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## MEMO

Stability and scour analysis, new design Arc Marine structures

## BACKGROUND

The natural development of areas rich in biodiversity within the North Sea is a lengthy process. The aim of the Rich North Sea program (Dutch: De Rijke Noordzee) is to enhance nature within offshore windfarms by stimulating biodiversity enhancement measures. One of these measures is to place a number of artificial reef structures on the seabed within the offshore wind farms (OWF's) vicinity.

One of the first locations where these reefs are placed is in the North Sea Innovation Lab (also named NSIL and Offshore Innovation Lab), off the coast of Scheveningen. Additionally, it is researched if these reefs can also be placed in the Borssele OWF, off the coast of Zeeland, next to the Beta substation of TenneT.

In a previous study, (WaterProof, 2020), WaterProof has looked into the stability of the proposed structures, designed by Arc Marine at these two locations. To this end, first the extreme MetOcean boundary conditions (waves, flow) were identified. Next, the expected scour in the vicinity of the structures was calculated considering the local morphological circumstances (soil composition, bedforms, depth, etc.). Finally, using both flow flume experiments and analytical calculations the stability of the structures was determined, both for the failure mechanism turning over as well as sliding. The result of the study was that (1) scour protection should be applied, to prevent the structures from sinking into the bed and (2) additional measures needed to be taken to prevent the structures against turning over / sliding, as for both locations the stability of the structures was not sufficient to be able to withstand a 1/100 year storm.

Based on these findings, Arc Marine has updated the design, in order to meet the stability requirements. As the form of the structures changed significantly, so do the total forces on the structures themselves. Therefore, the Rich North Sea has asked WaterProof to perform another analysis into the stability of this new design, for both locations. Additionally, WaterProof is asked to re-evaluate the scour that can occur and what degree of scour protection is needed in the case that the structures are placed at the Borssele OWF location.

The approach of this study is similar to the previous study (WaterProof, 2020<sup>1</sup>);

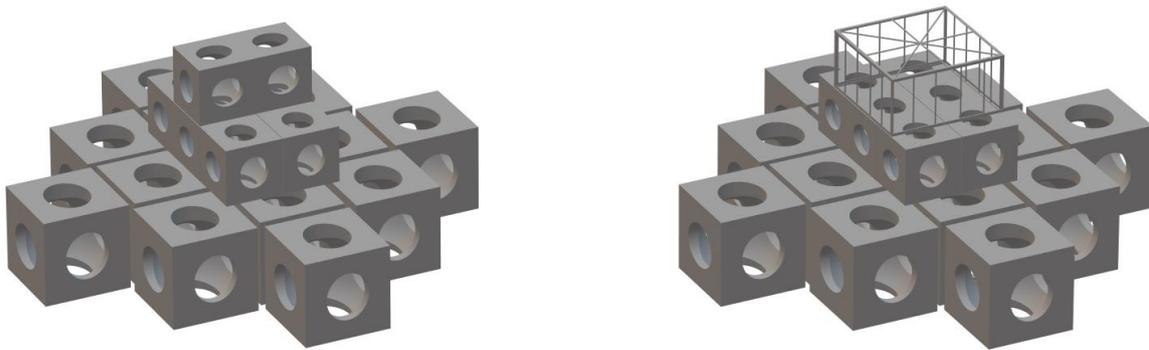
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<sup>1</sup> WP2020\_1218\_R1r1, Artificial reef structures North Sea, Structure stability analyses in Borssele OWF and NSIL

- The expected scour in the vicinity is studied, as well as the required amount of scour protection, with the use of the previously determined boundary conditions;
- The stability of the structures is studied, using both flow flume experiments (to determine the drag of the new design) and analytical calculations using the previously determined boundary conditions.

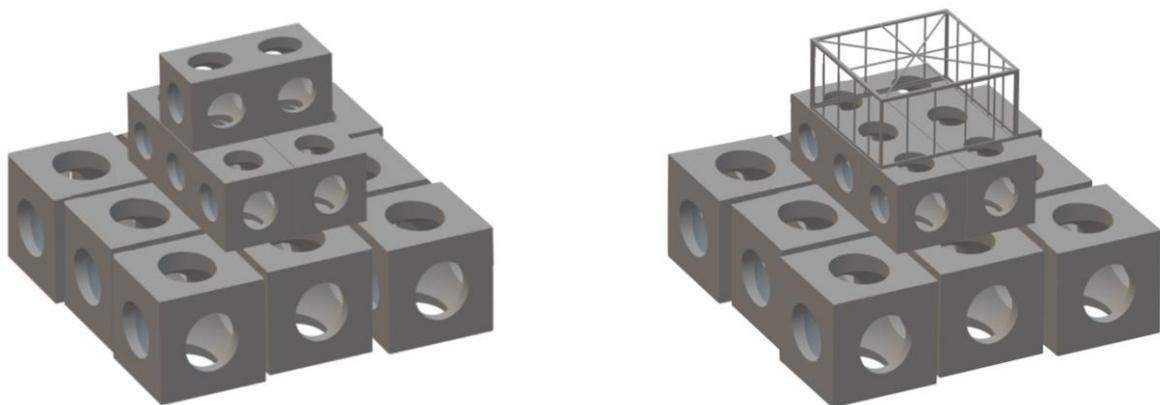
## UPDATED DESIGN ARC MARINE

The new designs for Option A and B have been provided by Arc Marine and are shown in Figure 1. The structures are formed of individual concrete blocks with dimensions of approx. 0.75 x 0.75 m for the bottom layer (roughly 540 kg per block) and with dimensions of approx. 0.5 x 0.5 m for the top layer(s) (roughly 160 kg per block (COAST, 2019)). These structures are made of a special (more porous) concrete to enhance marine growth on the structures. The structures are formed of 3 (Type A) or 2 (Type B) vertical layers of blocks. The blocks are hollow and the top layers are filled with smaller 0.15 m cubes.



*Figure 1: New designs made by Arc Marine. Left panel: Type A structure. Right panel: Type B structure.*

The outer 4 cubes in this new design have been added for stability robustness against tipping over. This addition however, brings some logistical challenges for the transport and installation of the structures. Therefore, The Rich Northsea has asked to perform the assessment without these outer cubes. This adaptation of the design is shown in Figure 2 for both structure options.



*Figure 2: Left panel: Type A structure, without outer 4 blocks. Right panel: Type B structure, without outer 4 blocks. Adapted from Arc Marine design as depicted in Figure 1.*

## SCOUR PROTECTION

The scour depth of new designs is re-evaluated in this section, using the same methodology as the previous study (WaterProof, 2020).

### Scour depth predictions

The tool SCOUR has been used to predict the maximum scour depth near the structures in the situation without scour protection during extreme current-wave conditions, at the Borssele OWF location.

This tool uses the boundary conditions as determined in the previous study (WaterProof, 2020) and the dimensions of the new design. Similarly to before, the scour analysis is performed for structure type A, as this structure is the most conservative in terms of potential scour depth.

For the calculations, the following is assumed:

- width of the structure perpendicular to the current direction= 2.25 m;
- height of the structure (including foundation) = 1.75 m;
- a streamline factor of 1.2;
- a safety factor of 1.2.

The results are shown in Table 1 for the Borssele OWF location.

*Table 1: Predicted scour depths; Borssele OWF, for the old and new design for structure type A.*

Return period [years]	Water depth [m]	High and Low Water to MSL [m]		Depth-averaged current velocity flood to NE and ebb to SW [m/s]		Significant wave height [m] and wave period [s]	Sediment size $d_{50}$ ; $d_{90}$ [mm]	Maximum scour depth [m]	
								Old design	New design
1	31	2.4	-1.8	1.1	1.08	5.22; 8.8	0.4; 1	1.40	1.15
5	31	2.7	-1.95	1.19	1.12	6.15; 9.5	0.4; 1	1.50	1.25
10	31	2.8	-2.05	1.22	1.14	6.57; 9.7	0.4; 1	1.55	1.30
50	31	3.1	-2.2	1.30	1.17	7.50; 10.5	0.4; 1	1.60	1.40
100	31	3.2	-2.25	1.33	1.19	7.87; 10.7	0.4; 1	1.65	1.45

From this tables it can be said that:

- The old design for structure type A had a maximum scour depth in the range of 1.4 to 1.65 m (current-dominated scour)
- The new design for structure type A had a maximum scour depth in the range of 1.15 to 1.45 m (current-dominated scour)

The maximum scour extent is expected to be similar for both the old and new design (5 to 10 m from axis of structure).

The maximum scour depth of the new design for structure type A is less than that of the old design, as it has a smaller structure height to width ratio. That being said, the structure will still be undermined along the flanks and gradually sink into the bed if no scour protection is used. It is expected that in practice the distance over which the structure will sink into the bed will be less than predicted by the empirical equation, as this equation is valid for a structure with a rectangular cross-section, whereas both designs have a more pyramid-type cross-section. Most likely, the new design will sink into the bed over a distance of about 0.75 m (thickness of base layer) when placed at the Borssele OWF location, if no scour protection is used.

### Bed protection around structures

To prevent the gradual burial of the structure into the bed, a scour protection around the structure is required.

Two basic types of scour protection structures can be distinguished:

- 1) loose stones/rocks; protection layer generally consists of geotextile placed on sea bed; filter layer of smaller stones with thickness of 2 times the mean stone size and upper armour layer of larger stones with thickness of 3 times the mean stone size (CIRIA, 2007). The thicknesses of the layers are generally chosen as such, to account for uncertainties in placement and due to deformation of the layers;
- 2) mattress of concrete blocks or rock-filled wire-cage (gabion); gabion type mattress generally consists of a lower mattress with geotextile in it and smaller stones and an upper mattress with larger stones; mattress thickness in range of 0.2 to 0.3 m.

The tool ARMOUR has been used in the previous study (WaterProof, 2020) to predict the rock/stone sizes for scour protection type 1 and associated damage level of the scour protection layer during extreme current-wave conditions. These sizes remain valid for the new design and are shown in Table 2.

Table 2: Required stone size and associated damage level; Location: Borssele OWF.

Return period [years]	Water depth [m]	Water to MSL [m]		Depth averaged current velocity [m/s]		Significant wave height [m] and wave period [s]	Safety factor = 1.2		Safety factor = 1	
		HWL	LWL	Flood (to NE)	Eb (to SW)		Required Stone size armour layer [m]	$s_d$ for 1 storm [-]	Required Stone size armour layer [m]	$s_d$ for 1 storm [-]
1	31	2.4	-1.8	1.1	1.08	5.22; 8.8	0.04	0.6	0.025	0.6
5	31	2.7	-1.95	1.19	1.12	6.15; 9.5	0.055	0.5	0.044	0.5
10	31	2.8	-2.05	1.22	1.14	6.57; 9.7	0.065	0.5	0.053	0.5
50	31	3.1	-2.2	1.30	1.17	7.50; 10.5	0.10	0.4	0.083	0.4
100	31	3.2	-2.25	1.33	1.19	7.87; 10.7	0.12	0.3	0.095	0.3

The required stone size is then used to determine what grading of material has to be used for the protection layer. Hereby, the required rock size should fall in the range of the chosen class, preferably as close as possible to the median size of that grading class. An overview of common rock grading classes is shown in Table 3.

*Table 3: Rock gradings (ND=normal density; HD=high density); rock sizes differ slightly for each quarry.*

Rock grading	Median size [mm]	Density [kg/m <sup>3</sup> ]	Type of layer
60-300 kg ND	470 (350-600)	2650	armour layer
40-200 kg ND	400 (300-520)	2650	armour layer
10-200 kg ND	350 (190-520)	2650	armour layer
10-60 kg ND	260 (190-350)	2650	armour layer
3-9 inch ND	125 (75-230)	2650	filter layer or single layer
3-9 inch HD	125 (75-230)	3000	filter layer or single layer
2-8 inch ND	100 (50-200)	2650	filter layer
2-8 inch HD	100 (50-200)	3050	filter layer

Based on these results, the protection layer can be determined. The design of the protection layer is dependent on;

- Choice of storm return period, and therefore the required rock size;
- Safety factor and acceptable risk; a lower safety factor increase the chance of damage to occur, but allows for a reduced rock size and smaller diameter;
- Stability of the individual rocks; are the stones going to withstand the storm or are they going to roll away;
- 1 or 2 layer system; by applying a filter layer (of smaller diameter stones) underneath the armour layer, the amount of big rocks that are required can be reduced;
- Placement method; first the scour protection and then the structure or vice versa. This also depends on the outcome of the stability results.

From these results, assuming only loose rocks and stones will be used, two bed protection designs are made for the new structure designs, if they are placed at the Borssele OWF location;

- 1) Traditional (more conservative) methodology;
- 2) Design where some damage might occur.

Both options assume that the foundation layer of the new structure design partially functions as an armour layer.

The following sections elaborate on these two design methods.

## 1. Traditional methodology

First a conservative approach is followed based on traditional bed protection designs for the wind industry based on a 1 layer bed protection:

- 1) 1 / 100 year storm occurrence;
- 2) Safety factor of 1.2;
- 3) Required radius of area which should be protected is the maximal expected extend of the scour; This radius can be reduced by 2 meter when we consider the foundation layer as protective layer of the structure (which in fact is the purpose of this layer).
- 4) A layer thick enough to ensure a minimal thickness of 3 x the required rock size, to account for uncertainties in placement and due to deformation of the layer (CIRIA, 2007).

Following the above mentioned parameter settings, the protection layer is composed as follows:

- 1) A required stone size in the range of 0.04 to 0.12 m; damage level below 1. This results in a grading of 2-8 inch;
- 2) A single layer with a thickness  $\cong$  0.6 m;
- 3) Horizontal diameter=13 m.

The volume of stones can be calculated with:

$$V = \frac{\pi}{4} D^2 h, \text{ with:}$$

D = diameter of protection layer

h = thickness of protection layer

Combined this leads to a volume of stones  $\cong 0.25 \times \pi \times 15^2 \times 0.75 = 80 \text{ m}^3 \cong 130$  tonnes;  
Estimated costs rock: Euro 6,500 (Estimate of Euro 50,- per ton)

## 2. Design where some damage might occur

Because the bed protection is not designed for a wind foundation but for an eco-structure a less conservative bed protection design might be enough and some damage may take place. The following parameters settings are applied:

- 1) 1 / 100 year storm occurrence;
- 2) Safety factor of 1;
- 3) Required radius of area which should be protected is the minimal expected extend of the scour; This radius can be reduced by 2 meter when we consider the foundation layer as protective layer of the structure (which in fact is the purpose of this layer).
- 4) A layer thickness of about 2 x the required rock size, to have (minimal) certainty of a sufficient thickness, even if stones start to roll away during storms or placement (CIRIA, 2007);
- 5) geotextile with diameter of 5 m attached to reef structure.

Following the above mentioned parameter settings, the design of the protection layer is as follows:

- 1) A required stone size in the range of 0.03 to 0.10 m; damage level below 1. This results in a grading of 2-8 inch;
- 2) A single layer with a thickness  $\cong 0.4$  m;
- 3) Horizontal diameter=8 m.

The volume of stones can be calculated with:

$$V = \frac{\pi}{4} D^2 h, \text{ with:}$$

D = diameter of protection layer

h = thickness of protection layer

Combined this leads to a volume of stones  $\cong 0.25 \times \pi \times 8^2 \times 0.4 = 20 \text{ m}^3 \cong 35$  tonnes;  
Estimated costs rock: Euro 1,750 (Estimate of Euro 50,- per ton)

## Conclusions

Based on the traditional methodology that we have applied above, bed protection should be applied under the foreseen structures to guarantee no scour hole formation.

Due to the changes in the new design shape (more like a pyramid), and accepting that the lower layer of the structure partially functions as an armour layer, the required volume for scour protection is significantly lower than that of the design considered in our previous study (WaterProof, 2020).

When it is accepted that some damage may take place on the scour protection around the structures, lower gradings of stones or smaller diameters of the protected area can be selected. This lowers the height and volume of the required protection layer.

It is noted that this will also bring in risks which the Client should be aware of. These risks include;

- Insufficient layer thickness because:
  - stones moved out of the protection layer during severe storms, or;
  - placement inaccuracies in relation to a relative thin layer thickness
- Erosion because of insufficient layer thickness
  - scour erosion process can start through gaps between individual stones
- Stability of the structure on top of the scour protection
  - The movement of the armour layer could affect the stability of the structure if the structures are placed directly on top of the protection layer.

Preventing stones to be transported out of the scour protection is especially important if the structures are placed at the Borssele OWF location, due to the proximity to the cables and structures. It is up to the Client if damage is accepted or not and which of the provided scour protection designs will be applied.

## STABILITY

In this section the stability of the structures is assessed, with the same methodology of the previous study.

The interaction between the hydraulic forces and structures can result in 2 failure mechanisms; failure due to turning over and failure due to movement out of foundation, see Figure 3.

For mechanism 1, the moments (Force x distance) on the structures are of importance. Whether or not the structure turns over depends on the balance of the acting moment by the flow/waves, and the counteracting moment due to the weight of the structure itself. The acting moment is the product of the force and its application point as determined by the Morison equation (WaterProof, 2020). The counteracting moment depends on the weight of the structure and the distance  $a_2$ : this is the distance from the centre of the structure to the turning point (see Figure 3).

Apart from structure turning over, the structures can be pushed out of the foundation area (mechanism 2, see right panel in Figure 3). Here, the balance between the horizontal force against the construction and the shear stresses between foundation and construction is of importance. The maximum shear stress (just before sliding occurs) depends on the weight of the structure, size and roughness of the structure, and roughness of the foundation layer.

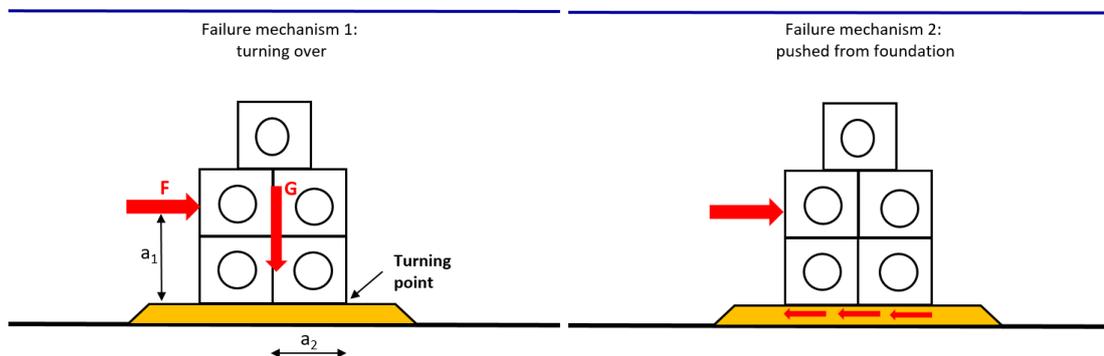


Figure 3: Failure mechanisms considered, with a schematic of the old design (from WaterProof, 2020).

### Forces on the structures

A worldwide used method to calculate forces under a combination of currents and waves is the (adapted) Morison equation. The Morison equation is the sum of two force components: an inertia force in phase with the local flow acceleration and a drag force proportional to the (signed) square of the instantaneous flow velocity.

$$F = \rho C_M V a + \frac{1}{2} \rho C_D A u |u|, \text{ where:}$$

- $\rho$  = density of water,
- $C_M$  = inertia coefficient,
- $V$  = volume of the structure,
- $a$  = acceleration at the structure,
- $C_D$  = drag coefficient,
- $u$  = flow velocities approaching the structure

It can be said that the stability of the reef structures depends on:

- The fluid flow velocities approaching the structure;
- The fluid accelerations at the structure due to waves;
- The effective surface area normal to the flow;
- The volume of the structure;
- The hydraulic drag coefficient ( $C_D$ ) and the inertia coefficient ( $C_M$ );
- The distance of the centre of the structure to the turning point ( $a_2$ ), only relevant for mechanism 1;
- The friction of the seabed / scour protection.

The first four points are dependent on the design and placement alone. The drag coefficient can be determined with laboratory experiments. The inertia and seabed friction coefficients are based on literature.

The highest uncertainties in the equations lie in the drag coefficient of the structure. To gain insight in the magnitude of the drag coefficients of the structures, the previous study performed several flume experiments. As the new design has changed significantly, the drag coefficients of the previous study cannot be adopted and have therefore been redetermined for the new design with a new flume test.

We have conducted the new flow flume experiment at a scaling of 1:17 (structure). Generally applicable scale rules have been used to scale the structures to representative dimensions. The flow velocity in the flume is increased from 0 to approx. 0.45 m/s in steps until the structure becomes unstable and turns over (critical conditions) and/or starts to slide. The vertical distribution of the fluid velocities is measured using an electro-magnetic current meter.

Table 4 shows the results of this flume test, such as the speeds at which the different mechanisms occur and the accompanying drag coefficient for the structure. The drag coefficient of the new design (approx. 1.9) is lower than that of the old design (approx. 2.2), most likely due to more 'pyramid' shape, allowing for a relatively smoother passage of flow around the structure

*Table 4: Results of the flume test, showing the maximum flow velocities at which the structures start to slide and turn over. Combined with the volume and density of the material, the drag coefficient  $C_D$  is determined.*

Structure	Density material [g/cc]	Volume of structure [mL]	Mechanism 1		Mechanism 2		$C_D$ [-]
			Max. flow for turning over [m/s]	Water depth [cm]	Max. flow for sliding [m/s]	Water depth [cm]	
A	1.29	583	0.41	14.5	0.26	15	1.93 +- 0.01

## Stability calculations

The methodology and assumptions from the previous study (WaterProof, 2020) are applied in this study as well, and are as follows:

- **Drag coefficient,  $C_D$**   
The laboratory results show that this parameter has a value between 1.92 - 1.94. It is important to mention that the application of additional attachments to the structure or marine growth can

further increase the value of this parameter. In order to take marine growth still into account, it is assumed that marine growth will increase the width of the structure by 10 cm at all sides.

- **Distance to turning point,  $a_2$  :**

The distance  $a_2$  equals the distance between the location of the centre of gravity and the turning point. This value is maximum when the turning point is at the corner of the structure. Therefore, the maximum value equals half of width parallel to flow. However, if structure placed on top of scour protection, uneven stone distribution or angled stones can lower this distance significantly by moving the turning point closer to the centre of the structure. Additionally, if the combined weight of the structure and the protection exceed bearing capacity, (uneven) settling could induce additional slope, which also lowers the distance. For the calculations performed in this section, the distance is assumed to be maximum. But, in order to account for the uncertainties, a safety factor is applied.

- **Inertia coefficient,  $C_M$ :**

This coefficient depends on the added mass to the structure; the extra inertia the structure will feel when water is accelerated (or decelerated). This dependence is expressed as (Bai, 2005):

$$C_M = C_a + 1$$

The presence of a fixed boundary has a pronounced effect on the inertia (and the added mass) coefficient; the smaller the distance to the bed, the larger this parameter becomes. As the structure is placed at the seabed,  $C_a$  becomes equal to 2. With the aforementioned dependence between the inertia coefficient and the added mass coefficient  $C_a$ ,  $C_M$  therefore becomes equal to 3.

- **Friction of bed, friction parameter  $\mu_d$**

The bed friction is an important parameter that determines the moment when sliding is initiated. The friction resulting from the weight of the structure is as follows:

$$\begin{aligned} F_{\text{friction}} &= F_{\text{weight}} * \mu_d, \text{ with,} \\ F_{\text{weight}} &= (\rho_{\text{structure}} - \rho_{\text{water}}) * \text{Volume}_{\text{structure}} * g \\ \rho_{\text{structure}} &= 2130 \text{ [kg/m}^3\text{]} \\ \rho_{\text{water}} &= 1025 \text{ [kg/m}^3\text{]} \text{ (salt water)} \\ g &= 9.81 \text{ [m/s}^2\text{]} \\ \mu_d &= \text{dynamic friction coefficient} \end{aligned}$$

The friction coefficient can be interpreted as follows; the lower the value is, the lower the friction force becomes, the easier it is for the structure to start sliding. Several studies have looked into the friction coefficient for sand. Depending on the sand type and its moisture contents (Fall, 2014) this value can vary. For wet sand, the friction value equals between 0.4 and 0.5. Our flume for example has a friction coefficient equal to 0.46. It is expected however, that in reality the structure will not slide smoothly, but will push itself into the sand / the scour protection layer. Additionally, rocks have a higher friction coefficient than sand. Therefore, this study assumes the seabed friction coefficient to be equal to 0.6.

▪ **Safety factor**

As explained above, there are a number of uncertainties; especially with respect to the drag parameter and the distance to the turning point. Based on these uncertainties a total safety factor of 1.2 is applied in the stability calculation for conservatism reasons.

Based on the above, the forces on the structures and moments due to these forces on the structures are calculated. Table 5 shows the results of these calculations at the Offshore Innovation Lab, Table 6 shows the results of the calculations at the OWF Borssele location.

Apart from the adapted design of options A and B (see Figure 1), an additional (rough) calculation is made for the original design of option A and B (see Figure 2), assuming the same drag coefficient. This calculation is made to evaluate the effect of the 4 additional cubes and assess whether they are necessary.

*Table 5: Resulting forces and moments on the structure. Location: Offshore Innovation Lab. The numbers are red if the forces are larger than the resistance of the structure (requirement is not met) and green if the forces are smaller than the resistance of the structure (requirement is met), based on the resistance as mentioned in Table 8.*

Structure	Return period [years]									
	1		5		10		50		100	
	F [kN]	M [kNm]	F [kN]	M [kNm]	F [kN]	M [kNm]	F [kN]	M [kNm]	F [kN]	M [kNm]
A, adapted	29.9	24.1	36.7	31.4	39.8	35	45.8	41.5	48.7	44.7
B, adapted	27.2	18.5	33.4	23.9	36.2	26.7	41.6	31.5	44.2	34
A, original	41.8	31	51.8	40.6	56.3	45.4	65.2	53.9	69.4	58.1
B, original	39.1	25.4	48.4	33.1	52.7	37.1	60.9	43.9	64.8	47.4

*Table 6: Resulting forces and moments on the structure. Location: OWF Borssele, near Beta platform. The numbers are red if the forces are larger than the resistance of the structure (requirement is not met) and green if the forces are smaller than the resistance of the structure (requirement is met), based on the resistance as mentioned in Table 8.*

Structure	Return period [years]									
	1		5		10		50		100	
	F [kN]	M [kNm]	F [kN]	M [kNm]	F [kN]	M [kNm]	F [kN]	M [kNm]	F [kN]	M [kNm]
A, adapted	12.6	8.5	16	11.5	17.4	12.9	22.6	17.4	23.6	19
B, adapted	11.4	6.5	14.4	8.6	15.7	9.6	20.4	12.8	21.1	14
A, original	17.1	10.7	21.7	14.5	23.7	16.2	31.1	22.1	32.5	24.2
B, original	15.9	8.6	20.2	11.5	22	12.9	28.8	17.5	29.9	19.1

It can be seen that:

- The forces and their resulting moments at the Offshore Innovation Lab are larger than at the OWF Borssele location. This difference can be explained by the smaller depth at the Offshore Innovation Lab, as the hydrodynamic conditions between the two locations are similar. Due to this smaller depth (and the structure height to depth ratio) it is easier for the forces to 'grab onto' the structure.
- The forces and moments on the structures are higher for the original design when compared to the adapted design. This difference can be explained by the larger volume of the structure (important for the inertia force) and a larger surface facing the flow (important for the drag force) for the original design.

### Resistance of the structure

For mechanism 1, this resistance depends on the weight of the structure and the moment arm  $a_2$ ; the distance from the centre of the structure to its tipping point. For mechanism 2, this resistance depends on the weight of the structure and the friction coefficient of the material it is placed on. The weight of the structures is shown in Table 7.

*Table 7: Weight of the structures, for both type A and B, for the new (and adapted new) design.*

Structure type	Weight of the structure [kg]	
	Original design	Adapted design
A	8500	6340
B	8100	5940

The structure are going to be installed with an installation frame. This frame is planned to stay attached to the structure, even after placement, to allow for relocation. The weight of the (steel) frame is approximately 750 kg.

In order to calculate the resistance of the structures against mechanism 1 and 2, the following is assumed:

- The arm  $a_2$  is taken as most optimal since a safety factor has been used in the calculations. Therefore,  $a_2$  is equal to half the width of the structure which is parallel to the flow.
- The seabed friction coefficient is equal to 0.6.

Based on the above, the resistance of the new design (original and adapted) is determined and shown in Table 8. If all blocks are filled, this resistance increases with 5%. The addition of the installation frame increases the resistance with approx. 20%, as is shown in Table 9.

Table 8: Estimated resistance of the individual structures, without the installation frame.

Structure	Resistance	
	Against sliding [kN]	Against tipping over [kNm]
A, adapted	19.37	36.32
B, adapted	18.15	34.03
A, original	25.96	81.11
B, original	24.73	77.29

Table 9: Estimated resistance of the individual structures, with the installation frame included.

Structure	Resistance	
	Against sliding [kN]	Against tipping over [kNm]
A, adapted	25.55	47.91
B, adapted	24.33	45.62
A, original	33.18	103.68
B, original	31.96	99.86

Based on the results in Table 5, Table 6, and Table 8 it can be said that:

- Adding the 4 outer cubes provide extra resistance against failure mechanism 2 (sliding) and a significant extra resistance against failure mechanism 1. On the other hand, the addition of these cubes adds extra volume to the structure and increases the surface area in the flow, therefore increasing the forces and moments that act upon the structure.
- If placed at OWF Borssele, the new design (original and adapted) always resists failure mechanism 1 (tipping over), and both designs resist failure mechanism 2 (sliding) up to a 1/10 year storm condition.
- When placed at the Offshore Innovation Lab, with respect to failure mechanism 1 (tipping over) the structure withstands a 1/10 year storm for the adapted new design and a 1/100 year storm for the original new design. With respect to failure mechanism 2 (sliding), the structures do not withstand any storm condition.
- Filling all blocks (so also the bottom layer) does increase the resistance against either of the two failure mechanisms, but not sufficiently to change the conclusions made above.

If the installation frame is planned to stay attached to the structure, it will provide extra resistance against both failure mechanisms, as shown in Table 9. Based on this added resistance it can be said that:

- If placed at OWF Borssele, the new design (original and adapted, including the installation frame) always resists failure mechanism 1 (tipping over), and failure mechanism 2 (sliding).

- When placed the Offshore Innovation Lab, the new design (original and adapted, including the installation frame) always resists failure mechanism 1 (tipping over). With respect to failure mechanism 2 (sliding), the structures still do not withstand any storm condition.

## CONCLUSIONS

Based on the scour and stability calculations the following can be concluded.

### Scour protection

Based on the traditional methodology that we have applied above, bed protection should be applied under the foreseen structures to guarantee no scour hole formation.

Due to the changes in the new design shape (more like a pyramid), and considering that the lower layer of the structure partially functions as an armour layer, the required volume of scour protection is significantly lower than calculated in the previous study (WaterProof, 2020).

When it is accepted that some damage may take place on the scour protection around the structures, lower gradings of stones or smaller diameters of the protected area can be selected. This lowers the height and volume of the required protection layer.

It is noted that this will also bring in risks which the Client should be aware of and include;

- Insufficient layer thickness because:
  - stones moved out of the protection layer during severe storms, or;
  - placement inaccuracies in relation to a relative thin layer thickness
- Erosion because of insufficient layer thickness
  - scour erosion process can start through gaps between individual stones
- Stability of the structure on top of the scour protection
  - The movement of the armour layer could affect the stability of the structure if the structures are placed directly on top of the protection layer.

Preventing stones to be transported out of the scour protection is especially important at the Borssele OWF location, due to the proximity to the cables and structures. It is up to the Client if damage is accepted or not and which of the provided scour protection designs will be applied.

### Stability

The flow flume experiment have been very useful to decrease the uncertainties of the stability calculations. Despite the help of the flow flume experiments, uncertainties remain. Therefore, a total safety factor of 1.2 is applied in the stability calculation for conservatism reasons.

It is again concluded that the forces and their resulting moments at the Offshore Innovation Lab are larger than at the OWF Borssele location. This difference can be explained by the smaller depth at the Offshore Innovation Lab, as the hydrodynamic conditions between the two locations are similar. Due to this smaller depth (and the structure height to depth ratio) it is easier for the forces to 'grab onto' the structure.

Based on the calculations in this study, it can be said that:

- If placed at OWF Borssele the structure does withstand a 1/100 year condition for mechanism 1 (tipping over), and a 1/10 year condition for mechanism 2 (sliding) for both the adapted and original new design.
- When placed at the Offshore Innovation Lab, with respect to failure mechanism 1 (tipping over) the structure withstands a 1/10 year storm for the adapted new design and a 1/100 year storm for the original new design.
- At the Offshore Innovation Lab, with respect to failure mechanism 2 (sliding), the structures do not withstand any storm condition.

If the installation frame is planned to stay attached to the structure, it will provide extra resistance against both failure mechanisms, as shown in Table 9. Based on this added resistance it can be said that:

- If placed at OWF Borssele, the new design (original and adapted, including the installation frame) always resists failure mechanism 1 (tipping over), and failure mechanism 2 (sliding).
- When placed at the Offshore Innovation Lab, the new design (original and adapted, including the installation frame) always resists failure mechanism 1 (tipping over). With respect to failure mechanism 2 (sliding), the structures still do not withstand any storm condition.

## General recommendations

We expect that in reality, the resistance against sliding is larger than our calculations, as it is expected that the structure will dig itself into the scour protection layer at the initiation of sliding. Based on the calculations, if the structures are placed at the OWF Borssele site and the installation frame is removed, the 1/50 and 1/100 year storm conditions are only just not met. Therefore, it is expected that at OWF Borssele, the structures will be able to resist failure mechanism, even under a 1/100 year storm condition, for both the adapted and original new design.

At the innovation lab, the original design (including the 4 outer blocks) is recommended, to at least ensure stability against failure mechanism 1 (tipping over) for all conditions, if the installation frame will be removed after placement. If the installation frame will remain attached, the adapted design (without the 4 outer blocks) will also always resist failure mechanism 2. At this site, the resistance against sliding is too low for all designs, even including the installation frame and even if it is assumed that the structure will dig itself into the scour protection layer. Therefore, if scour protection is applied at this location, it is recommended to increase the resistance of the structure by e.g. the application of steel rods or other rough protrusions underneath the structure. These will enhance the stability for mechanism 2 and prevent sliding.

If no scour protection is used at the Offshore Innovation Lab, it is expected the structures sink into the surrounding bed due to a formation of a scour hole. As was concluded in the previous study (WaterProof, 2020), the formation of the scour hole is expected to be larger at the innovation lab, due to the lower depth and finer bed material. The structure will slowly “sink” in the seabed over a vertical distance of approx. 0.75 m. The advantage of this mechanism is that the structure is enclosed by the seabed, which is expected to provide an additional resistance against sliding. Although difficult to make quantitative we expect that sliding of the structure will be stopped by this process.