SCOUR DEVELOPMENT IN LAYERED SOILS AROUND OFFSHORE MONOPILE FOUNDATIONS

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ABSTRACT

In this paper, the development of scour in layered soils around offshore monopile foundations is investigated. Physical model tests were performed to study the scour hole geometry for soils composed of fine sediments covered by a layer of gravel in an alternating current. Varying gravel layer thicknesses were tested as well as a reference case with non-layered sediments. Results of the tests were analyzed based on continuous interface scour depth measurements. It was shown that compared to vertically homogeneous soils a gravel top layer may i) significantly reduce the maximum scour depth around the monopile and ii) increase the non-uniformity of the scour geometry.

INTRODUCTION

Monopiles are the most commonly used foundations in the offshore wind developments around the world. When installed in offshore conditions with waves and/or currents, the monopile interacts with the local hydrodynamics, causing flow amplification and an increase in turbulence levels. When the surrounding seabed consists of erodible sediment, this results in increased sediment transport and the development of a scour hole around the foundation.

The processes governing scour development around slender piles have been extensively studied for homogenous soils (e.g. Breusers et al., 1977; Hoffmans et al., 1997; Sumer, 2002; Rudolph et al., 2006). As wind farms are expanding towards areas where more complex soil conditions are present, understanding scour development in layered soils becomes increasingly important. The presence of a layer of coarse material within the soil profile may significantly influence the scour hole development.

Only a limited number of studies have been published regarding the scour hole geometry around foundations installed in soils composed of a gravel top-layer in hydraulic environments. Melville (1975) and Neill and Morris (1980) were the first to identify scouring processes around bridge piers and abutments in such armored beds. They found that the magnitude of critical shear velocity for the threshold motion of bed particles is extended by the armor layer, increasing the range of clear-water scour condition up to the limiting stability of surface particles. This effect was experimentally investigated by Ettema (1980) and Raudkivi and Ettema (1985) for abutments, demonstrating that depending on the structure width, flow conditions, thickness of the armor layer, and bed sand sizes scour depths may be greater for armored beds than for vertically homogeneous soils. Porter et al. (2012) have demonstrated that scour development in layered soils is not correctly predicted using standard empirical approaches as scouring may be enhanced or reduced above that predicted for a uniform non-cohesive sediment. Harris (2013) developed an engineering tool to predict the time evolution of scour around a monopile in layered granular soils in the marine environment. Though both the equilibrium scour depth and backfilling effects were reasonably reproduced, the physics of these processes and the interaction between different soil layers remains are still not well understood. This may lead to an underprediction of estimated scour depths around offshore wind turbines and therefore to potential unconservative scour protection designs.

This paper describes laboratory experiments carried out to investigate scour processes in soils composed of fine sediments covered by a layer of gravel with variable thickness. In the present model tests five cases are investigated for armored beds around offshore monopile foundations to study the effect of a gravel layer on the scour hole geometry in a controlled environment. An overview of the test campaign is described in the sections below.

PHYSICAL MODEL TESTS

Test facility

Physical model tests were performed in the Atlantic Basin facility of Deltares. This basin has a length of 75 m and a width of 8.7 m. Its basin's paddle type wave generator and pumps allow for offshore conditions to be accurately reproduced. The current in the Atlantic Basin can be generated in two directions (either following the waves or in the opposing direction). This is vital for investigating the scour development in an alternating current, because it results in more realistic scour patterns similar to the ones achieved under tidal conditions in the field.

Scaling criteria

For the water motion in free surface waves, gravitational and inertial forces are the dominant forces. Consequently, the ratio of these forces should be equal in model and nature, to preserve dynamic similarity. This is achieved by reproducing the Froude number (Fr) on a scale of

$$n_{Fr} = \frac{Fr_{prototype}}{Fr_{model}} = 1.$$

Froude scaling can usually be fulfilled for most parameters, such as wave height and structural dimensions (length-related), current velocity (velocity-related) and wave periods (time-related). To allow for much smaller model scales, Froude similarity is no longer satisfied for the sediment particle size. Instead, the scaling methodology is aimed at reproducing a similar relative mobility in the model as in the field. The relative mobility is defined as:

$$MOB = \frac{\Theta}{\Theta_c} \quad , \quad MOB_{field} = MOB_{model},$$

where θ is the Shields parameter, θc is the critical Shields parameter and MOB is the ratio between them. The mobility similarity criterion is used to correctly scale the sediment, ensuring similar mobility in the field and at model scale. On model scale, it was attempted to achieve a relative mobility of ~2.0 of the sand (live-bed regime) and <1.0 of the gravel (clear-water regime) to have a sufficiently pronounced difference in behavior.

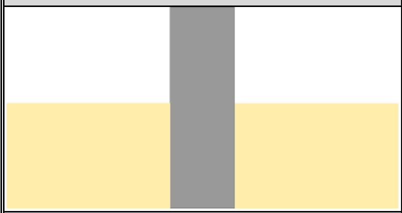
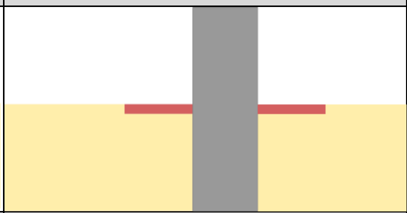
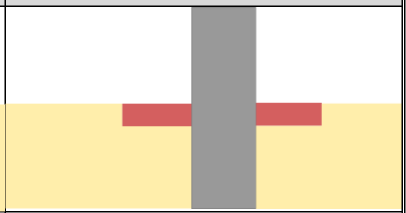
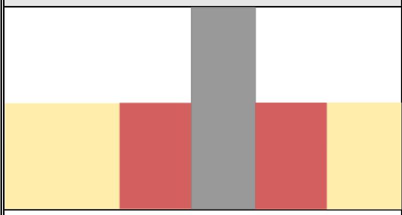
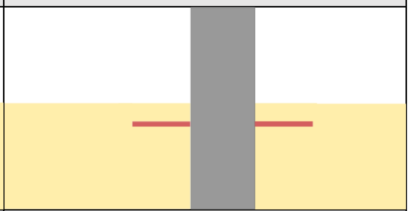
Test setup

A total of five test layouts were tested throughout the test programme (Table 1). Flow velocities were measured with three electro-magnetic current velocity meters. The instruments were placed 3 m upstream of the scale models, thereby ensuring that the hydrodynamic conditions are measured close to the models without causing any flow disturbance to the test setup.

The development of the local scour holes is dominated by tidal conditions. The steady, uniform flow in the basin was selected to reflect sediment mobilities that are typically found in offshore conditions. The mobility is defined as the theoretical undisturbed relative mobility and describes the ratio between the bed shear stress exerted on sediment particles by the hydrodynamic load and the critical bed shear stress. This approach is commonly applied and the work by for example Rudolph et al. (2008) and Raaijmakers et al. (2008) shows good correlation between field measurements and model tests applying this approach.

Median grain size (d_{50}) of the sand and (mobility scaled) gravel layers were 0.18 mm and 1.40 mm, respectively. The monopiles were represented by cylindrical Perspex piles with a diameter (D_p) of 15 cm (selected to achieve realistic offshore flow conditions around the pile). The piles were embedded in a 45 cm deep sand bed.

Table 1. Overview of test setup with five monopiles buried in soil composed of fine sediments with a gravel layer of varying thickness.

Pile 1	Pile 2	Pile 3
		
Vertically homogeneous soil composed of fine sediment	Fine sediment covered by gravel with a thickness of 1 cm	Fine sediment covered by gravel with a thickness of 3.5 cm
Pile 4	**Pile 5**	
		
Full gravel	0.5 cm gravel covered by 3.5 cm of fine sediment	

Internal cameras installed inside the Perspex piles were equipped with a fish-eye lens, which enabled the continuous measurement of scour development around the circumference of the pile by means of digital sand-pile interface recognition. This technique was developed in-house at Deltares, see e.g. Raaijmakers et al. (2008) and De Sonneville (2010).

The test programme consisted of eight consecutive tests performed with an alternating current (four cycles of ebb and flood current). An overview of the conditions is shown in Table 2, in which h_w denotes the water depth, $U_{c,da}$ the depth-averaged approach flow velocity, and MOB the theoretical undisturbed relative mobility of the sand.

In the following sections, first a descriptive overview of the scouring process in layered soils is provided, after which an in-depth analysis of the scour development is provided.

Table 2. Overview of test conditions.

Condition	h_w [m]	$U_{c,da}$ [m/s]	MOB [-]		Duration [s]
			Sand	Gravel	
Tidal	0.6	±0.40	~2.0	~0.8	1200

DYNAMICS OF SCOUR DEVELOPMENT IN LAYERED SOILS

Although static images can never provide a fully comprehensive impression of the dynamical scour process, an attempt is made with Figure 1 to show various observed stages in the scouring process for a layered soil. The case of sand covered with 3.5 cm of gravel is selected to illustrate the scouring process for a layered soil configuration.

In Figure 1, six different stages are indicated:

1. Initial condition of the soil; sand covered by 3.5 cm of gravel.
2. Initiation of the scouring process, erosion occurs at the upstream side of the monopile and on the sides, deposition of material occurs on the downstream side.
3. Growth of the scour hole in gravel: further erosion at the upstream side of the monopile and on the sides, further deposition on the downstream side
4. First exposure of the sand: accelerated growth seems to occur.
5. Growth of the scour hole in the sand: the gravel is uplifted by the horseshoe vortex, thereby exposing the sand and allowing for further growth of the scour hole.
6. Steady continuous development: gravel is continuously uplifted by the horseshoe vortex and sliding back down during calmer periods (demonstrating the intermittency of the horseshoe vortex), whilst a steady growth of the scour depth on the upstream side of the monopile and on the sides occur. Meanwhile deposition on the downstream side increases, contributing to significant asymmetry in the scour hole geometry.

The video stills show distinct phases in the development of the scour hole. Initially, scour occurs mostly on the sides of the monopile. After this initial development stage, the development of the horseshoe vortex becomes more pronounced, leading to a more significant development on the upstream face of the pile. The presence of the horseshoe vortex is clearly visualized in the video by the gravel continuously being transported upslope and sliding down again. When the gravel is transported upslope, the underlying sand becomes exposed and is further eroded. In the remainder of this paper, it is investigated if the presence of the layer of gravel will impact the scour hole depth around the monopile and the scour hole geometry.

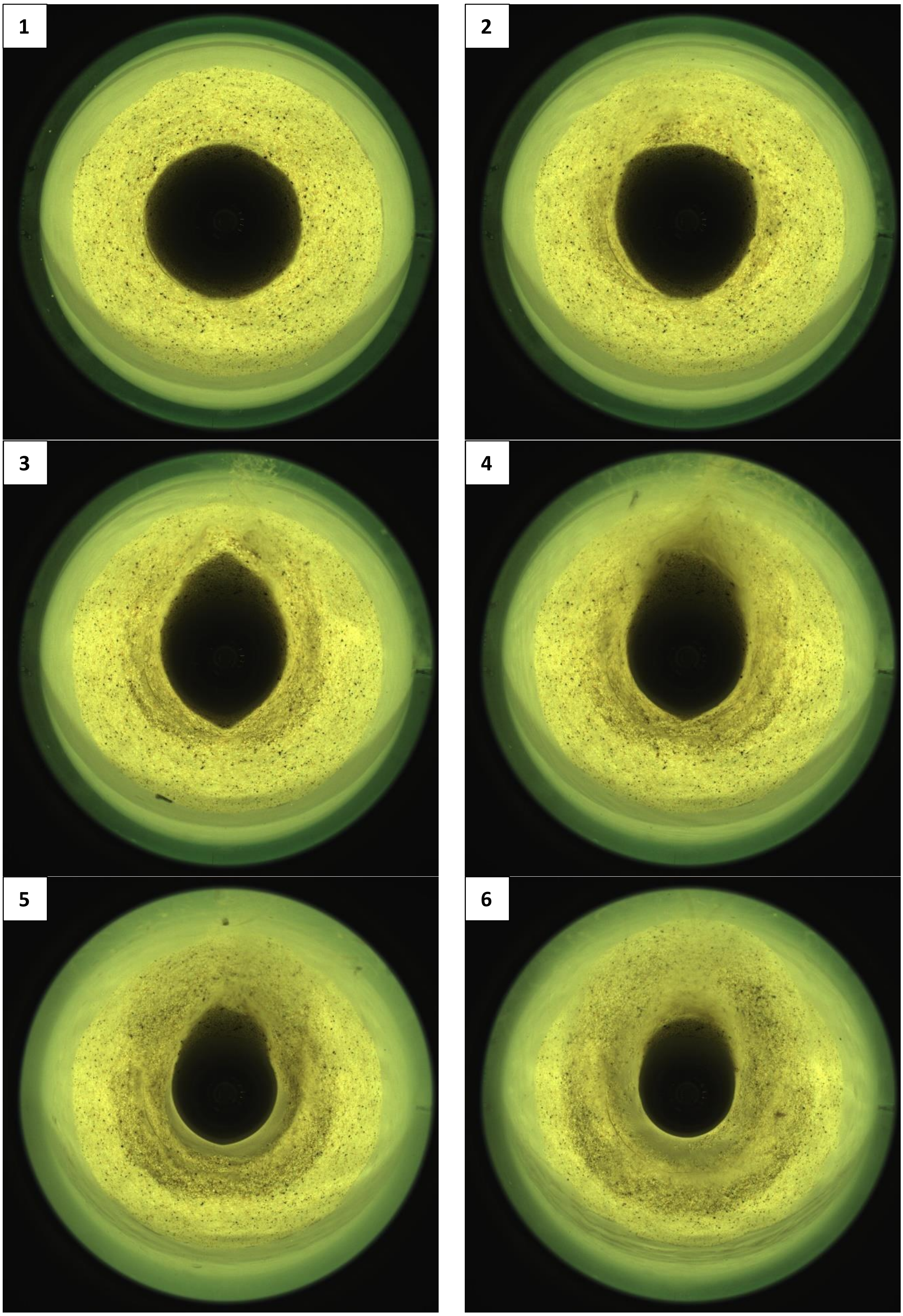


Figure 1. Example of video stills taken from the 3.5 cm gravel cover on top of a sandy seabed showing the dynamics of the scour hole development process. 1) Initial situation, 2) initiation of erosion at sides, 3) growth scour hole in gravel, 4) first exposure of sand, 5) sand exposed and gravel lifted by horseshoe vortex, 6) steady erosion of sand.

ANALYSIS OF SCOUR HOLE CHARACTERISTICS

This section provides a concise presentation and interpretation of the most important observations from the physical model tests programme. First, the development of the scour hole depth is provided, next the geometry of the scour hole is discussed.

Scour hole depth

With the internal camera technique, the bed level at the face of the monopile is continuously monitored. The scour depth along the pile was determined for radial transects with a resolution of 1 degree to also monitor the variability of the scour hole along the face of the pile. This provides a bandwidth of scour depth at each measured time, allowing the extraction of non-exceedance percentage values of the scour depth along the pile face.

In Figure 2 (upper panel) the median scour depth development (S_{50}) over time is presented for each test case as presented in Table 1. The lower panel of Figure 2 zooms in on the first 5 minutes of scour hole development.

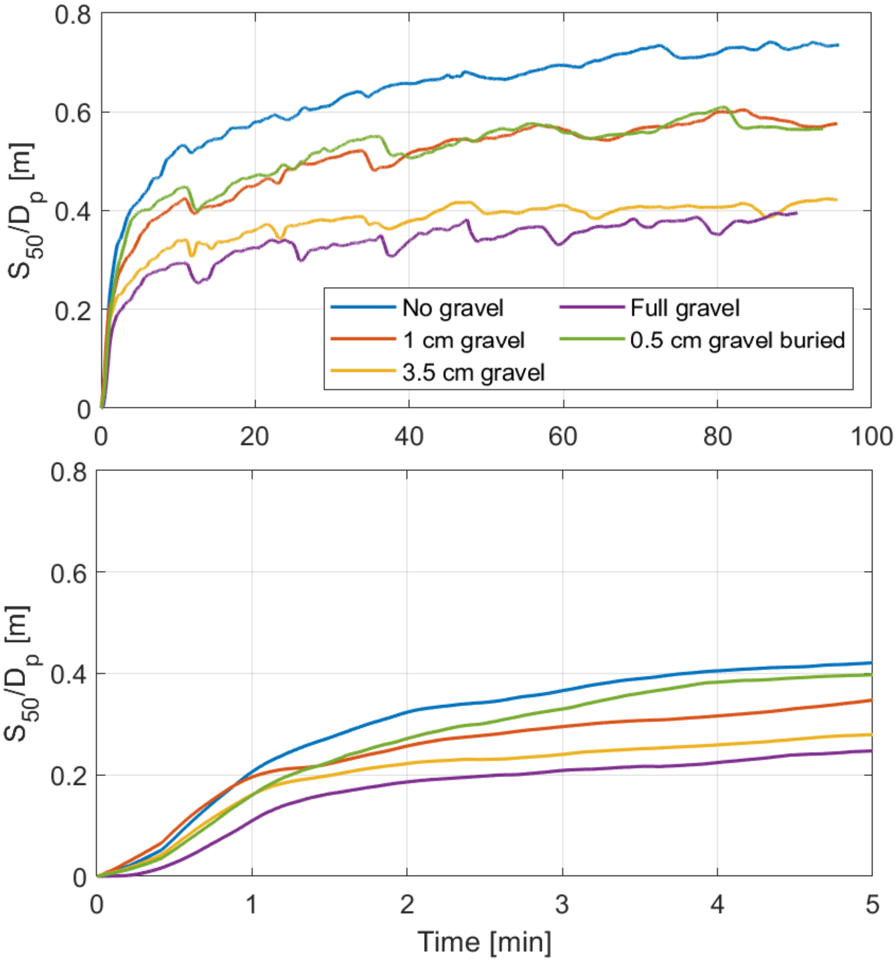


Figure 2. Scour hole development for each test case.

In general, the scour hole depth appears to become smaller if the more erodible (i.e., sand) material is covered by a thicker layer of less erodible material (i.e., gravel). Based on the videos (i.e., Figure 1), it is hypothesized that the presence of gravel reduces the scour depth by influencing the pick-up capacity of the horseshoe vortex. By moving the gravel upslope, less energy is available to pick up the sand from the scour hole, thus reducing the final scour depth.

For larger amounts of available gravel, the behavior converges to that of a gravel-only case. The smallest scour depth is found in case the soil is fully composed of gravel. The figure demonstrates that for the tests with a 0.5 cm gravel layer buried in the sand and for soil covered by 1.0 cm thick gravel layer at the surface, scour development is very similar. It is not completely certain if a surface layer of 0.5 cm gravel would lead to a larger scour depth than a surface layer of 1.0 cm gravel. However, based on the observed trends this is likely, thus indicating that the vertical position of the less erodible material also impacts the final scour depth in case of non-homogeneous soils. The findings suggest that when predicting scour in layered soils, the prediction is more complex than simply adding the possible scour depths for each separate layer.

The lower panel of Figure 2 shows the first 5 minutes of the scouring process. The case where the soil profile consists of only gravel shows the slowest development. The cases where either only sand or a sand-gravel mixture is present (with various gravel layer thicknesses) show a faster initial development. The gravel-only case does show significant slower initial development. It would have been expected that the initial development of the gravel covered sand is similar to that of the gravel-only case. These differences in the first minute of scour development could also be related to small differences in initiation of the flow in the basin, showing that the seabed response is sensitive to how the conditions are initialized. Hence, for a qualitative comparison the scour depth development from 1 minute onward is considered.

The scour development from minute 1 to minute 5 between the gravel-only and the 3.5 cm gravel coverage cases is practically the same. The scour depth for those cases up until 5 minutes stays below 3.5 cm, thus indeed demonstrating similar behavior. The red line shows a development that better resembles the case with no gravel, although differences are still clearly present. This is further illustrated by the gradient in scour depth (Figure 3), demonstrating that for a scour depth larger than 1 cm the soil covered by 1 cm of gravel becomes a sand-gravel mixture. This mixture shows different erosion rates than the gravel-only and sand-only cases. The case where a thin layer of gravel is buried below the sand shows similar behavior as the sand-only case up until 1.5-2 minutes. After this time, the gravel becomes exposed, thus influencing the scouring process, if only temporarily, after which the sediment behaves as a sand-gravel mixture.

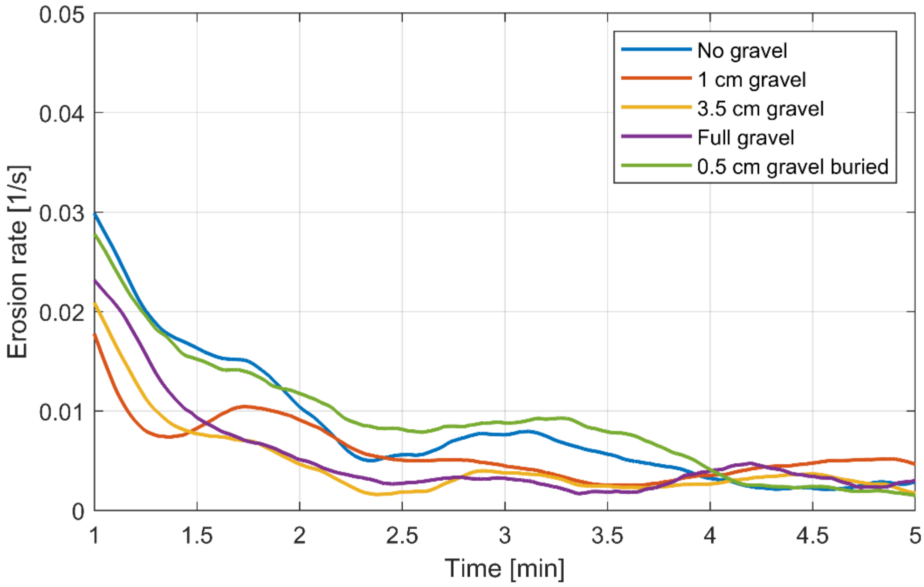


Figure 3. Time derivative of the scour depth presented in Figure 2.

Scour hole geometry

Figure 4 illustrates the temporal evolution of the scour hole in radial direction from the monopile for the test without gravel (left figure) and with fine sediment covered by 3.5 cm gravel (right figure). It shows the alternating current direction in distinct bands with increasing scour depths over time. Most striking is the increased non-uniformity of the layered soil that tends to become greater during a tidal cycle, reduces again after flow reversal and then increases again. How this looks like at the end of such a tidal cycle can also be observed in the photographs of both scour holes presented in Figure 5. These photos show the layout of the scour hole after the latest tidal flow test, with the sand-only geometry on the left and the gravel-sand geometry on the right. Looking at the cylinder, it can be clearly observed that for the sand-only configuration the depth-difference between the up- and downstream side of the pile is smaller than for the sand-gravel case. Although difficult to spot, it also appears that the side slopes of the sand-gravel scour hole are steeper than for the sand-only scour hole.

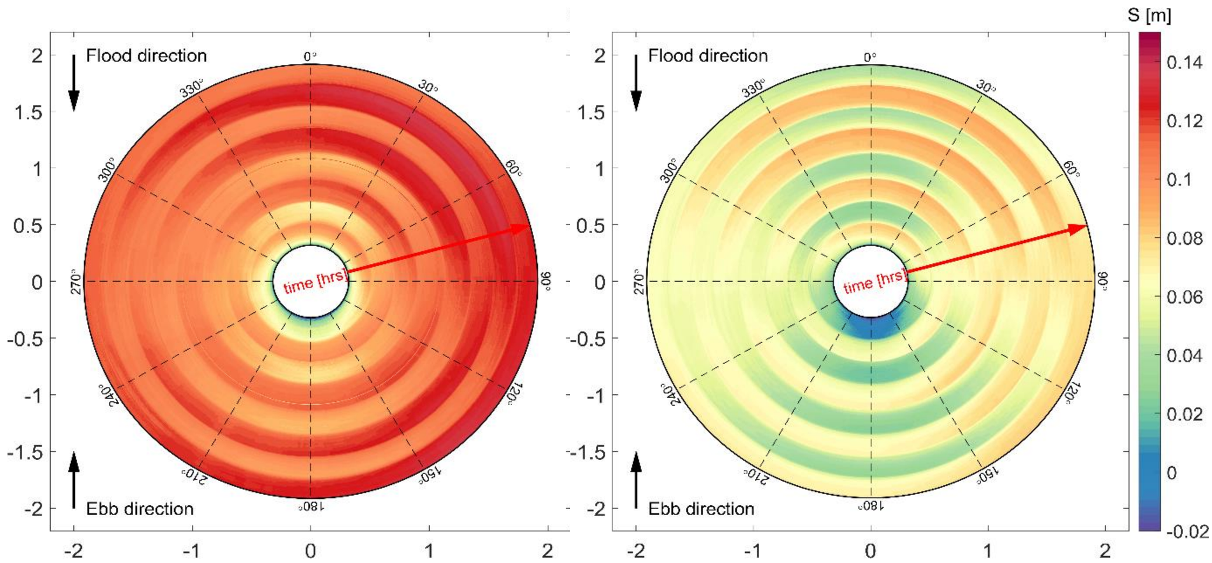


Figure 4. Scour development in radial direction from the monopile for homogeneous sandy soil (pile 1, left panel) and fine sediment covered by 3.5 cm gravel (pile 2, right panel). The distinct bands show the alternating flood-ebb tidal flow.

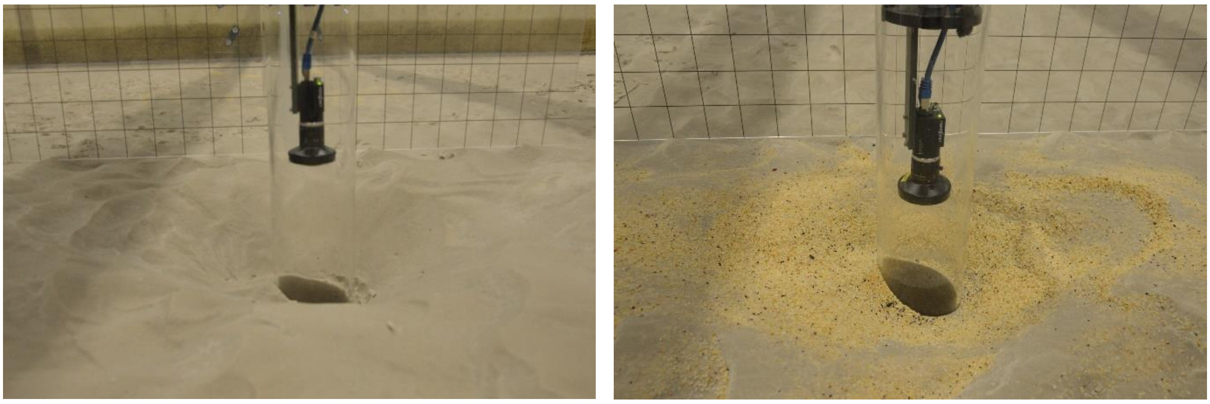


Figure 5. Photo of the final scour hole geometry for a soil with only fine sediment (left) and for the test with a 3.5 cm layer of gravel (right).

The spatial non-uniformity of the scour hole depth around the monopile for various soil conditions is further demonstrated in Figure 6, in which for each time step (dt = 1 s) the S_{90}/S_{10} ratio is shown for a gravel layer thickness of 1 cm and 3.5 cm, compared to the sand-only case (upper panel) and to the gravel-only case (lower panel). The closer this ratio is to 1, the more uniform the scour depth is around the pile, whereas for low values the non-uniformity is larger. Results from the layout with a buried gravel layer of 0.5 cm thickness were very similar to the case with a 1 cm gravel layer and are therefore not presented. Figure 6 shows that for a sand-only case, the ratio between S_{90} and S_{10} is roughly 0.8, whereas for the 1 cm gravel coverage case this value reduces to 0.4-0.5 and to 0.3-0.4 for a gravel coverage of 3.5 cm. In comparison, for gravel-only this number converges to roughly 0.4. Thus, for a coverage of 3.5 cm the non-uniformity of the scour hole shows comparable behavior to that of the gravel-only case. Another interesting observation to point out is that the non-uniformity for ebb flows is typically smaller (i.e., value of S_{90}/S_{10} is larger) than for flood flows. For the 1 cm gravel coverage case, this non-uniformity is even similar to that of the sand-only case. These results therefore show the importance of temporal effects and directionality of the flow for the scour hole geometry around the foundation.

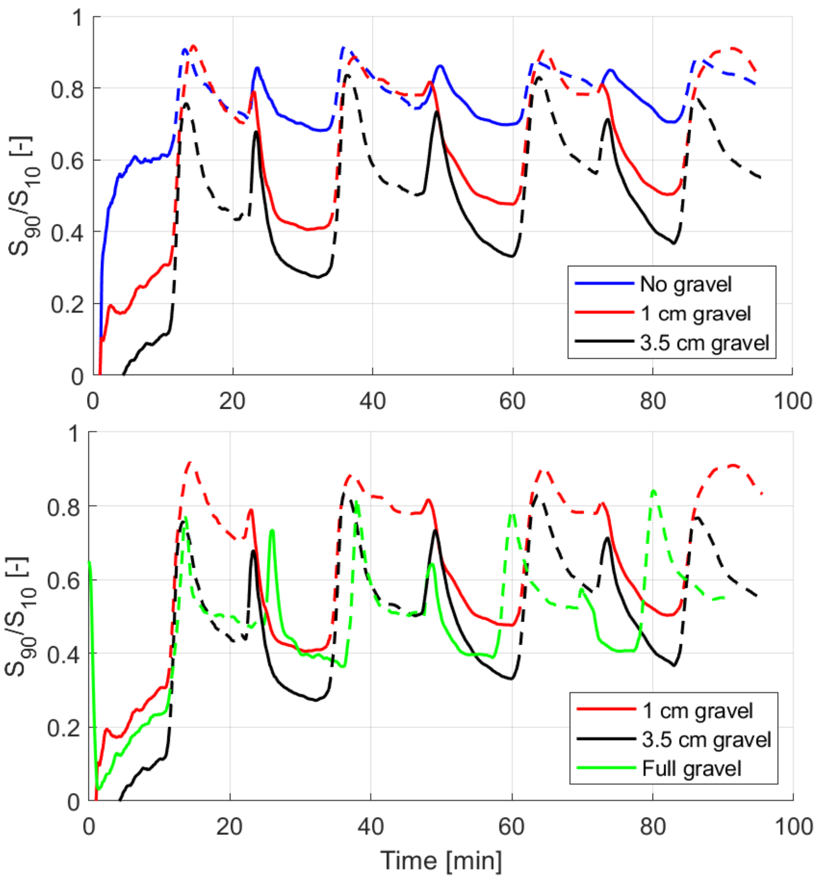


Figure 6. Ratio of the 90% over the 10% exceedance scour value for increasing gravel layer thickness. Solid lines indicate flood conditions whereas dashed lines represent ebb flow.

CONCLUSIONS

Physical model tests were carried out to investigate the effect of a gravel layer of varying thickness covering fine sediment on the shape of a scour hole formed under tidal conditions around a monopile foundation.

A total of six different stages of scour were identified for soils configurations where fine sediments are covered by a layer of gravel, eventually leading to continuous up and down motions of the gravel layer at the slope of the scour hole caused by the presence of a horseshoe vortex around the pile. When the gravel is transported upslope, the underlying sand becomes exposed and is further eroded. It was shown that the scour depth is limited in case a gravel layer in the soil is present, with a maximum constraint for sediments fully composed of gravelly soil. The results presented in this paper also indicated that compared to vertically homogeneous soils, erosion rates for sand-gravel mixtures are different and more difficult to predict. This may ultimately lead to inaccurate scour depth estimations. It was furthermore demonstrated that the non-uniformity of the scour hole increased for thicker layers of gravel covering fine sediment. This non-uniformity tends to be greater for flood conditions, thereby corroborating the importance of temporal effects and directionality of the flow for the scour hole geometry around monopile foundations embedded in layered soils. The results provide valuable insight into the relevant phenomena for scour in layered soils that can be used to improve predictions for these conditions.

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