Truelsen et al. [15] reported settlement of sphere of around 0.5D in live bed conditions. This result was relatively insensitive to specific density of the sphere (over the range of conditions tested) and to whether or not the sphere was constrained to settle vertically or allowed to translate during settlement. Friedrichs et al. [8] summarised the settlement depth for a wider range of objects including horizontal cylinders, spheres and tapered cylinders; interestingly they never observed complete self-burial (e.g. settlement was generally less than 1.0D). At Shields parameters close to the transition from clear-water to live bed conditions (similar to that tested here) the settlement depth reached around 0.3-0.8D depending on the object shape. Finally, Sumer and Fredsøe [16] summarise a significant amount of literature for settlement of pipelines. This indicates that the scour hole depth below a pipeline varies linearly with Shields parameter in clear water conditions. Using this scour depth as an estimate of peak settlement depth suggests settlement on the order of 0.5D to 1.0D in live bed conditions and potentially smaller in clear water conditions.

Collectively, the comparison of the present results to existing literature therefore suggests that the scour-induced settlement of the spudcans observed in the present testing is small compared to other objects such as spheres and pipelines. This result is perhaps not surprising given the streamlined geometry of spudcans and the fact that the present experiments where conducted in the clear water regime. Of course, this paper only reports preliminary experimental results (and may not have observed final equilibrium settlements). To achieve more complete understanding of the scour-induced settlement of spudcans further tests are required across a range of flow conditions.

Finally it is noted that the present experiments are not straight-forward to scale up to real world field conditions directly. The reason for this is due to the problem being both hydrodynamic and geotechnical in nature. It is not possible to satisfy scaling for both conditions; altering the soil properties to ensure geotechnical similitude would mean that it is not possible to achieve similitude in the scour processes. Nevertheless, what can be related to real world field conditions is the scour profile and scour mechanisms as these are assumed to remain comparable (in the sense that the hydrodynamic flow structures are likely to scale with the dimensions of the structure). If scour controls the settlement, adopting this assumption would suggest that settlement scales linearly and the field settlement will therefore scale by the spudcan scale factor of 161.5. Similarly the soil volume would scale by a factor of 161.5^3 and erosion rate by a factor of 1/161.5. Further work is needed to investigate if this scaling is appropriate.

Limitations and future work

Although the tests have revealed novel coupled scour and settlement mechanisms that will have applicability to the behaviour of offshore jack-ups, only a small range of possible initial conditions have been investigated in the tests. Further work is required to investigate a wider range of initial spudcan penetrations, different density seabeds, different still water load levels and preload ratios.

A limitation of the testing apparatus is that it does not allow the leg assembly to translate laterally or rotate. In reality the spudcan is not horizontally restrained and will move into the scour hole as it develops (if all legs of the jack-up are experiencing the same amount of scour). Furthermore, the apparatus applies an unchanging (‘still water’) dead weight loading. In practice, if storm events occur, additional vertical and horizontal leg loading will occur and this, following local scour, could provoke differential leg penetration. Such testing would require either modelling of a whole jack-up rig assembly or testing a single foundation but using a horizontal and vertical control actuator to mimic coincident storm loadings.

The flow and seabed condition are also idealized conditions (unidirectional flow with a flat seabed in the far-field). The flow velocity was set at just under the critical velocity for transition to live bed. If the flow transitioned to live bed conditions, sediment supply from upstream is likely to limit the development of the scour hole and the settlement of the spudcan. Also, previous research shows that steady current conditions can generate more scour than wave or combined current and wave conditions at the same Shields number. Therefore, it is suspected that the tests reported in this work could represent the most onerous condition for local scour and spudcan settlement. However, the complex interaction between flow, spudcan and seabed is not well-understood. More research will be needed on this topic to achieve better predictions of scour induced spudcan settlement and potential instability.

CONCLUSIONS

Results from a series of experiments conducted in a circulating flume designed to investigate scour induced settlement of jack-ups on sandy seabeds have been presented. Through combining digital imagery and settlement measurements, the tests revealed combined hydrodynamic, scour and geotechnical mechanisms which occur at the start of the scour process, but also revealed that these mechanisms may change as the penetration of the spudcans increase due to scour.

The mechanisms revealed by the tests give insight into the processes occurring and, with further study, may lead to improvements to calculation methods able to predict such detrimental scouring events.

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