Scaling and performance of a flexible mesh bag scour protection

Hendrik Jan Riezebos[1], Greta van Velzen[1], Niek Bruinsma[1], Niels G. Jacobsen[1], Saskia Waßmuth[2]

[1] Deltares, Department of Harbour, Coastal and Offshore engineering, P.O. Box 177, 2600 MH Delft, The Netherlands; e-mail of corresponding author: hendrikjan.riezebos@deltares.nl.
[2] wpd offshore solutions GmbH, Stephanitorsbollwerk 3, Bremen, 28217, Germany.

ABSTRACT

Several potential sites for new offshore wind farms have significantly higher wave loading than typically found in the North Sea, the cradle of offshore wind. The larger wave loading results in new challenges, one of which is the scour protection design for the turbine foundations. For the development of the Yunlin Offshore Wind Farm (OWF) in Taiwan the high wave loading resulted in dismissing a conventional loose rock scour protection as a suitable option. Instead, a scour protection concept using mesh bags filled with rock was designed and tested. This paper discusses the scaling, testing and observed failure modes of a mesh bag scour protection solution around a monopile foundation, under severe hydraulic loading.

INTRODUCTION

The site has an erodible seabed and the tidal velocities are relatively high, scour is therefore expected to develop around the monopile foundations. Predictions using the formulations and the scour prediction model by Raaijmakers et al. (2008, 2014) show equilibrium scour depths of one to almost two times the pile diameter. A scour protection is therefore required at these locations.

Scour protection design for Yunlin OWF is challenging due to the high wave loading. A further complicating factor is the morphological change that will occur over the lifetime of the wind farm: seabed level changes of more than 10 m are predicted at some of the foundations. Scour protections experiencing such extreme bed level drops will have an increased hydraulic load, as they are protruding from the surrounding seabed and will be located relatively high in the water column (see for example Riezebos et al. 2016). Based on a first investigation it was deemed infeasible to create a scour protection with loose rock only.

It was decided to design the armour layer of the scour protection with mesh bags: fibrous netting filled with a wide-graded loose rock filling material of small diameter. Such mesh bags typically have a weight of several metric tonnes, an average height up to one metre and a diameter in the order of one to three metres. This paper aims to provide a generic overview of important scaling considerations and failure modes of these armour units.

SCALING METHODOLOGY

It is important to consider various failure modes that need to be realistically represented on a smaller scale, when scaling mesh bag armour units. These failure modes link to the criteria for every scour protection: external stability, flexibility, internal stability and integrity/durability. The identified failure modes of the mesh bags for each criterion (and the associated characteristic parameters) are summarized below:

1. **External stability:** failure due to movement of the entire mesh bag. With characteristic parameters: Underwater weight, dimensions, permeability.
2. **Flexibility:** failure due to gradual rotation or sinking of the element following residual displacement of filling material or undermining by edge scour holes. With characteristic parameters: Dimensions of filling material, filling ratio of the bag, flexibility of the mesh bag material.
3. **Internal stability criterion:** loss of underlying sediment through the element, leading to gradual lowering of the armour layer. With characteristic parameters: Dimensions of filling material relative to the dimensions of the underlying sediment, total layer thickness of the mesh bag armour, placement arrangement.
4. **Integrity/durability criterion:** Loss of filling material due to too large mesh size and/or rupture of the bag; with characteristic parameters: mesh dimensions relative to filling material, mesh bag material properties.

The third and fourth failure modes are outside the scope of the present paper: internal stability was ensured by applying a filter layer underneath the mesh bag armour layer and the integrity/durability of the elements should be ensured by selecting a proper filling material (relative to the mesh size) and a high quality product. Looking at the first two criteria, we zoom in from macro dimensions (foundation size, mesh bag arrangement) to intermediate dimensions (individual mesh bag size) to micro dimensions (filling material particle size, mesh size).

A generic example case is used throughout this paper for quantification of the approach: A 6T (T: metric tonne) mesh bag filled with rock (D_{n50} = 0.1 m, n = 0.4) is installed around a 9 m monopile foundation and it needs to be scaled down with a factor of 30 to allow for model testing at a reasonable scale. The assumed hydraulic conditions are a significant wave height, H_{m0} = 12 m, with an associated peak wave period, T_p = 15 s in a water depth of h = 30 m. Assumed densities are: rock 2650 kg/m^3, seawater 1030 kg/m^3, and freshwater (used in lab) 1000 kg/m^3.

Scaling of macro dimensions

For scour protection systems the scaling is preferably done according to Froude's law. This means that dynamic (gravitational and inertial) forces are kept similar at field and at model scale. This leads to linear scaling of all spatial dimensions (e.g. the 9 m monopile becomes 9/30 = 0.3 m at model scale). As a result, the viscous forces are not equally scaled down, which means that the Reynolds number will not be the same between field and model scale when model geometry and hydrodynamics are scaled according to the Froude scaling law.

A common approach is therefore to scale the hydrodynamics according to Froude, but to check that the flow stays in the same Reynolds regime. When the scaled flow remains sufficiently turbulent, phenomena such as vortex shedding and dimensions of eddies are represented correctly. In the present example case, the Reynolds numbers are O(10^7) at field scale and become two orders of magnitude smaller when Froude scaled. This is deemed sufficient to limit any viscous effects (Whitehouse, 1998 and Sumer&Fredsøe, 2006). Therefore, the dimensions of the scaled foundation and thickness and diameter of the scour protection system can be determined directly by linear scaling, i.e. 1:30.

Scaling of individual mesh bags

A rock-filled mesh bag can be displaced due to inertia, drag, and lift forces. This means that dimensions of the element and the bulk density of it should be correctly scaled. For the scaling of the dimensions and underwater weight of the elements (related to the external stability of the elements) mobility scaling is applied (see for example Riezebos et al., 2016, Raaijmakers et al., 2010 and Den Boon et al., 2004). Hereby, the density difference of water between the prototype and the model is accounted for, as well as the effect of the wave friction and the position of a particle (mesh bag) on the Shields curve. Please note that choosing this approach means that each mesh bag filled with loose rock is now represented as an individual element (i.e. sphere) with a similar volume. In other words, it is assumed that the forces on each element are similar to the forces acting on a rock. Evaluation of the mobility number requires the wave friction factor, which is determined with the method by Dixen (2008).

The effect of mobility scaling compared to Froude scaling is illustrated with the example case. First, the 6T mesh bag filled with rock (ρ=2650 kg/m^3, n=0.4) is represented as a single sphere with a bulk density of 1590 kg/m^3, a diameter 1.93 m and a relative mobility of 0.272. The Froude scaled mesh bag would have a diameter of 64.3 mm (n_{scale} = 30) and weight of 222 g. The mobility number for this scaled mesh bag is MOB = 0.259, which is 5% lower than the field scale value and hence not conservative for testing. When applying mobility scaling, a correction of 5% to the schematized diameter is found. Since the diameter (or radius) is to the third power in the volume calculation, the mobility scaled weight is almost 15% smaller than the Froude scaled weight. The mobility scaled mesh bags therefore weigh 190 g with a corresponding mobility number of 0.272; which is equal to the theoretical mobility at field scale. For the outer dimensions of the mesh bags, it is proposed to use the 5% correction as well. If these were kept at Froude scaling, the internal dimensions would be off. i.e. either the filling ratio of the bag would be too low, or the filling material should have lower density, see next section.

Scaling of filling material and mesh size

The scaling of the loose rock filling material inside the mesh bags should reflect the various types of expected failure mechanisms. This means that the individual rocks should behave realistically to correctly represent internal movement and subsequent deformation of the elements and that the bulk of the filling material should have realistic properties as well (i.e. total weight, filling ratio, porosity and permeability).

Most of the criteria can be satisfied by using mobility scaled loose rock with similar underwater density and porosity as in the field. However, this can contradict with correct scaling of the permeability of the elements. The effect of permeability scaling was investigated (see next section), but it was found to result in unacceptable deviations from the mobility scaled dimensions. Mobility scaling was therefore applied for the filling material as well.

Mobility scaling of the filling ratio leads to slightly larger particles than when Froude scaled. This means that the size of the openings in the net is no longer a driving factor for the correct scaling of a mesh bag element. Pragmatically, it is proposed to use as flexible material for the mesh as possible and a mesh size that is proportional to the mobility-scaled particle size. Care should be taken not to use a too stiff or rigid material, because the reshaping of an element due to undermining and/or displacement of filling material might then be incorrectly modelled. Furthermore, the mesh material itself should correctly represent the volume and weight of the material at field scale, to achieve similar buoyancy of it.

Prioritizing mobility scaling over permeability scaling

The mesh bags' core function is to displace the water away from the underlying filter layer. The displacement of the water over the elements results in lift and drag forces. The drag and lift forces are assumed correctly scaled, if the influence of the scaled mesh bag on the water is correctly represented and the arrangement of the elements represents the field arrangement. This effectively means that the filter velocity within each element should scale according to Froude scaling.

The flow resistance in permeable media under time varying conditions is given by the linearized Navier-Stokes equations (e.g. Jensen et al., 2014), which, combined with the parameterization of a and b in Van Gent (1995) requires an estimate of the material coefficients α and β. Regularly encountered values for α are in the range 200 – 1000 (Losada et al. 2016). Typical combination of α and β are $\{\alpha;\beta\}=\{1000;1.1\}$ (Van Gent, 1995) and $\{\alpha;\beta\}=\{500,2.0\}$ (Jensen et al., 2014). Both are used in the present assessment, as well as a third set which combines the lower bound for α from Losada et al. with the proposed value for β from Jensen et al.: $\{\alpha;\beta\}=\{200,2.0\}$.

By calculating the pressure gradient from the presence of waves at both model and field scale (approximated by linear wave theory at the seabed using the spectral wave height H_{m0} and the peak wave period T_p) and varying the $D_{n50;model}$ to achieve equal filter velocities, the required particle size at model scale can be obtained. The obtained values for $D_{n50,model}$ are given in Table 1 for the three sets of α and β. The values are provided for the fictitious example case where D_{n50} = 0.1 m. It is seen that the obtained scaled rock sizes are significantly larger compared to both Froude and mobility scaled rocks. Even the most optimistic combination of parameters still yields an apparent scale factor of $D_{n50,field} / D_{n50,model}$ = 15.8. The table furthermore shows mobility-scaled $D_{n50;model}$ calculated with Soulsby (1997) and Dixen (2008).

Because of the large rock sizes following from permeability scaling, mobility scaling of the filling material is prioritized over permeability scaling. In that way the scaled units will be a better representation of the elements at field scale. Not only will the filling material be scaled more realistically in this case and show more realistic internal deformation of the filling material, the mobility scaled $D_{n50,model}$ is also smaller than when permeability scaled. A smaller particle size of the filling material reduces the permeability of the elements, so the forces on the mobility scaled bulk element are expected to be conservative for establishing the stability limits in a laboratory.

Table 1: Filling material particle size, for various scaling cases.

Case	α = 1000 β = 1.1	α = 500 β = 2.0	α = 200 β = 2.0	Mobility (Soulsby, 1997)	Mobility (Dixen, 2008)	Froude (no correction)
$D_{n50,model}$	12.8 mm	7.0 mm	6.3 mm	4.1 mm	4.5 mm	3.3 mm
$\frac{D_{n50,field}}{D_{n50,model}}$	7.8	14.3	15.8	24.5	22.4	30

OVERVIEW OF PHYSICAL MODEL TESTS

The mesh bag scour protection solution around a monopile foundation was investigated in a physical model test programme. This section provides an overview of the test facility, set-up and instrumentation, considered mesh bag arrangements and the test programme.

Test Facility

The tests were performed in Deltares' Atlantic Basin. This basin has a length of 75 m and a width of 8.7 m. The basin's paddle type wave generator can generate any wave spectrum with a significant wave height up to 0.25 m in water depths up to 1 m. The current in the Atlantic Basin can be generated in two directions (either following the waves or in the opposing direction).

Set-up and instrumentation

Three monopile scale models were placed side by side in the test section. This allowed for simultaneous testing of multiple layouts under identical conditions. The models consisted of a transparent Perspex cylindrical piles, equipped with internal, downward looking cameras with fish-eye lenses for a 360º view. This allowed for continuous observation of deformation and displacements of the elements all around the monopile, see e.g. Raaijmakers et al. (2008), De Sonneville (2010) and Aleksandrova et al. (2020). Each scale model was also instrumented with at least one external underwater camera. Furthermore, a stereophotography technique was used to more accurately observe and quantify the observed deformation and displacement of the elements. This technique is extensively discussed in Raaijmakers et al. (2012). A 3D measurement of the scour protection system and surrounding bathymetry was performed before and after each test to obtain detailed 3D images of any deformations. Hydrodynamics were measured with an array of electromagnetic current velocity sensors and wave gauges around the models.

Mesh bag arrangement

The scour protection consisted of mesh bags placed in a single-layered or double-layered grid arrangement around the monopile, see Figure 1 for a schematic representation. Note that the precise arrangement is typically case specific and dependent on the relative dimensions of the monopile and the mesh bags.

Next to the single- and double-layered arrangements, the influence of the size of the elements on the performance of the scour protection was tested by making similar arrangements with differently sized mesh bags. Additionally, the spacing between the elements in the grid was varied, since a more densely packed arrangement can improve the interlocking of mesh bags and the coverage of the underlying layer.

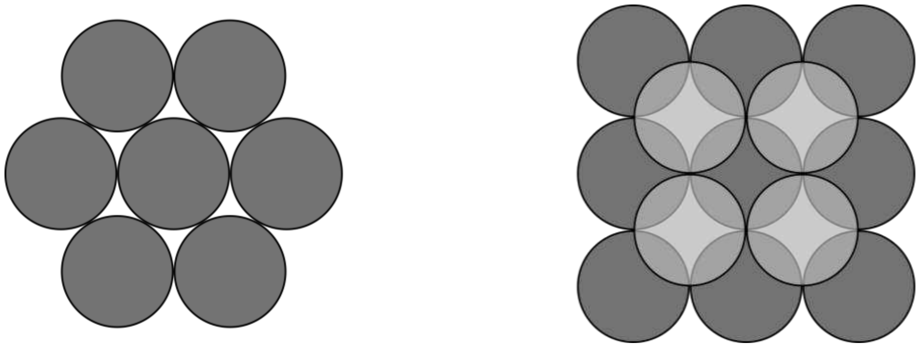

Figure 1: Schematic representation of mesh bag arrangement principles. (left) Single-layered arrangement and (right) double-layered staggered arrangement.

Test programme

A large number of mesh bag layouts was tested in physical model tests. The test conditions cannot be disclosed due to confidentiality, but the scour protection systems are tested with three consecutive combined current and wave conditions, corresponding with increasingly severe storm conditions. Each test had a duration of more than 2000 waves. The results in the next section are given as qualitative description of the observed failure modes.

ANALYSIS OF OBSERVED FAILURE MECHANISMS

The observed four failure mechanisms are described in this section: undermining of elements, reshaping of elements, rolling over of elements and instantaneous displacement of elements (from grid). They are linked to the flexibility and external stability criteria discussed in the scaling methodology. Note that the use of "failure mechanism" relates to individual mesh bags and not to failure of the entire scour protection system.

Undermining of elements

The physical model tests showed that the mesh bags at the perimeter of the layout can be undermined by edge scour holes. Figure 2 (left) shows an example of an undermined mesh bag, here the mesh bag is settled slightly into the edge scour hole. With more severe edge scour, the elements can move completely out of the grid, thereby losing their interlocking with the surrounding elements. In Figure 2 (left) it can be observed that the side of the mesh bag facing the camera is much more exposed to the flow. This decreases the stability of the mesh bag to such an extent that some mesh bags at the edge are seen to be picked up and flipped over by the waves. It is hypothesised that increasing the overall flexibility of the mesh bags (so they can better follow edge effects), may increase their stability.

Reshaping of elements

Deformation of the filling material inside the mesh bags is observed during the physical model tests. The deformation results in gradual reshaping of individual elements. Figure 2 (right) shows an example of such a reshaped mesh bag, here it can be seen that filling material is displaced inside the mesh bag from right to left. Reshaping of an element reduces the stability of the element and it can also increase exposure of the neighbouring elements: individual mesh bags are more exposed to the flow and interlocking between mesh bags is reduced. Reshaping of the element can occur when for the filling material can move inside the mesh bag. Internal movement requires that the filling material is sufficiently mobile and that there is room inside the bag (i.e. low filling ratio). It is hypothesised that stiffer elements, larger filling material and/or more densely packed grid placement reduce deformation and reshaping of elements. This also shows that the choice of mobility scaling over permeability scaling of the filling material is important in order to capture this failure mechanism.

Figure 2: (left) Undermining of a mesh bag due to gradual removal of the base layer. (right) Reshaping of a single mesh bag by deformation of the filling material.

Rolling over of elements

Individual mesh bag elements are observed to gradually roll over. Figure 3 (left) shows an example of a mesh bag that is rolled over. The rolling over of the element in the figure is caused by gradual displacement of the filter material in the mesh bag (see also Figure 2, right). This reshaping of the mesh bag de-stabilises the element to such an extent that it eventually rolls over. Rolling over of elements can also occur in case of undermining due to edge scour, which might create a steep slope along which the mesh bag rolls. Once a single mesh bag has rolled over, the exposure of the surrounding elements is increased, and they will typically show deformation as well. The displaced element can be observed rocking back-and-forth on top of the scour protection, gradually moving downstream. It is hypothesised that rounder and more flexible elements are more susceptible to rolling over, while wider and flatter elements are more resilient to it.

Instantaneous displacement of element (from grid)

The mesh bags are also observed to be abruptly removed from the placement grid (i.e. in a single wave). This happens in the most extreme wave conditions. Figure 3 (right) shows such an instantaneously removed mesh bag from the grid. Once the element has been displaced the surrounding elements are exposed, and typically additional deformation follows (either rolling or instantaneous displacement). This failure mechanism is most influenced by the bags' permeability, which was conservatively scaled. Besides the obvious solution of using larger bags, it is hypothesised that a higher permeability would reduce the occurrence of this type of failure.

Figure 3: (left) Rolling over of a single mesh bag due to gradual residual displacement of filling material. (right) Instantaneous removal of a mesh bag element from the grid in a single layered arrangement.

DISCUSSION OF TEST RESULTS

This section discusses the effect of different design choices on the performance of a mesh bag scour protection.

Size of elements

As expected, heavier elements have a higher external stability and show significantly less instantaneous removal during extreme storm events. The larger elements also appear less prone to rolling over, as they are flatter than the more spherical smaller elements. On the other hand, the larger elements were observed to be more prone to internal deformation (movement of filling material). It is hypothesised that somehow limiting the capacity for internal deformation would further increase the overall performance.

Single- and double layered arrangement

Applying a single layer of mesh bags as armour significantly reduces the total number of elements required, though it also reduces the performance of the scour protection layout. Displacement of elements in the single-layered layout typically occurred close to the pile, where the grid had a 'weak spot': a relatively large opening in the grid resulting in exposed sides of the adjacent elements (see also Figure 2, right). By adjusting the arrangement, it is likely that performance of the single-layer arrangement can be increased. It is hypothesised that a double-layered arrangement has more ‘vertical interlocking’: the top layer is placed in the gaps of the lower layer (see also Figure 1, right) adding significant resistance against the hydraulic load.

Denser placement within grid arrangement

Tests performed with a denser placement (i.e. mesh bags more ‘squeezed together’) showed a slightly improved stability. However, the changed placement grid typically introduced new weak spots in the layout, and a less optimal vertical staggering of the double-layered arrangement. The overall performance of the scour protection layout was therefore not significantly increased. For double-layered arrangements, the vertical interlocking was observed to be as important as the horizontal interlocking.

CONCLUSIONS & DISCUSSION

The scaling methodology for mesh bag scour protections was illustrated by means of a fictitious example case and applied on real physical model experiments. Three scaling methods are considered: Froude scaling, mobility scaling and permeability scaling. Mobility scaling accounts for differences in density and friction of the elements, which was shown to lead to more realistic behaviour than Froude scaling. Permeability scaling leads to contradicting scaling requirements compared to Froude and/or mobility scaling and Froude or mobility scaling is conservative with respect to permeability. Permeability scaling is therefore dismissed when scaling mesh bag scour protections. It has been shown that for a moderate scale factor (e.g. 1:30) the field conditions can still be realistically scaled down.

Four main failure mechanisms, observed in the physical model tests, were described: Undermining, reshaping, rolling over and instantaneous removal of mesh bags. The absolute weight of the mesh bags was observed to be the most important parameter for the stability of individual elements. Second to this, the stability of the filling material (and space for reshaping thereof) turned out to be important: gradual displacement of filling material leads to more exposure of the mesh bags and ultimately rolling over of the elements. The placement arrangement (single-layer vs. double-layer) is an important parameter for overall scour protection stability as it affects both vertical and horizontal interlocking between the bags.

The stability of the mesh bag elements is not solely dependent on the macro dimensions of the bags. The filling ratio and size of the filling material are equally important. On smaller scales it becomes more difficult to achieve accurate scaling of all parameters. Moreover, the different scaling approaches (Froude, Reynolds, mobility, permeability) cannot all be fulfilled at scale and sometimes lead to contradicting requirements. It is therefore strongly recommended to perform experiments with complex elements such as mesh bags at as large a scale as possible, thereby minimizing scale effects.

REFERENCES

Aleksandrova, N., Riezebos, H.J., Emmanouil, A., Broekema, Y., Waßmuth, S. (2020). "Offshore scour development in non-homogeneous soil with a subsurface non-erodible layer." *International Conference on Scour and Erosion.* 2020 (in prep.).

De Sonneville, B., Daniel Rudolph, and T. C. Raaijmakers. (2010) "Scour reduction by collars around offshore monopiles." *Scour and Erosion*. 460-470.

Den Boon, J., Sutherland, J., Whitehouse, R., Soulsby, R., Stam, C., Verhoeven, K., Høgedal, M., and Hald, T. (2004). "Scour behaviour and scour protection for monopile foundations of offshore wind turbines". *Proceedings of the European Wind Energy Conference.*

Dixen, M., Hatipoglu, F., Sumer, B.M., Fredsøe, J. (2008) "Wave boundary layer over a stone-covered bed". *Coastal Engineering*, 55, 1-20.

Jensen, B. Jacobsen, N.G. and Christensen, E.D. (2014). "Investigations on the porous media equations and resistance coefficients for coastal structures". *Coastal Engineering,* 84, 56-72.

Losada, I.J., Lara, J.L. and Del Jesus, M. (2016). "Modeling the interaction of water waves with porous coastal structures". *Journal of Waterway, Port, Coastal and Ocean Engineering,* 142(6), 1-18.

Raaijmakers, T., and Rudolph, D. (2008). "Time-dependent scour development under combined current and waves conditions-laboratory experiments with online monitoring technique." *Proc. 4th International Conference on Scour and Erosion*, Tokyo, 152-161.

Raaijmakers, T., Van Oeveren, M., Rudolph, D., Leenders, V., and Sinjou, W. (2010). "Field performance of scour protection around offshore monopiles." *Proc. 5th International Conference on Scour and Erosion*, ASCE, 428-339.

Raaijmakers, T., Liefhebber, F., Hofland, B., & Meys, P. (2012). "Mapping of 3D-bathymetries and structures using stereophotography through an air-water-interface." *Coastlab*, *12*, 17-20.

Riezebos, H.J., Raaijmakers, T.C., Tönnies-Lohmann, A., Waßmuth, S., and Van Steijn, P.W. (2016). "Scour protection design in highly morphodynamic environments". *Proc. 8th International Conference on Scour and Erosion*, 301-311.

Rudolph, D., Raaijmakers, T. C., and Stam, C. J. M. (2008). "Time dependent scour development under combined current and wave conditions – hindcast of field measurements." *Proc. 5th International Conference on Scour and Erosion,* ASCE, 428-339.

Sumer, B.M. and Fredsøe, J. (2006). "Hydrodynamics Around Cylindrical Structures". Advanced Series on Ocean Engineering - Volume 25, World Scientific, New Jersey, second/revised edition.

Soulsby, R. (1997). "Dynamics of marine sands: a manual for practical applications". *Thomas Telford.*

Van Gent, M.R.A. (1995). "Porous flow through rubble mound material". *Journal of Waterway, Port, Coastal and Ocean Engineering* – ASCE, 121(3), 176-181.

Whitehouse, R.J.S. (1998). "Scour at marine structures." London: Thomas Telford Limited.