MEMO: MOG2 ELIMINATED ALTERNATIVES

From	: Yannick Steenman
To	: ELIA
Date	: 1 December 2022
Reference	: 2094/U22391/B/YSTE
Checked by	: Bas van Leeuwen
Status	: Final

1 INTRODUCTION

At the start of the MOG2 project in 2021 an explorative study was carried out to form a basis for the eventual MOG2 island design study. This explorative study aimed to gain insight into potential island locations, feasible island designs, and rough estimations of the OPEX and CAPEX of the island. At the start of the Tender Design phase this culminated in the elimination of a number of locations and design options. This memo presents aspects of that elimination process. This process has taken place mainly in 2021: the exploratory design phase (CDR and Svašek for and in collaboration with Elia) and the early part of the tender design phase (CDR, IMDC, and Svašek for and in collaboration with Elia). Within this process, Svašek Hydraulics has predominantly been responsible for the numerical modelling and resulting environmental analyses, explained in detail in this memorandum. However, the environmental aspect was not the sole consideration for the selection of variants and locations. For the complete picture, other analyses and considerations resulting from the collaboration of parties have been included in this memorandum.

This memorandum serves to highlight the process behind the eliminations. The results have earlier been presented in a number of power point presentations (CDR & Svašek Hydraulics, 2021); (IMDC, CDR & Svašek Hydraulics, 2022), and early design documents in the Tender Design for the Energy Island. This memorandum collects that information and presents it comprehensively. However, new insights as obtained since the explorative study (during the later tender design and especially the EIA studies) have *not* been incorporated in this memo.

Naming conventions of the island locations have been updated to correspond to the EIA study, to prevent confusion.

Please note that although it is mostly presented in this memo as a linear affair, the process of elimination was – in reality - an iterative design process. This means that certain locations: such as the East location and a certain perimeter protection option (revetment) received significant attention before being ultimately abandoned.

Within this memorandum, the methodology, numerical models, and eventual results which have led to the elimination of several design alternatives during the explorative study of the MOG2 island and early Tender Design are presented. In Chapter 2 the basis of design, as was available during the exploratory phase of the MOG2 island, is briefly summarized. The employed numerical software and the resulting numerical model are explained in Chapter 3, followed by an explanation of the considered island locations and boundary conditions in Chapter 4. In Chapter 5 the differences between the potential island protective structures are explained, after which the island design analysis is highlighted in Chapter 6. The island design analysis is followed by the island location analysis in Chapter 7, which leads to the elimination of the alternatives in island design and location in Chapter 8.

2 BASIS OF DESIGN

During the exploratory phase and the early Tender Design of the MOG2 island, a certain number of requirements and constraints for the MOG2 island were set to formulate a basis of the design process. The basis of design as was determined in the exploratory phase is described in this chapter, although it should be noted that in later stages of the project some of these requirements and constraints were changed. Only requirements and constraints relevant for this memorandum have been presented. For a full list of the basis of design, consult CDR & Svašek Hydraulics (2021).

2.1 Land use requirements

- Total useable area: 5 ha:
  - Primary use: <3 ha
  - Other potential uses: <2 ha[1]
- Surplus:
  - Infrastructure
  - Cable landings
  - Buffer zones
  - Shore protection
  - Underwater foot print
- Maximum island footprint on the seabed, including erosion protection: 25 ha

2.2 Functional requirements

- Multi-functional island that is expandable[2]
- Primary function: energy transmission (‘hub’) and transfer
  - HVAC 220 kV transmission to 66 kV
  - 42 cables of 66 kV to 6 export cables of 220 kV
- Secondary functions (must)
  - Berthing facility
  - Refuel and Bunkering
  - Water and waste
  - Storage/Laydown area/warehouse
  - Living quarters/offices/control rooms
  - Heli port
  - Road infrastructure (SPMT?)
- Potential additional functions:

[1] Multifunctionality of the island was abandoned at a later design phase. Current island design only provides space for transmission infrastructure (energy island).

[2] Requirements that were abandoned at a later design phase.

- Energy storage (hydrogen, batteries)
- Offshore support O&G
- Connector hub international
- Data centre
- 5G

2.3 Berthing requirements

- Vertical quay is required:
  - Quay length of minimum 100 m (depth of 8 m) for supply vessels and barge, but given that the RoRo is an option, **or**;
  - Quay length of 180 m – 200 m (depth of 10 m) to accommodate lifting vessels (FIV).
- This quay will also accommodate:
  - Supply vessels (O&M)
  - Lifting goods from CTV (O&M and construction)
  - Coasters (construction)
- In case berthing requirements for O&M phase are met, the requirements during construction phase are easily met as well
- Options depend on type of shore protection
- Caisson
  - Vertical quay is easily included in the concept
- Revetment
  - For revetment solution a (vertical) quay needs to be included
  - The slope for RoRo ramp including SPMT is governing and does not fit easy in a (small CTV) basin. Unless on the outer perimeter of the island.
  - In case of a (longer) quay: RoRo ramp might be obsolete as lifting becomes a viable option

3 NUMERICAL MODEL SET-UP

The simulations within this memo are carried out using the computational flow software FINEL, which has been developed in-house by Svašek Hydraulics. FINEL allows for both hydrodynamic and morphological simulations, and is used in 2-dimensional-horizontal setting within all simulations. Information regarding the FINEL software and the employed model within the simulations can be found in Appendix 9A. This chapter serves to highlight the differences between the model employed within the exploratory phase of the MOG2 project compared to later phases of the project.

3.1 Calibration

The Southern part of the North Sea is an area which is modelled frequently. The 2D FINEL flow model of the European Continental Shelf used for this area has been calibrated and validated for various metocean and morphological studies like Borssele, VIKING and IJmuiden Ver. Nevertheless, contrary to the model employed within the MER simulations, the model version did not yet include the Metocean calibration, which is included in later versions of the model.

3.2 Mesh resolution

The unstructured mesh allows for local refinements around the project locations. Within the hydrodynamic simulations which are described in this memorandum, the finest element size equals approximately 15 meters. Within the morphological simulations, this is increased to approximately 40 meters to maintain feasible computational times.

4 ISLAND LOCATIONS AND BOUNDARY CONDITIONS

Five island locations have been explored during the exploratory phase of the MOG2 project. An overview of these locations is shown in Figure 4-1, together with the names assigned to each location. At the beginning of the exploratory phase the East location was the location of interest. However, the East locations (1 and 2) are positioned relatively close to the Natura2000 area, and also close to the crest of the Westhinder. Both of these factors led to the exploration of a location slightly further away from the Natura2000 area and without a sand bar crest in its vicinity: the West location.

To reduce impact on Nature 2000 areas, new locations were sought further North from the Natura2000 area. First, the East and West search locations were expanded further North, leading to the East 2 and the West 2 locations. One location significantly further North was also explored: the Noord location at the Noordhinderbank.

This chapter gives insight into the five chosen island locations and the boundary conditions at each location in chronological order. Most of the research was carried out at the East location, as this had been the considered project location for a large portion of the exploratory phase of the MOG2 island. Nevertheless, several boundary conditions have been considered at other locations as well.

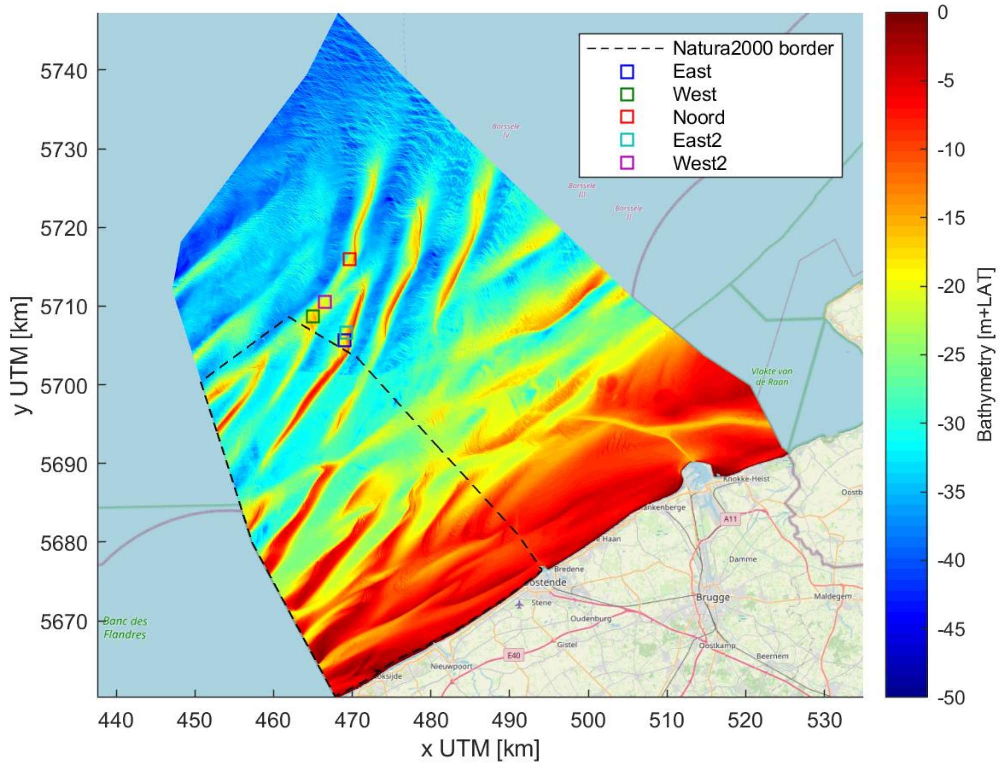


Figure 4-1: Overview of potential locations for the MOG2 project within the exploratory design phase.

4.1 East location

The most extensive research has been carried out at the East location, as this was the initially preferred project location. A concise summary of the findings in the initial analysis at the East location can be separated in the local bathymetry, the current rose, the wave rose, and the sediment properties at the East location.

4.1.1 Location and bathymetry

Figure 4-2 shows a zoom-in of the bathymetry around the East location. The average water depth around the island location equals -18.75 m+LAT. Aside from the Westhinderbank, smaller bed forms (sand dunes) can be found around the island location. An analysis of two bathymetries, one from 2003 and one from 2018, showed the bed forms towards the West of the Westhinderbank move northward with approximately 3-4 m/year, whereas the sand dunes towards the East of the Westhinderbank move southward.

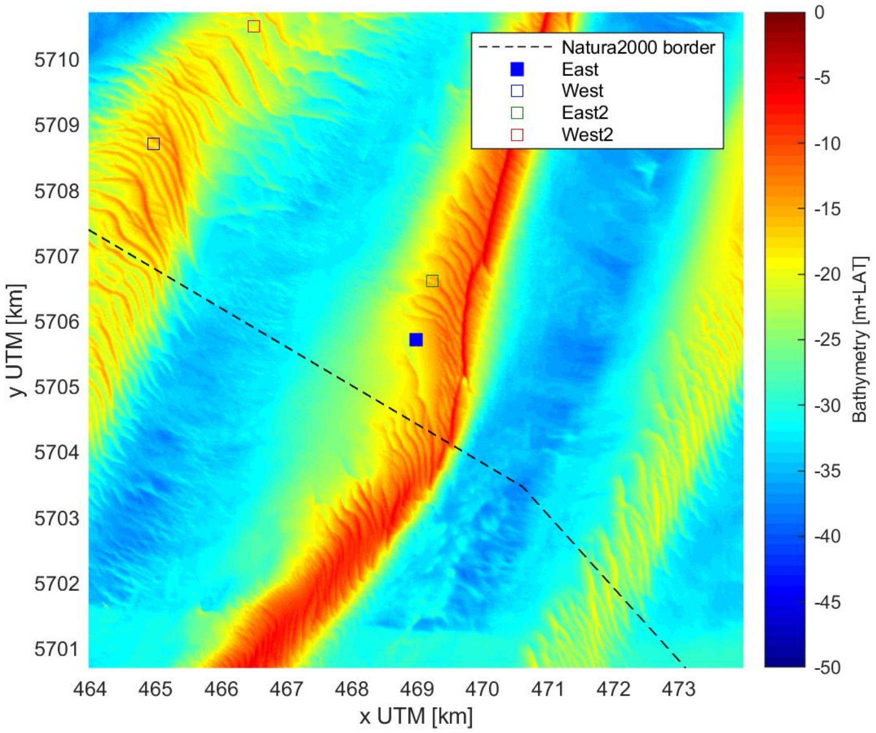


Figure 4-2: Zoom-in of bathymetry around the East location with respect to the Natura2000 area and other (nearby) island locations

4.1.2 Current rose

The current rose at the East location was simulated using the FINEL model for 4.25 days to gain insight in the tidal movement within several tidal cycles. The resulting current rose is shown in Figure 4-3. From the current rose, it is concluded that the dominant flood and ebb currents are non-aligning. The system is flood-dominated, with the dominant direction and exposure time coming from 50°N.

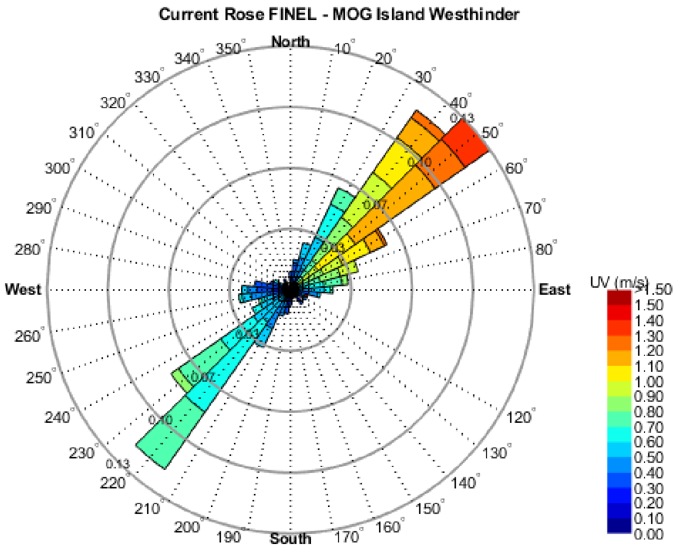


Figure 4-3: Current rose at the East location based on a numerical simulation of 4.25 days with the FINEL software

4.1.3 Sediment properties

Sediment data is obtained from Deleu et. al. (2004), who thoroughly studied the kink in the Westhinderbank. From their results it was deducted that the bed material varied between 250 µm and 450 µm, see Figure 4-4.

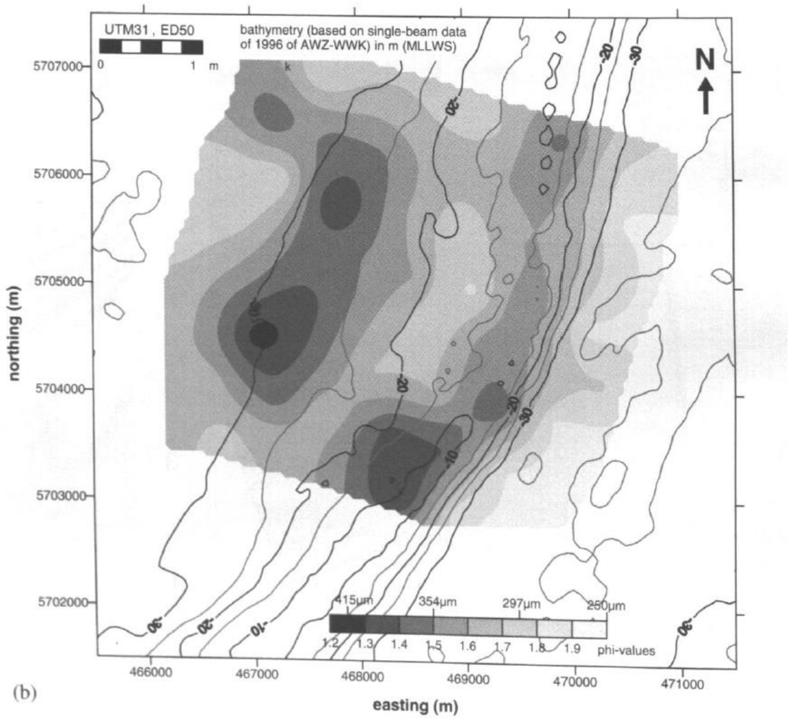


Figure 4-4: Representation of the mean grain size of the sand fraction around the East location (Deleu et. al., 2004)

4.2 West location

For efficiency, not all studies were repeated for the West location, as it became evident that several locations would have to be considered. Nevertheless, several site-specific conditions required to be analysed regardless.

It is noted that the West location has changed during the island tender design phase of the MOG2 project with respect to the West location considered in the exploratory phase. The West1 location in the island tender design phase is displaced 200 m towards the East with respect to the West location considered in this memorandum.

4.2.1 Location and bathymetry

Figure 4-5 shows a zoom-in of the bathymetry around the West location. The average water depth around the island location is approximately -17.5 m+LAT. Compared to the East location, no tidal ridge is present at the West location. Nevertheless, several sand dunes are present with an average wavelength of approximately 150 meters.

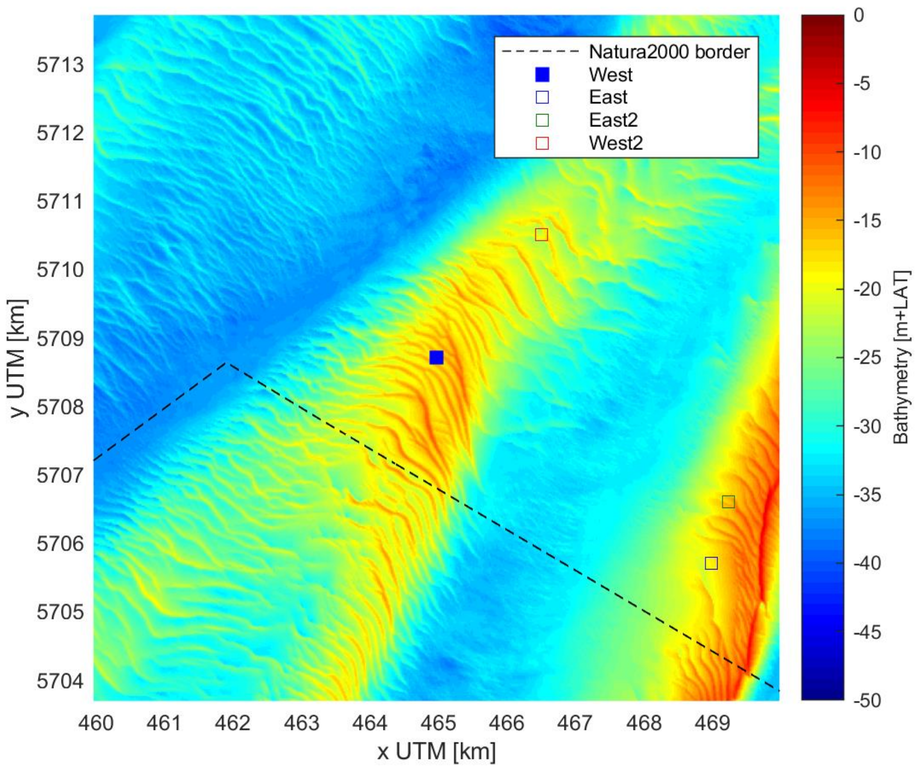


Figure 4-5 : Zoom-in of bathymetry around the West location with respect to the Natura2000 area and other (nearby) island locations

4.2.2 Current rose

The current rose at the West location was simulated using the FINEL model for 4.25 days to gain insight of a few tidal cycles. The resulting current rose is shown in Figure 4-6. From the current rose, it is concluded that the dominant flood and ebb currents are aligning, with the dominant flood flow coming from 30°N and the dominant ebb flow coming from 210°N.

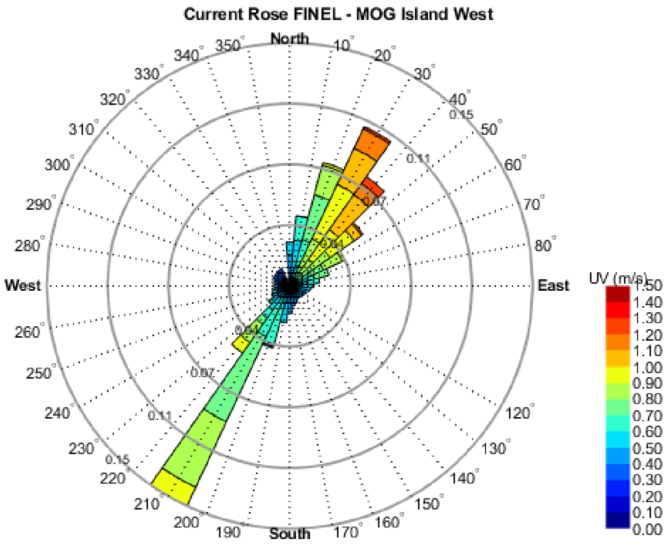


Figure 4-6: Current rose at the West location based on a numerical simulation of 4.25 days with the FINEL software

4.3 Noord location

The Noord location is positioned significantly further North compared to the other four island locations. The primary purpose if this large displacement lies in a potential reduction in the environmental impact of the MOG2 island on the Natura2000 area, which is further discussed in Chapter 7.

4.3.1 Location and bathymetry

Figure 4-7 shows a zoom-in of the bathymetry around the Noord location. The average water depth around the island location is approximately -20.5 m+LAT. Similar to the East location, the Noord location is positioned close to the crest of a large bed form to reduce the average water depth. In case of the Noord location, this is the Noordhinderbank. Contrary to the East location, less research has been performed at the Noord location considering the movement of the bed forms or the bed material.

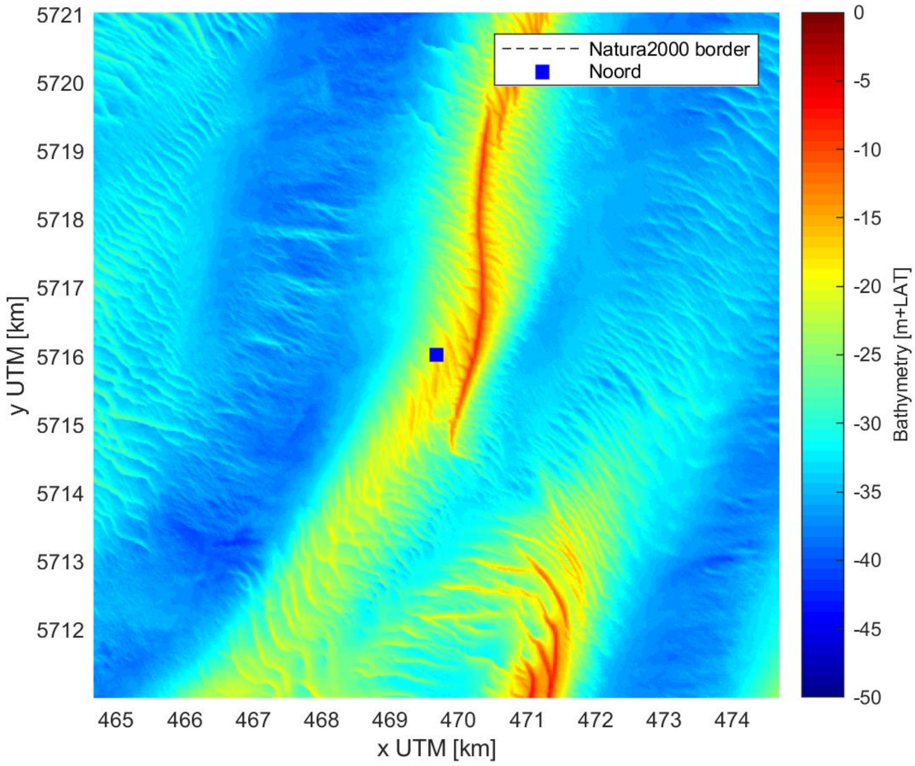


Figure 4-7 : Zoom-in of bathymetry around the Noord location with respect to the Natura2000 area and other (nearby) island locations

4.3.2 Current rose

The current rose at the West location was simulated using the FINEL model for 4.25 days to gain insight of a few tidal cycles. The resulting current rose is shown in Figure 4-8. From the current rose, it is concluded that the dominant flood and ebb currents are aligning, with the dominant flood flow coming from 50°N and the dominant ebb flow coming from 230°N.

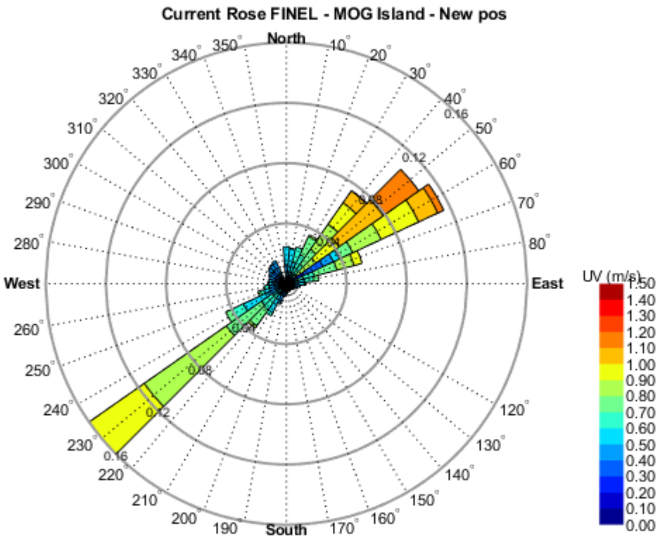


Figure 4-8 : Current rose at the Noord location based on a numerical simulation of 4.25 days with the FINEL software

4.4 East 2 location

The East 2 location is similar to the East location, but displaced slightly further north. Resulting in similar wave conditions to the East location. A closeup of the bathymetry near the East 2 location is shown in Figure 4-9. The average local water depth around the East2 location is slightly shallower compared to the East location at -16.5 m+LAT.

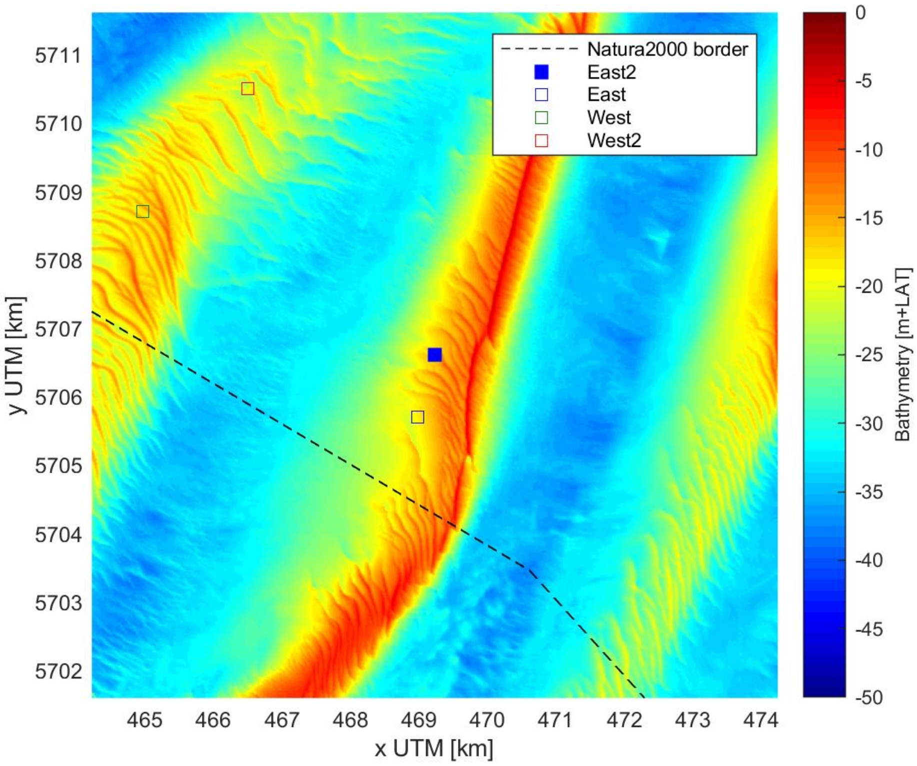


Figure 4-9 : Zoom-in of bathymetry around the East2 location with respect to the Natura2000 area and other (nearby) island locations

4.5 West 2 location

The West 2 location is similar to the West location, but displaced slightly further north. Resulting in similar wave conditions to the West location.. A closeup of the bathymetry near the West 2 location is shown in Figure 4-10. The average local water depth around the West 2 location is significantly deeper compared to the West location at -20.25 m+LAT.

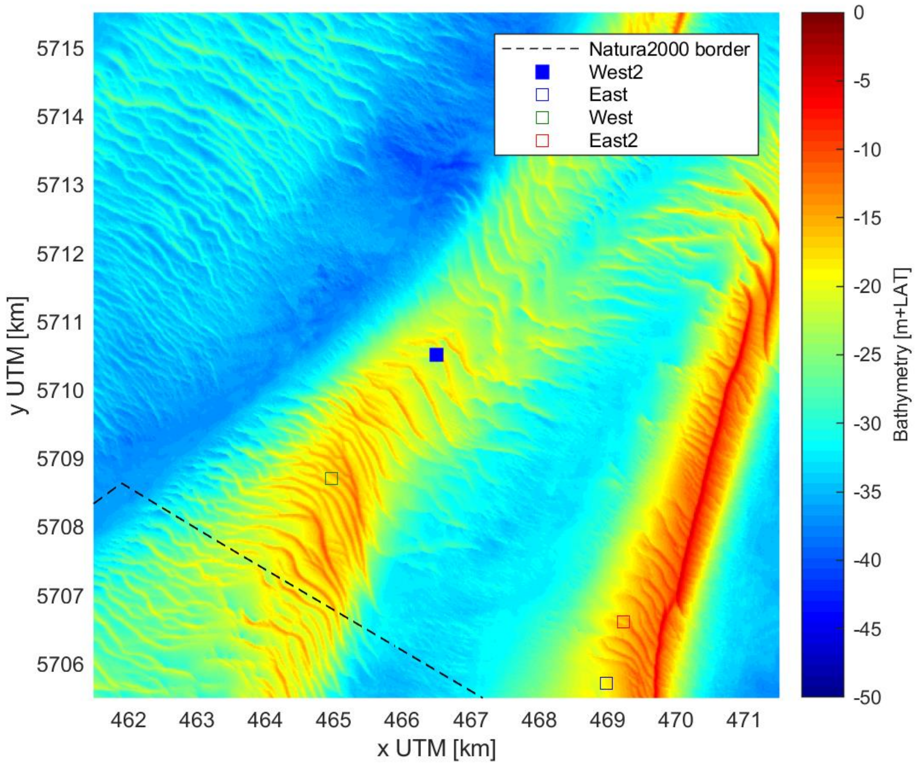


Figure 4-10: Zoom-in of bathymetry around the West2 location with respect to the Natura2000 area and other (nearby) island locations

5 ISLAND PROTECTIVE STRUCTURES

Two design options for the island's protective structure are considered, being a caisson structure and a revetment structure. In the exploratory studies, a design of either protection type was made for the East location. These designs are shown in Figure 5-1. This chapter serves to highlight the differences between either protective structure and their implications for the MOG2 island. Most of the information in this chapter stems from the PowerPoint presentation IMDC, CDR, Svašek Hydraulics (2022): Assessment of alternatives (protection & layout). This chapter was added to complete the reasoning behind the elimination of the alternatives.

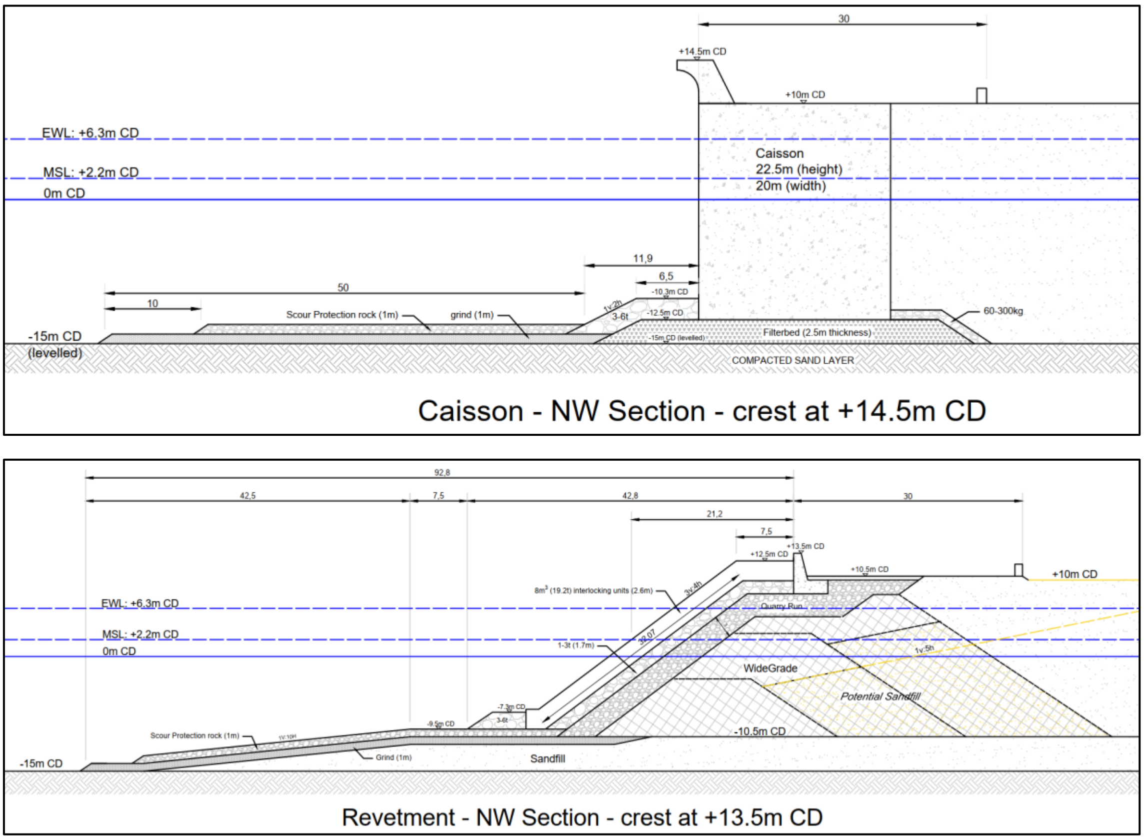


Figure 5-1: Overview of the initial caisson (upper) and revetment (lower) design solutions for the MOG2 island

5.1 Wave interactions

Wave overtopping is different for caissons and revetments. At a caisson, the overtopping is more 'vertical', while at a revetment there is more run-up and 'horizontal' overtopping. For the same allowable limits, the protection level of a caisson is (slightly) higher, but the overtopping distance (necessary buffer) can be smaller.

A revetment is less reflective than a caisson. The revetment will absorb the wave energy, and slopes cause less reflection compared to vertical walls. A revetment-type is therefore preferred to protect possible port areas, as a breakwater is much better in absorbing the wave energy inside the basins. Vertical walls have nearly 100% reflection, and therefore the wave energy 'bounces around' in the basins. The impact of reflection on navigability (such as entering the port) is also considered; for this aspect breakwaters are preferred as well.

High wave reflection around caissons generally leads to the need of scour protection of increased size and length.

5.2 Footprint

The footprint of a revetment becomes increasingly larger for increased depths. This is mainly due to the sloped revetment. An estimate of the island footprint with respect to the two protection types is shown in Figure 5-2, based on a relatively steep 2:3 revetment slope. The resulting footprints of the island are compared to the maximum allowable footprint as was described in the Basis of Design in Chapter 2. It can be concluded that a revetment design is only allowed at depths <-18 m LAT.

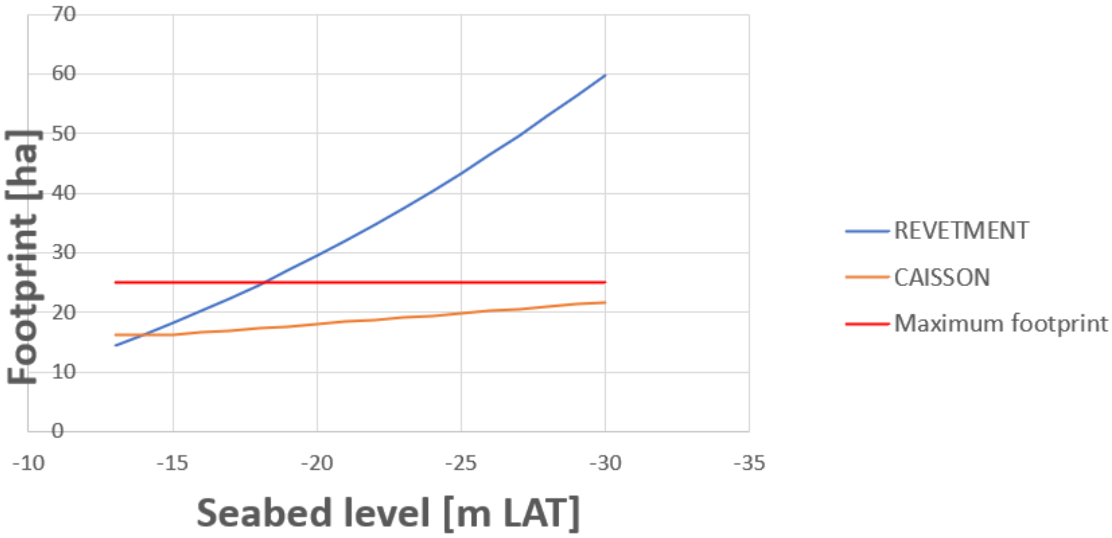


Figure 5-2: Footprint vs Seabed level for caisson structures (orange) and revetment structures (blue), compared to the maximum allowable footprint as determined in the Basis of design (red)

5.3 Constructability

The construction period for a revetment type is 6-8 months. Though the construction of a revetment for the MOG2 island is feasible and realistic, it requires a high volume of material and a lot of site logistics.

Workable limits for the transport of caissons to the site location are stricter than for barges and supply vessels for revetment solutions. The preferred construction period for caissons is relatively small, and during a year with bad weather there may not be sufficient time windows for the placement of the caissons. This poses a risk to the constructability and time planning of the island, and thus of the costs of the installation. On the other hand for caissons a lot of onshore preparations are possible.

5.4 Environmental impact

Installation of a revetment island requires more loose material, and thus gives rise to increased fine sediment concentrations in the water column due to washing out of fine material. This process is unfavourable for the overall environmental impact of the island. Wide grade material generally contains 0-5% fines. The spreading of fine material due to the construction of the island is further highlighted in Chapter 7.

More concrete is used for the caisson solution compared to the armour units of the revetment. This is important considering the CO_2 emissions of the construction of the island, because CO_2

emission is high for production of concrete. Furthermore, the revetment with rock and concrete armour could potentially provide a good habitat for fish and plants.

5.5 Cable landing

There are significant differences in cable landings on revetments and caissons. These differences, however, have not led to exclusion of one or the other. Please refer to the design documents for an overview.

5.6 Quay area

As described in the Basis of Design in Chapter 2, a vertical quay wall is required at the MOG2 island. When considering a caisson solution this condition is easily met. The caisson structures themselves are vertical and can thus be rather straightforwardly adapted for use as a quay wall. As revetments are sloping structures, the revetment cannot fulfil the requirement of a vertical quay wall. Instead, caissons need to be placed to serve as a vertical quay wall at the berthing facility. This indicates a 'revetment only' solution for the MOG2 island is not possible, as caissons or other wall like structures are always a necessity to fulfil the vertical quay wall condition. In practice it is expected that inclusion of some caissons will prove the most realistic option for providing a quay in a revetment island.

The combination of a caisson and revetment solution combines the advantages and disadvantages of both solutions. The transition between the sloped revetment and the caisson is complex. However, the combination of protective designs reduces the risk involved in the placement of many caissons in a short time window.

5.7 Costs

The costs of a caisson island, a revetment island, and a combined island have been estimated based on a conceptual island design and with conceptual design parameters. The capital expenditure (CAPEX) of a revetment island was estimated at €115,000.00 per meter protection, whereas the CAPEX of a caisson island was estimated at a similar €112,500.00 per meter. Thus, the expected costs of either solution is similar, with the caisson island being slightly cheaper. However, as was discussed in Section 5.5, a revetment-only island is not possible as a vertical quay wall is required. As this vertical quay wall is most easily constructed using caissons, a combination island should be considered instead of a revetment-only island. The CAPEX of a combination island was estimated at €150,000.00 per meter, which is significantly higher compared to the caisson-only or revetment-only solutions. The primary cause for this increase in CAPEX is the requirement of an additional supply chain for caissons. The start-up costs of a caisson supply chain are relatively high, making caissons more cost-efficient when used in larger quantities. Thus, the costs per caisson for the caisson-only island are significantly lower compared to the costs per caisson for the combination island, as significantly fewer caissons are required for the construction of the vertical quay.

6 ISLAND DESIGN ANALYSIS

The philosophy behind the island design has always been to minimize the impact of the island on the environment within feasible boundaries. The shape, the footprint, and the alignment of the island play important roles within this minimization. Thus, the environmental impact of different designs of the MOG2 island is analysed within the island design analysis. The design analysis is carried out at the original East location, see also Chapter 4, and it is assumed the results are valid for the other island locations as well.

This chapter serves to highlight the methodology and results of this analysis, combined with the assumptions made within the process.

6.1 Variability in island designs

6.1.1 Island shapes

The shape of the island largely determines the way the tidal flow flows around the island. It is known that more rounded shapes tend to be less disruptive to the flow compared to more rectangular shapes. Within the determination of different island shapes, the total useful area of the island was kept constant at 5 Ha. The considered shapes within the island design analysis are summarized in Table 1. An overview of all the shapes are shown in Figure 6-1**.**

Though most shapes are relatively self-explanatory, the pill and bullet shape require a bit more background. The bullet shape serves as a compromise between a rounded design and a rectangular design, and is essentially a rectangle with half of an ellipse attached to one side, see Figure 6-2 (left). The bullet shape facilitated one side with a streamlined design, which could be aligned with the dominant tidal direction (for locations where there is a clear tidal asymmetry, mainly the East locations), and one flat side, which allowed for expandability.

The pill design is in principle a rectangular body with half-ellipses attached to either side, see Figure 6-2 (right). Though in theory similar to a full ellipse, the crucial difference lies in the rectangular body, which allows more efficient interior design compared to the curved body of an ellipse.

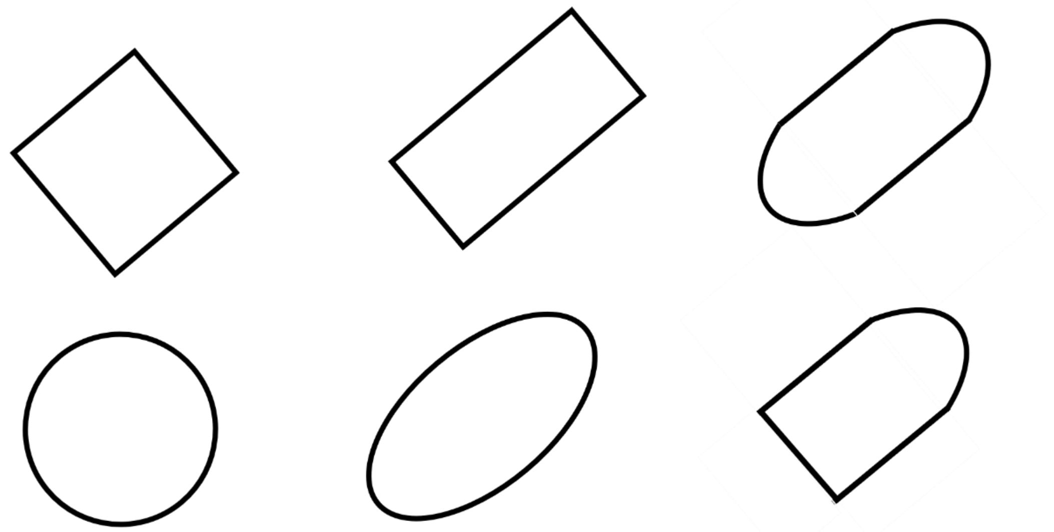


Figure 6-1: Considered shapes in the island design analysis. Upper row: left = square, middle = rectangle, right = pill. Bottom row : left = circle, middle = ellipse, right = bullet.

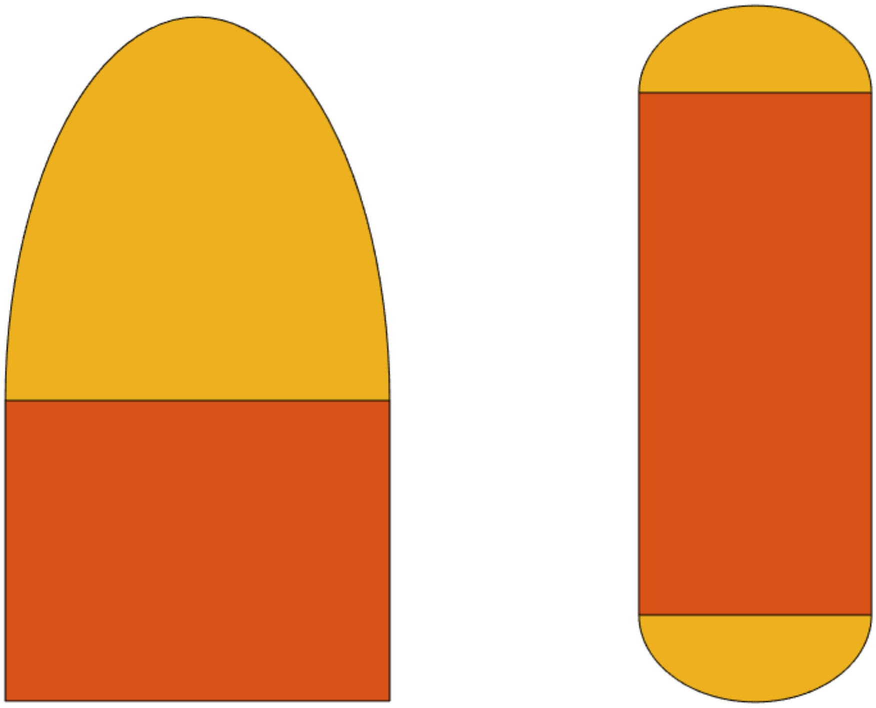


Figure 6-2: Indication of the construction of the bullet shape (left) and the pill shape (right) in the design analysis

6.1.2 Island dimensions

Within the scope of one shape of the island, a lot of variability remains in the corresponding dimensions. For an island which is perfectly aligned with the tidal flow, it is expected that more elongated shapes yield less flow disturbance compared to broader shapes. In the island design study, the dimensions of the island are described in the width-to-length ratio. Two distinct width-to-length ratios were considered, being 1:2 (relatively broad) and 1:3 (relatively elongated). The 1:3 width-to-length ratio is considered the most elongated limit of the island where the required equipment could still be placed in the island interior in an efficient manner.

The different width-to-length ratios which were considered for the different island shapes are summarized in Table 1. For the bullet and pill designs, two sets of dimensions are of importance, being the dimensions of the rectangular body, and the dimensions of the ellipse(s). The width-to-length ratio of these shapes are shown under width-to-length ratio in Table 1. As an example, a bullet shape with width-to-length ratio 1:3 consists of half of an ellipse with the semi-major axis three times as long as the semi-minor axis, and a rectangular body with the length equal to three times the width. For the pill shape, additional variation was added, where the width-to-length ratio of the ellipses was decreased from 1:3 to 1:6 for one simulation.

It is noted that the aspect ratios refer to the usable area of the island only, any additional width of the protective perimeter, is added to that.

6.1.3 Island protective structure

As discussed in Chapter 5, either a revetment protection or a caisson protection is considered for the MOG2 island. The choice for the specific protection type influences the total footprint of the MOG2 island, as the protective structure effectively broadens the island, especially at increasing depths, see section 5.2.

As mentioned, the design analysis is carried out at the East location, where the mean water depth around the island location equals approximately -18.75 m+LAT. At this depth, the caisson solution was estimated to be approximately 30 meters in width, whereas the breakwater solution was estimated to be approximately 70 meters in width at the sea floor. Above the water, the breakwater would equal approximately 55 meters in width. See also Figure 5-1 for more precise dimensions. The different structures as used in the design analysis are shown in Table 1. As mentioned in the previous paragraph, the additional width required for the perimeter protection is added to the aspect ratio of the usable area, for which all the design options use 5 ha.

Table 1: Summary of considered island designs in island design analysis

Name	Shape	Width-to-length	Protective structure
CS Square	Square	1:1	Caisson
BW Square	Square	1:1	Breakwater
BW Circle	Circle	1:1	Breakwater
BW Rectangle 1-3	Rectangle	1:3	Breakwater
BW Rectangle 1-2	Rectangle	1:2	Breakwater
CS Rectangle 1-3	Rectangle	1:3	Caisson
BW Ellipse 1-3	Ellipse	1:3	Breakwater
BW Bullet 1-3	Bullet	1:3	Breakwater
BW Bullet 1-2	Bullet	1:2	Breakwater
BW Pill 1-3 1-3	Pill	1:3 & 1:3	Breakwater
BW Pill 1-3 1-6	Pill	1:3 & 1:6	Breakwater

6.2 Shape study methodology

During the exploration study the environmental impact of the island was largely defined as the local erosion and sedimentation, which are thus the preferred parameters to rate each individual island design. However, performing morphological simulations for each different island design variation is too computational costly to perform. Thus, the comparison between designs was mostly done using hydrodynamical simulations, with a few morphological simulations to validate the results. Within the simulations, the island – at the east location - was oriented at 50°N to align with the dominant flood flow (see Chapter 4).

6.2.1 Hydrodynamic simulations

For each island design, a hydrodynamic simulation of 4.25 days was carried out. On time intervals of 30 minutes, the tidal flow in the simulation with the island design is compared to the tidal flow in an identical timestep in a simulation without the island present. Both the zones of accelerated and zones of decelerated flows can be determined within the comparison, together with flow disturbances on the local sediment balance. The latter is done using the Soulsby & van Rijn sediment transport equation (van Rijn, 1948). Thus, per half an hour, the areas of accelerated and decelerated flows and the expected volume of eroded sediment and the volume of deposited sediment can be calculated. The total areas of accelerated and decelerated flows are used in the hydrodynamic ranking of the island shapes, whereas the total volume of sediment for the entire simulation is related to other island designs to obtain a morphological ranking of the island design.

It is noted that no morphological feedback is involved in this process. The CS-Square design is considered the reference design, indicating the morphological and hydrodynamic rankings are defined at 2.

6.2.2 Morphological simulations

Several assumptions regarding the sediment balance underly the hydrodynamic simulations and analysis. The time resolution is relatively low, and the feedback between the bed and the sediment transports is not taken into account. Thus, to validate the rankings of the island designs as followed from the hydrodynamic simulations, several morphological simulations are carried out. Within the morphological simulations the sediment transports are calculated for each time step (~0.25 seconds), and the bed is updated accordingly. A nominal grain size of 250 μm is used in the computation, since the analysis of the bed material at the East location (Chapter 4) showed that this is the finest material found around the island.

The morphological simulations were carried out using a morphological acceleration factor of 25 and a hydrodynamic simulation period of 4 spring-neap tidal cycles. As a result, 4 morphological years are calculated. A morphological simulation with a certain island design is compared to an identical morphological simulation without the island present to isolate the effect of the island design on the local sediment balance. From the simulation, the total erosion volume and the total sedimentation volume are calculated in order to rank the island design with respect to other designs. This rating is compared to the ranking as obtained from the hydrodynamic simulations.

The designs which included a morphological simulation are:

- BW Ellipse 1-3
- BW Bullet 1-3
- CS Rectangle 1-3
- BW Bullet 1-2
- BW Rectangle 1-3
- BW Rectangle 1-2

6.3 Island shape study results

The results from the hydrodynamic analysis are presented in Table 3, and the results from the morphological analysis are portrayed in Table 2

Table 2: Island designs ranked based on their hydrodynamic score based on the results from the island design study. A lower score indicates less impact of the island design on the surrounding flow.

Run	Total influenced area [HA]	Score
BW-Ellipse-1-3	50.5	0.89
BW-Pill 1-3-1-3	50.9	0.89
BW-Pill-1-3-1-6	55.1	0.97
BW-Bullet-1-3	58.9	1.03
CS-Rectangle-1-3	65.8	1.15
BW-Rectangle-1-3	67.0	1.18
BW-Bullet-1-2	69.3	1.22
BW-Circle	81.3	1.43
BW-Square	97.4	1.71
CS-Square	114.0	2.00

Table 3: Island designs ranked based on their morphological score based on the results from the island design study. A lower score indicates less morphological impact of the island design.

Run	Total morphological score
BW-Ellipse-1-3	1.35
BW-Pill-1-3-1-6	1.39
BW-Pill 1-3-1-3	1.40
BW-Bullet-1-3	1.42
CS-Rectangle-1-3	1.51
BW-Bullet-1-2	1.52
BW-Rectangle-1-3	1.57
BW-Circle	1.66
BW-Square	1.84
CS-Square	2.00

Table 2 and Table 3 show that rounded shapes (bullet, ellipse, pill) perform better compared to rectangular shapes (rectangle, square). Within the rounded shapes, the ellipse performs best, because of their streamlined shapes.

Elongated shapes are shown to perform better compared to wider shapes. This can be seen by comparing the BW Bullet 1-2 and BW Bullet 1-3.

Caissons perform slightly better than breakwater solutions (BW Rectangle 1-3 to CS Rectangle 1-3). However, it should be noted that the East location is relatively shallow compared to most other potential island locations, see Chapter 4. Which means that the footprint of a breakwater solution will be larger at other locations. Thus, the discrepancy between the environmental impact of caissons compared to the environmental impact of revetments is expected to increase at the island locations which are deeper than the East location.

7 ENVIRONMENTAL IMPACT ANALYSIS

One of the considerations when searching for suitable island locations is the environmental impact of the island at each potential location. With the collaboration with BMM during the final stages of the exploratory study, it became clear that several gravel beds exist throughout the Hinderbank area which are sensitive to sedimentation. Thus, these gravel bed locations have become the primary focus of the environmental impact analysis. The locations of these gravel beds with respect to the five considered island locations are shown in Figure 7-1. The locations of these gravel beds are determined from two distinct parametrical studies, and thus not from sediment samples taken from the considered location. The first study was carried out in 2012, and yielded potential gravel bed locations in a large section of the Belgian part of the North Sea (light-grey dotted line in Figure 7-1). The second study was carried out in 2020. The spatial scope of this 2020 study was limited to a certain section of the Natura2000 area, and thus only shows potential gravel bed locations within this section (black dots in Figure 7-1). It is noted that, as these gravel bed locations are determined based on parametrical studies rather than measurements, the positions of the gravel beds themselves are an additional uncertainty which is to be considered within the results of the environmental impact analysis[3].

This chapter serves to highlight the methodology and the results of this exploratory environmental impact assessment (performed in 2021).

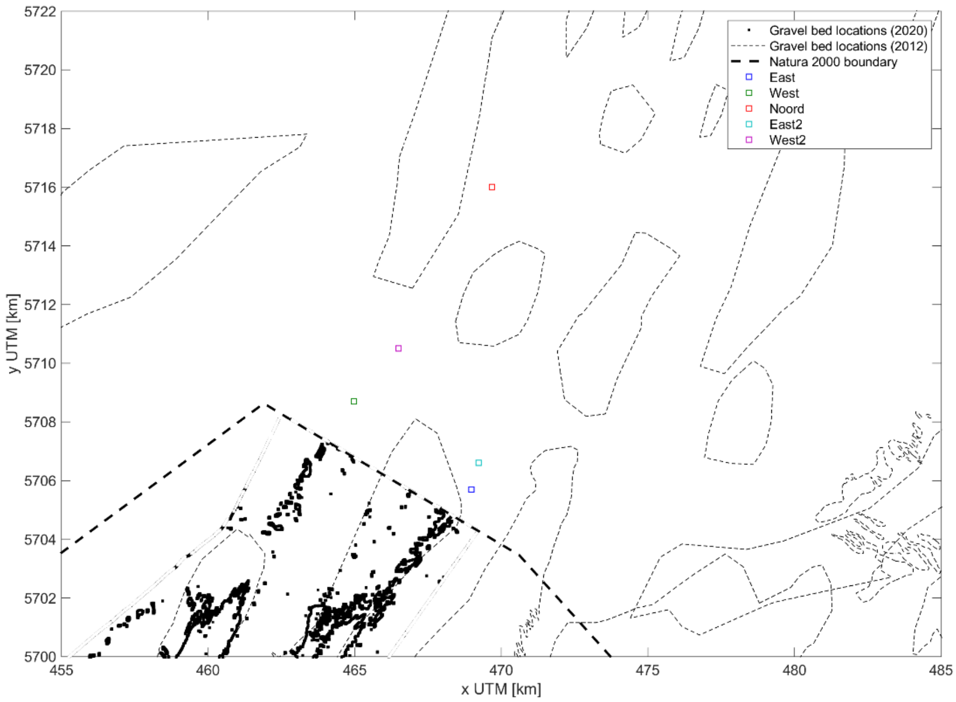


Figure 7-1: Overview of the gravel bed locations of the 2020 study and the 2012 study with respect to the Natur2000 area and the five potential island locations

[3] Later within the MOG2 project, the results of a new gravel bed study (2022 results) showed several differences in gravel bed presence around the five potential island locations.

7.1 Sand scour simulations

7.1.1 Methodology

The environmental impact analysis can be separated in two distinct analyses, being an analysis of the spreading of bed material after construction of the island, and an analysis of the spreading of fine material during construction and after construction of the island.

The sand scour simulations consider the spreading of bed material, represented with a nominal diameter of 250 mum, after the construction of the island. The construction of the island is assumed to be finalized at the start of the simulation, t=0. This analysis shows the formation of the erosion holes and sedimentation of the eroded sediment but also of sediments in the lee of the island. The bed level is fully dynamic in the corresponding simulation, allowing for both erosion and sedimentation.

7.1.2 Settings

Grain sizes

Similar to the morphological simulations of the design analysis in Chapter 6, a nominal grain size diameter of d50 = 250 μm was considered to be representative for the bed material. The time span of the exploratory phase of the MOG2 island did not allow for further analyses for the other island locations. Thus, to maintain a fair comparison between island locations, the nominal grain size diameter of d50 = 250 μm was used for all five island locations. The 90% diameter was estimated to be 1.5 times the nominal diameter, yielding d90 = 375 μm.

Hydrodynamic and morphological simulation periods

Within the sand scour simulations with bed-update a morphological acceleration factor of 25 is employed. As a result, a hydrodynamic period of one spring-neap tidal cycle equals one morphological year. At the East and West locations simulations with a hydrodynamic period of 4 spring-neap tidal cycles were carried out, which translate to 4 morphological years. From these simulations it was found that the development of the erosion and sedimentation around the island was most severe in the first year after construction. Thus, it was decided to compare the impact of the island after one morphological year, and the simulations at the West2, East2, and Noord locations were carried out with this timeframe.

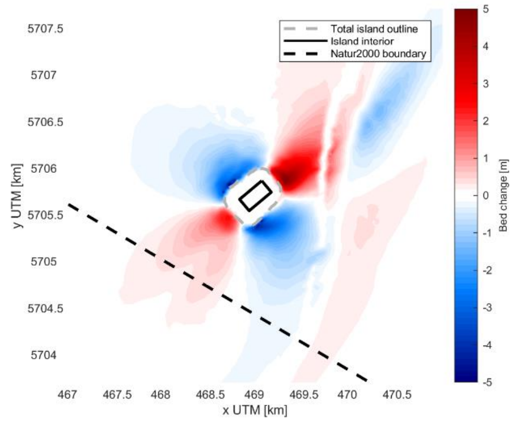
Island design

The BW-Rectangle-1:2 design was used within all simulations with the MOG2 island present.

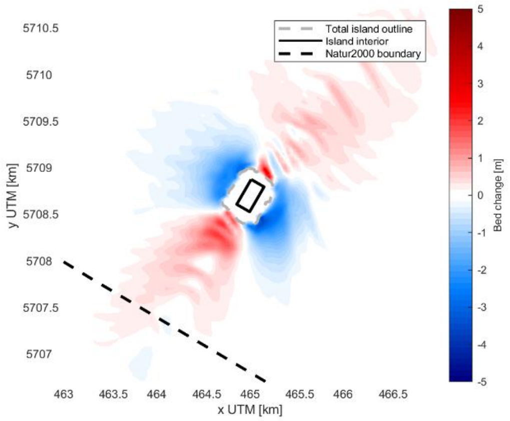
7.1.3 Results

Figure 7-2(a) to (e) show the erosion-sedimentation patterns around the island after one morphological year for all five island locations. The corresponding erosion volumes, as used in the fine sand and silt simulations for the East, West, and North locations, are listed in Table 4. It is noted that erosion is defined at every position where the bed deepens as a result of the island, including minimal changes resulting from the comparison between a simulation with and without island[4].

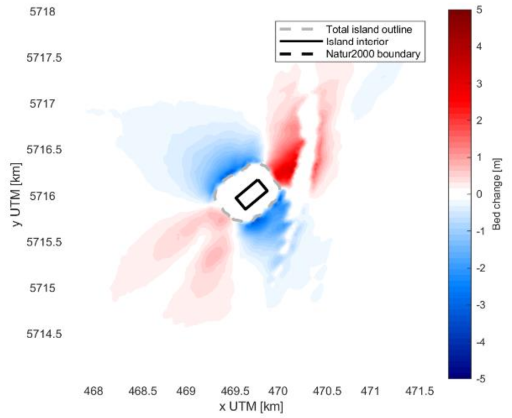
[4] Later in the MOG2 project, the definition of erosion was changed to only include bed changes higher than a certain threshold to ensure only the erosion closest to the island is taken into account.



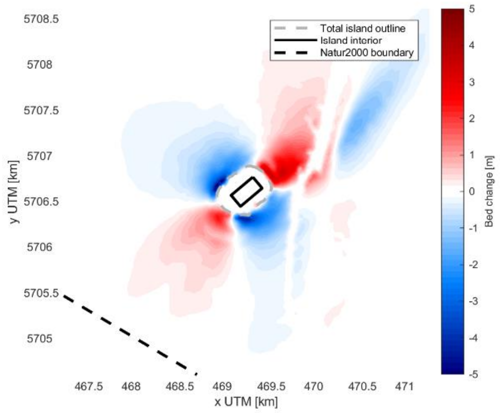
(a) East



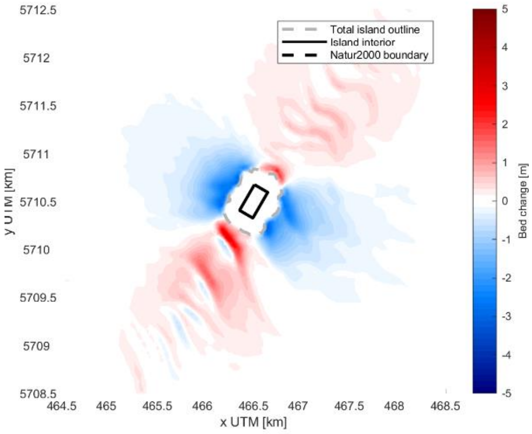
(b) West



(c) Noord



(d) East2



(e) West2

Figure 7-2: Local erosion and sedimentation after one morphological year for all five island locations: (a) East location, (b) West location, (c) Noord location, (d) East2 location, (e) West2 location.

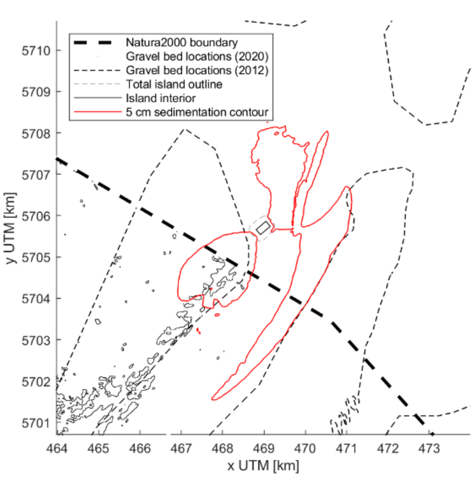
Table 4: Erosion volumes after one morphological year at the East, West, and Noord locations

Location	Erosion volume [10^6 m^3]
East	2.50

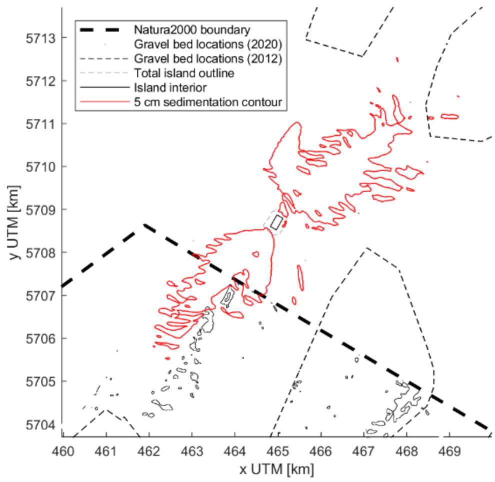
West	2.30
Noord	2.15

7.1.4 Sedimentation on gravel beds

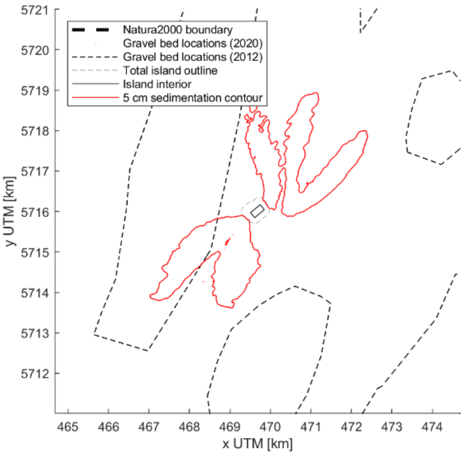
The sedimentation on the gravel beds is visualized using a sedimentation contour of 5 cm. This implies that the layer of sediment that is deposited in the area which is enclosed by the contour line is 5 cm or thicker. The results per location are shown in Figure 7-3(a) to (e), and the results of all five island locations combined is shown in Figure 7-4.



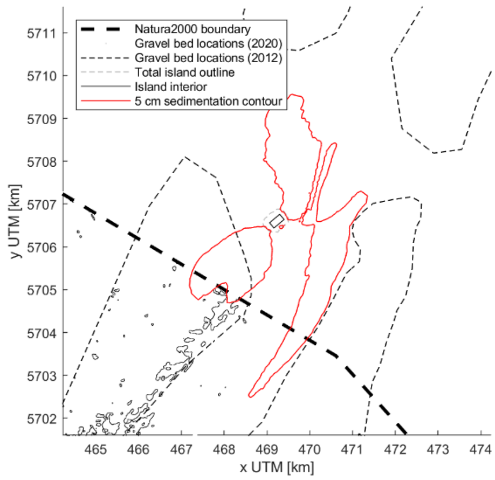
(a) East



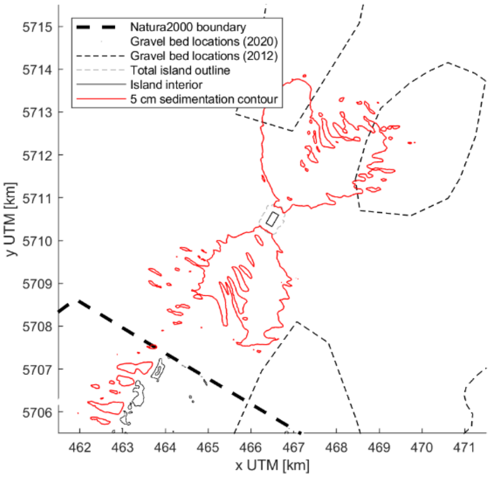
(b) West



(c) Noord



(d) East2



(e) West2

Figure 7-3: Contour of the areas in which 5 cm sediment or more has been deposited due to the MOG2 island with respect to the Natura2000 and gravel bed areas for all five island locations : (a) East location, (b) West location, (c) Noord location, (d) East2 location, (e) West2 location.

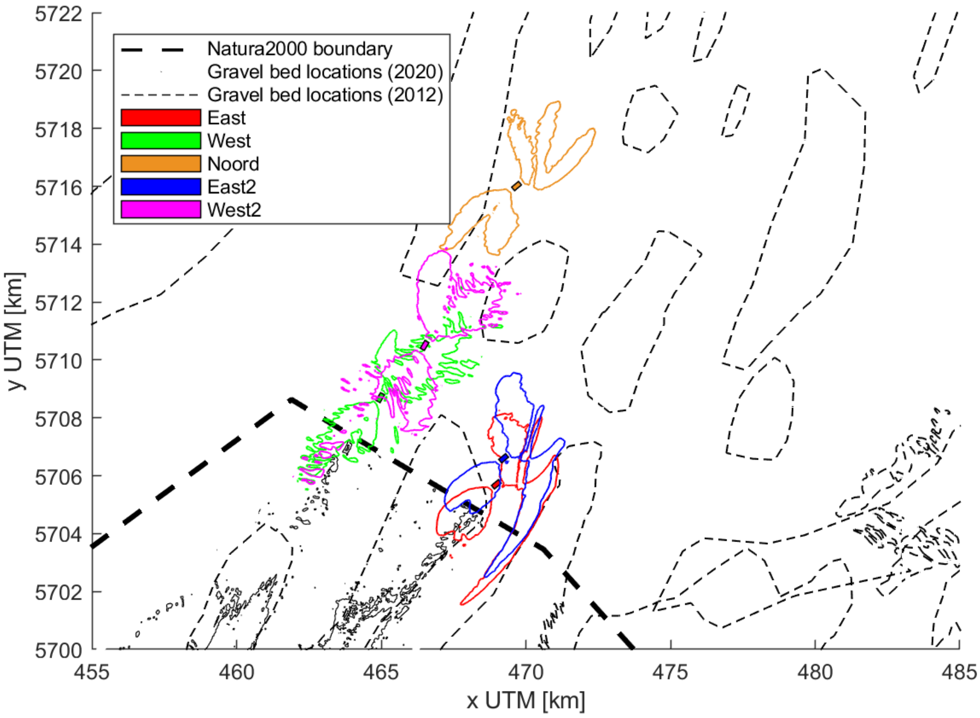


Figure 7-4: Contour of the areas in which 5 cm sediment or more has been deposited due to the MOG2 island for all five island locations combined

7.2 Fine material dispersion simulations

7.2.1 Methodology

The fine material dispersion simulations consider the spreading of fine material as a result of the placement of the island. This includes spreading of fine material during the construction of the island (based on estimated island construction volumes and fine percentages), and spreading of fine material due to the erosion around the island as follows from the sand scour simulations.

In the simulations during construction, the island is assumed to be absent as a simplification. Thus, the full simulation is run without the MOG2 island in place. In reality, the island would slowly be built-up over time. In the simulation after construction, the full MOG2 island is assumed to be present at t=0.

The spreading of fine materials during and after constructions are determined based on the same simulations. This simulation is set-up to reproduce the spreading of fine material during construction, and the results are later scaled to match the considered erosion volumes and timescales after construction.

"Fine material" is split-up in two parts, being silt and fine sands, of which the spreading is determined in individual simulations. As the constructed model assumes a vertical concentration profile, the fine sediment is assumed to mix instantly over the entire water column. This is a conservative assumption to make, as the actual deposition methods are expected to be more precise.

The released fine sediment is brought into the simulation as a continuous source along the middle of the long sides of the island, as these are the locations where erosion is expected. The existing bed level is fixed in the corresponding simulations, which is deemed an appropriate assumption on this time scale. This means that only sedimentation of suspended materials can occur but no resuspension.

7.2.2 Settings

Sediment grain size

For the spreading of fine sands a nominal diameter of d_{50} = 100 µm was used. For the silt dispersion simulations no grain size is applicable. Instead, a fall velocity of w_s = 0.12 mm/s is used.

Hydrodynamic and morphological simulation times

For the timeframe of the fine material simulations the construction time of the island was estimated to take 3 months (90 days) of continuous work. To maintain feasible simulation times, the hydrodynamic period within the simulations spanned 2 months (60 days), and the results were scaled to the estimated 3 months in the post-processing. Similarly, the results were scaled to 1 year to determine the spreading of the fine material due to the erosion around the island.

Island design

The BW-Rectangle-1:2 design was used within all simulations with the MOG2 island present.

Island volumes and deposition of fine material

To conservatively estimate the required amount of sand for the construction of the island, it was assumed that the entire MOG2 island would be build-up with sand. This would yield the following sand volumes at the relevant island locations:

- East 4.30 Mm^3
- West 3.90 Mm^3

- North 4.85 Mm^3

Of these total sand volumes it was conservatively estimated that 10% of the material would consist of silt, and another 10% of the material would consist of fine sand[5].

7.2.3 Results

The average fine sand concentration increase around the MOG2 island during construction are shown in figures Figure 7-5**Error! Reference source not found.** to Figure 7-7 for the three considered island locations. The impact of the release of fine sand after construction is lower than during construction, as the erosion volumes after construction are lower compared to the assumed sediment volumes required for construction. Thus, the figures after construction are not shown here. Furthermore, the erosion after construction is spread over 1 year, whereas the construction takes place in 3 months. Thus, the image would be similar, but with lower magnitudes.

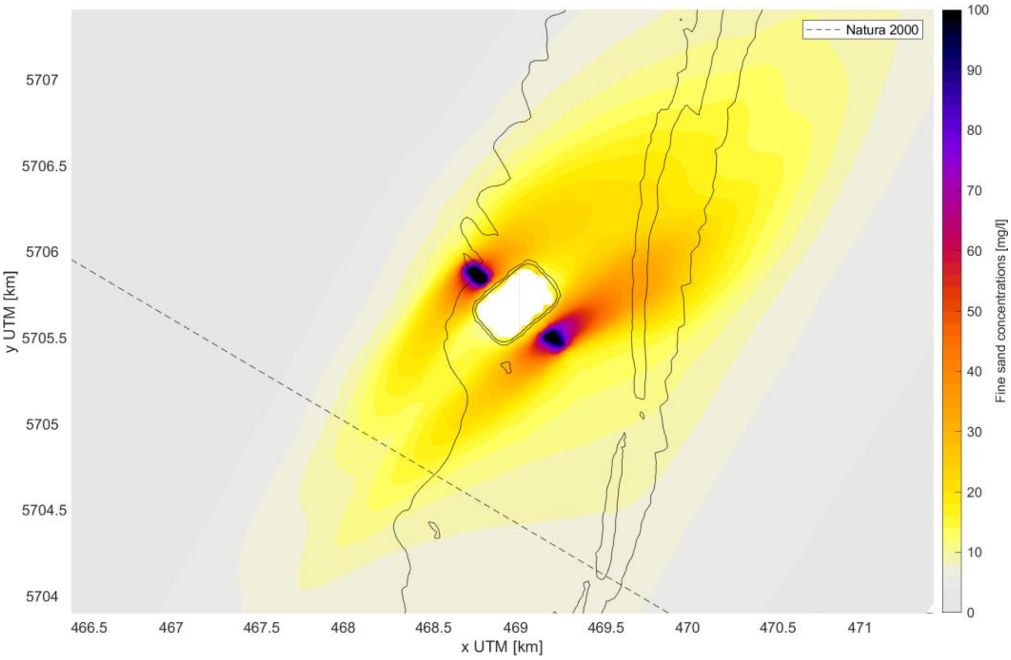


Figure 7-5: Average increase in fine sand concentration during the construction of the island at the East location

[5] Later in the design process it became clear that this is a significant overestimation for both the fine sand and the silt

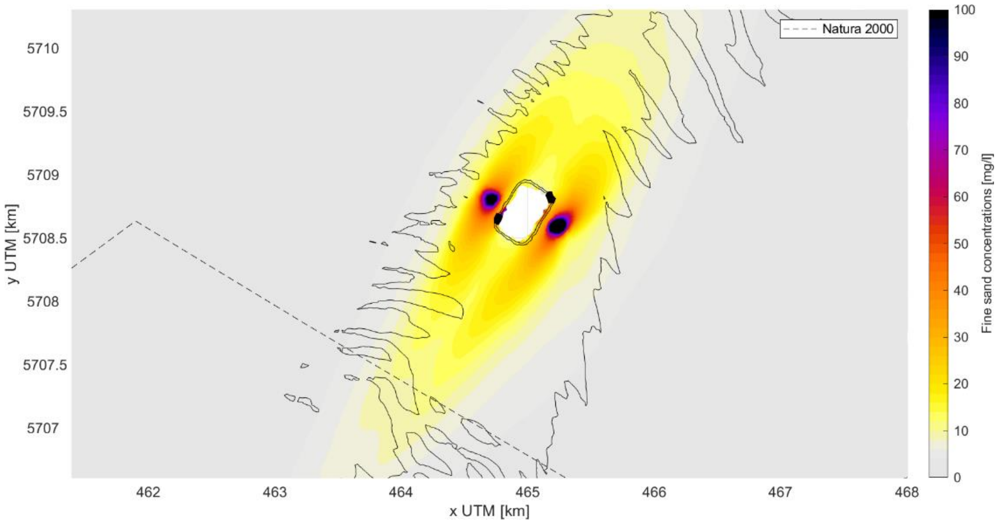


Figure 7-6: Average increase in fine sand concentration during the construction of the island at the West location

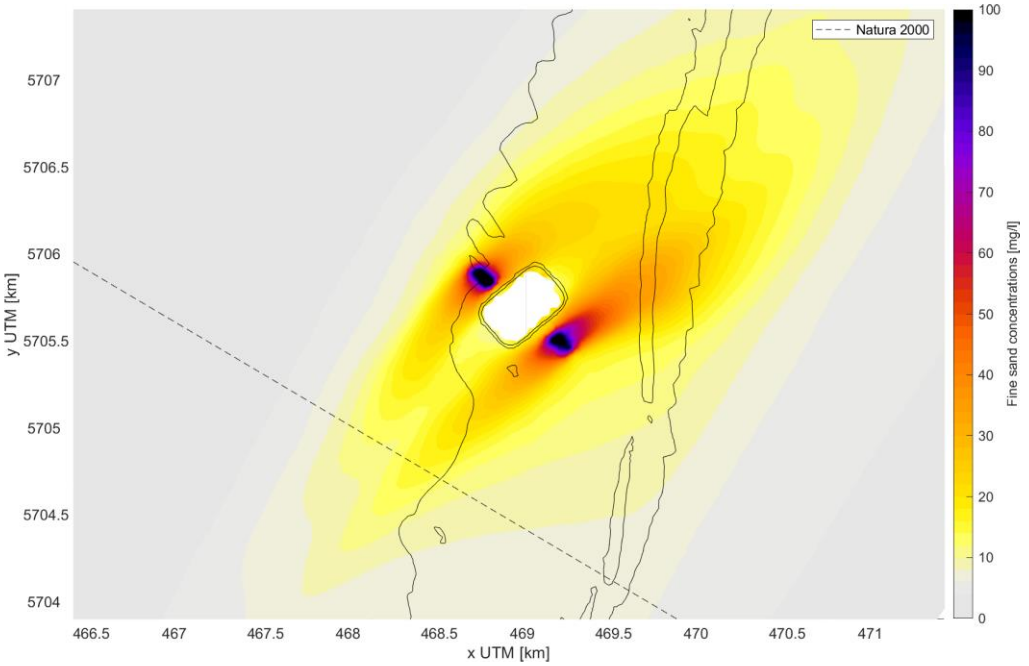


Figure 7-7 : Average increase in fine sand concentration during the construction of the island at the Noord location

It was also analysed whether the fine sand would be deposited around the island. However, it was found that only in the close proximity of the island a small layer of fine sand remains stationary after being deposited. Elsewhere, the fine sand is resuspended within the next tidal cycle, and displaced again. Thus, no severe contribution to the sedimentation on gravel beds from the fine sand is considered.

7.2.4 Silt dispersion

The average silt concentration increase around the MOG2 island during construction is shown in figures Figure 7-8 to Figure 7-10 for the three considered island locations. The impact of the release of fine sand after construction is lower than during construction, as the erosion volumes after construction are lower compared to the assumed sediment volumes required for construction. Thus, the figures after construction are not shown here. Furthermore, the erosion is spread over 1 year, whereas the construction takes place in 3 months. Thus, the image would be similar, but with lower magnitudes.

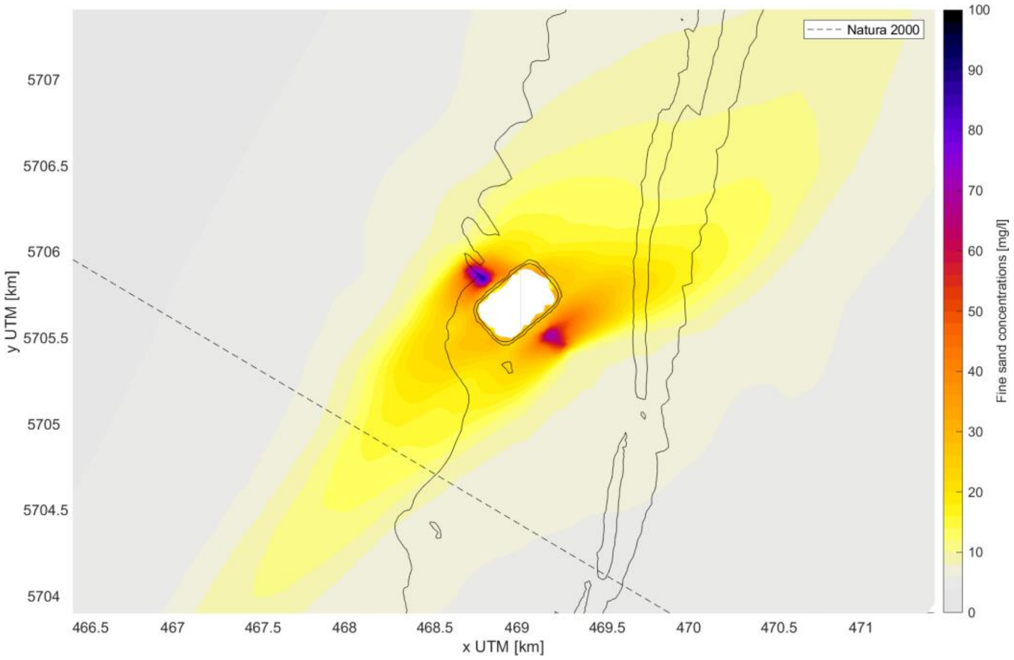


Figure 7-8: Average increase in silt concentration during the construction of the island at the East location

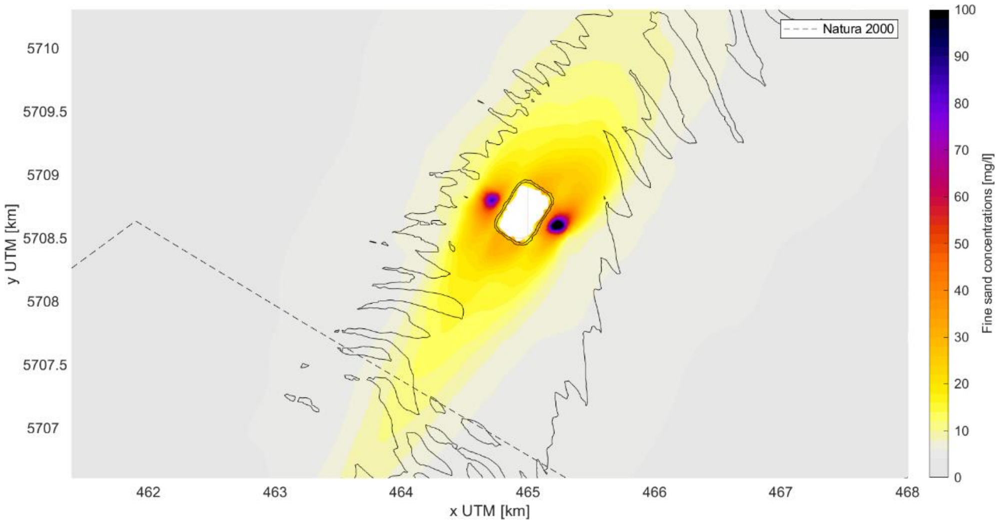


Figure 7-9: Average increase in silt concentration during the construction of the island at the West location

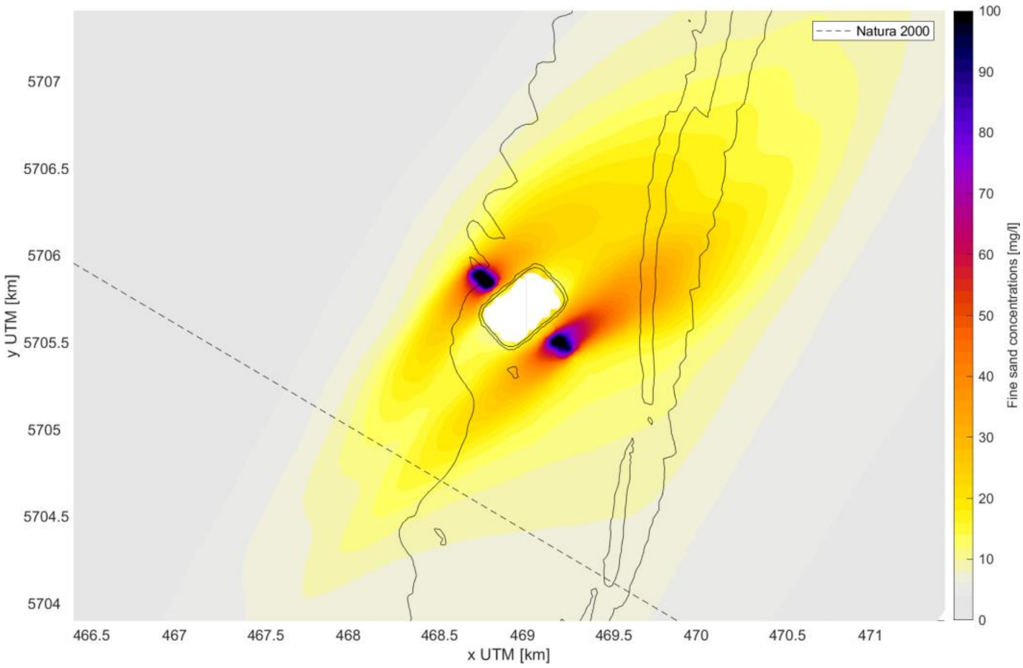


Figure 7-10 : Average increase in silt concentration during the construction of the island at the Noord location

It was also analysed whether the silt would be deposited around the island. However, it was found that only in the close proximity of the island a small layer of silt remains stationary after being deposited. Elsewhere, the silt is resuspended within the next tidal cycle, and displaced again. Thus, no severe contribution to the sedimentation on gravel beds from the silt is considered. This is consistent with the live bed conditions known to occur in the area, in reality some fine sediments may be captured between and below coarser grains.

8 ELIMINATED ALTERNATIVES

Based on the analyses that were carried out during the exploratory phase of the MOG2 project, several alternatives to the island design and location have been eliminated. The remaining options would be investigated and assessed in more detail in a later stage of the project. This chapter serves to highlight the reasoning behind the eliminations, and can also be read as a concise summary of the memorandum. The process of elimination as described below has been part of the exploratory design phase (CDR and Svašek for and in collaboration with Elia) and the early tender design phase (CDR, IMDC, and Svašek for and in collaboration with Elia). The analyses performed by Svašek Hydraulics - aimed at assessing the environmental impact - as explained in Chapter 6 and Chapter 7 were used as input for the elimination process, but were not always governing for the conclusions. For the full picture, results and considerations originating in other parts of the early design process have been added here. For more information, see IMDC, CDR, Svašek Hydraulics (2022).

8.1 Island design

8.1.1 Protective structure

It was highlighted that two options were considered for the island protective structure: a caisson solution or a revetment solution. The requirement of a vertical quay wall makes a revetment-only solution infeasible, and caissons seem the most realistic option for that vertical wall. Thus, the two considered options are 1) a caisson-only solution or a 2) combination solution. It was estimated that the costs for 1) would be significantly lower compared to 2). The primary cause for this increase in costs for the combination solution lies in the increased costs per caisson: setting up a supply chain for caissons is costly, making caissons more cost-effective the more caissons are used.

Furthermore, the island design study showed that due to the lower footprint of the MOG2 island, caisson solutions yielded less environmental impact. Thus, the caisson was chosen as the primary island protective structure and the revetment has been eliminated.

8.1.2 Island shape

The island design study showed that rounded shapes yield less environmental impact compared to rectangular shapes. As a result, a rounded shape is preferred from an environmental standpoint. However, as discussed above, caisson structures have been chosen as the island's protective structure. Rounded island shapes are more difficult to construct using the rectangular caissons. Thus, different caisson formats are required to construct the island. An indication of how this can be done is shown in Figure 8-1 for the bullet shape.

Aside from the increased production costs, the interior design of the island is less efficient using the rounded shapes, as most of the objects which are to be placed on the island have rectangular shapes. As shown in Figure 8-1, the caissons on the north side each have their own orientation, which is complex to deal with when considering the load on the caissons in the form of waves. Furthermore, the construction of the island is hampered with the new caisson design, as caissons are no longer inter-exchangeable, posing more risks during construction. It is noted that all these effects are amplified when considering even rounder shapes than the bullet in Figure 8-1, such as the pill and ellipse.

Finally, the level of rounding that can be obtained via these tapered caisson is linked to the amount of caissons available to make the curve. When considering more elongated shapes (i.e. 1:3) the amount of caissons available means a truly rounded form is more difficult to achieve. Furthermore, the rounding would be smaller (and thus less effective).

Based on these arguments, it was chosen to use a rectangular shape in combination with the caisson protection.

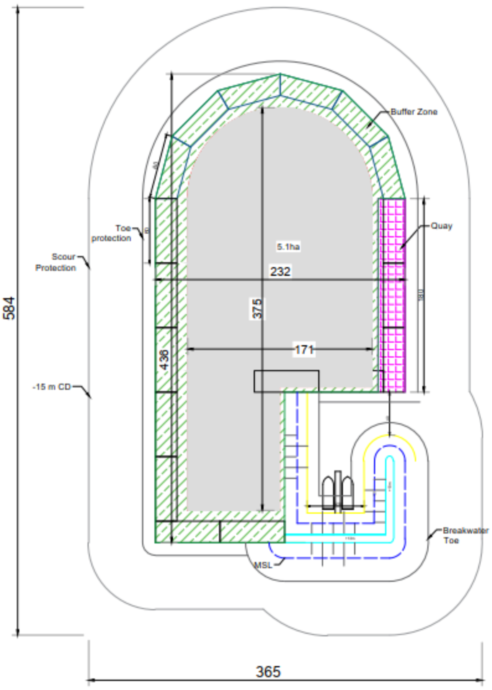


Figure 8-1: Bullet shape island design using caissons as protective structure (ultimately eliminated)

8.1.3 Island dimensions

The island design study showed that elongated shapes perform better compared to broader shapes (less impact on currents and morphology). Thus, it was decided to elongate the island as much as feasible in streamwise direction, yielding a 1:3 width-to-length ratio for the island design. The elongation is restricted to the width of the largest substation module.

As a result, the chosen island design is the CS-Rectangle-1:3.

8.2 Island location

The elimination of the island locations was mostly performed based on the impact of the island at the different locations on nearby potential gravel bed locations as defined in the 2012 and 2020 studies. Of which the 2020 locations where given most weight, because their position in the Natura2000 area means more significant restrictions on the allowed sedimentation on the gravel beds. As is evident in the overview of the gravel bed locations (Figure 7-1), the gravel bed positions within the 2020 study are significantly more scattered compared to the gravel beds from the 2012 study. Primarily close to the northern border of the Natura2000 area, several small gravel areas are found, whereas further south larger and more cohesive gravel bed structures can be found. Sedimentation should be especially avoided on these large, coherent gravel beds.

Based on the sedimentation patterns at the different island locations (Figure 7-4), it is evident the Noord location is most favourable considering sedimentation on the large, coherent gravel beds. However, the Noord location is less than ideal considering other project-related issues, especially the length of the inter-array cables, and is thus not as evident of a choice for the island location. Both the West1 and West2 location show some sedimentation of the scattered gravel bed areas towards the north of the Natura2000 area, but remain far away from the large coherent gravel bed towards the south. Furthermore, the sedimentation pattern further towards the south is patchy for both locations, indicating the zone falls outside the direct wake of the island. Considering the East and East2 locations, a clear sedimentation zone spreading towards the south of the Natura2000 area can be observed. Furthermore, the East and East2 locations are positioned significantly closer to both the border of the Natura2000 area and the large-scale gravel beds in the Natura2000 area.

Based on consultation with BMM, it was decided to eliminate the East and East2 locations based on the sedimentation patterns. It should be noted that, neither of the five locations poses a direct threat to the large-scale gravel beds from the 2020 study after one year, sedimentation zones are expected to increase in size for longer simulations.

The East and East2 locations were considered to be potentially the most harmful for the gravel beds and were thus eliminated.

8.3 Conclusion

To summarize the above: below the design aspects are listed, as eliminated in the exploratory phase and the early tender design phase.

- Perimeter protection via revetment
- Aspect ratio's less elongated than 1 :3
- Rounded caisson designs
- The East1 and East2 locations

The elimination was made in part on ecological impact considerations, and in part on considerations of planning and costs. The above has led to a caisson island with a 1:3 aspect ratio on the West1, West2 or Noord location.

9 REFERENCES

CDR & Svašek Hydraulics (2021). Explorative Design Variant Study MOGII Energy Island. PowerPoint presentation, May 12th. Reference: 2067/U21175/A/BvL

Deleu, S., Van Lancker, V., Van den Eynde, D., & Moerkerke, G. (2004). Morphodynamic evolution of the kink of an offshore tidal sandbank: the Westhinder Bank (Southern North Sea). Continental Shelf Research, 24(15), 1587-1610.

Engelund, F., & Hansen, E. (1967). A monograph on sediment transport in alluvial streams. Technical University of Denmark 0stervoldgade 10, Copenhagen K.

Glaister, P., (1993). Flux difference splitting for open-channel flows. International Journal for Numerical Methods in Fluids 16: p. 629-654.

Hervouet, J.M., (2007). Hydrodynamics of Free-Surface Flows: Modelling with the Finite Element Method. Appendix A, Tide-generating force. John Wiley & Sons.

Hughes, T.J.R., (1987). The finite element method. Englewood Cliff. New Jersey: Prentice-Hall.

IMDC, CDR, Svasek Hydraulics (2022). Assessment of alternatives (protection & layout). PowerPoint presentation.

Labeur, R.J. (2009). Finite element modelling of transport and non-hydrostatic flow in environmental fluid mechanics. Ph.D. Thesis, Delft University of Technology, Delft

Labeur, R.J., Wells, G.N. (2012). Energy stable and momentum conservative interface stabilised Finite Element Method for the incompressible Navier-Stokes equations. SIAM Journal on Scientific Computing, 34(2), A889-A913

Schrama, E.J.O., (2020). Lecture Notes on Planetary sciences and Satellite Orbit Determination. Delft University of Technology, Faculty of Aerospace, Astrodynamics and Satellite missions.

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

Van Rijn, L. C. (1984). Sediment transport. Journal of hydraulic engineering, 110(12), 1733-1754.

A NUMERICAL MODEL SET-UP

A.1 Hydrodynamic model FINEL

FINEL is a two-dimensional numerical flow model based on the finite element method. The underlying equations are the shallow water equations in combination with a hydrostatic pressure assumption and a constant density. The continuity and impulse equation read:

$$\frac{\partial h}{\partial t} + \frac{\partial uH}{\partial x} + \frac{\partial vH}{\partial y} = 0$$

$$\frac{\partial Hu}{\partial t} + \frac{\partial Hu^2}{\partial x} + \frac{\partial Huv}{\partial y} - fHv + \frac{H}{\rho}\frac{\partial p}{\partial x} - \frac{1}{\rho}\left(\tau_{x,b} + \tau_{x,w} + \tau_{x,r}\right) = 0$$

$$\frac{\partial Hv}{\partial t} + \frac{\partial Huv}{\partial x} + \frac{\partial Hv^2}{\partial y} + fHu + \frac{H}{\rho}\frac{\partial p}{\partial y} - \frac{1}{\rho}\left(\tau_{y,b} + \tau_{y,w} + \tau_{y,r}\right) = 0$$

s

In which:

H = $h+z$ the water depth (m)
h = water level (m+MSL)
z = bottom level (m+MSL)
u, v = depth averaged velocity in x- and y-direction (m/s)
f = Coriolis parameter (s^{-1})
ρ = density of water (kg/m^3)
p = $p_{atm}+\rho gH$
p_{atm} = atmospheric pressure (N/m^2)
g = acceleration of gravity (m/s^2)
$\tau_{x,y\ b}$ = bottom shear stress (N/m^2)
$\tau_{x,y\ w}$ = wind shear stress (N/m^2)
$\tau_{x,y\ r}$ = wave forces (N/m^2)

The finite element method works with triangular elements. Discontinued Galerkin (*Hughes*, 1987) is applied to solve the above differential equations. Within every element, the water level and velocity are assumed constant. The solution is found with a Riemann solver named Roe, see *Glaister* (*1993*).

In mathematical terms the Roe solver in FINEL is a first order upwind scheme. This method guarantees strict mass and momentum conservation, but suffers from some numerical diffusion in stream-wise direction. An explicit time integration scheme is used. As this method restricts the time step, the time step is controlled automatically for optimum performance.

Apart from the commonly known tidal harmonic boundary conditions along open sea boundaries, FINEL has the option of applying a tidal potential to the water mass that is present within the model area. Tidal potential accounts for the net effect of direct tidal forces exerted on the Earth by Sun and Moon; this net tidal force consists of gravitational as well as centrifugal forces, and its variation is influenced by both the motion of Sun and Moon and the rotation of the Earth. In terms of hydrodynamic modelling, tidal potential may become important as soon as the total water mass becomes so extensive that its tidal behaviour is not fully governed by mere boundary conditions anymore. This is the case if the sea/ocean model exceeds a size of typically a few 100 km's (or equivalently, a few tidal wave lengths). Physically, tidal potential is a function of a large amount of given astronomical and geophysical parameters. Two implementations of tidal potential forces are included in the FINEL package, *Hervouet* (*2007*) and *Schrama* (2020). For this project, the second implementation is used in the modelling of the flow conditions in the North Sea.

A.2 Morphological module FINEL

The morphological module of FINEL uses current velocities and orbital velocities and/or bottom shear stresses by currents and waves to calculate sand transport. Several transport formulas are available in FINEL2D, including Engelund, F., & Hansen, E. (1967), Soulsby (1997), and van Rijn (1984).

Sediment fluxes are determined every hydrodynamic time step and translated to bottom changes. These bottom changes are multiplied by the morphological acceleration factor and used to calculate the new bed level. The new bed level is used for the hydrodynamic calculation on the next time step.

A.3 North Sea FINEL flow model set-up

The Southern part of the North Sea is an area which is modelled frequently. The 2D FINEL flow model of the European Continental Shelf used for this area has been calibrated and validated for various metocean and morphological studies like Borssele, VIKING and IJmuiden Ver. Nevertheless, contrary to the model employed within the MER simulations, the model version did not yet include the Metocean calibration, which is included in later versions of the model.

A.4 Computational grid

The model domain of the FINEL North Sea flow model consists of the full European Continental Shelf, see Figure 6.1 and Figure 6.2, ensuring that the tidal and wind driven currents are well captured by the model. FINEL employs an unstructured triangular mesh, which enables the user to fit boundaries accurately within the model and to increase resolution in the region of interest in a very flexible way, without the need for nesting of grids. The grid resolution at ocean boundaries is around 8000 m and refines to 2000 m in the West part of the North Sea and the English Channel.

Several different computational grids were constructed for the explorative design study, as each potential island location requires a unique computational grid to maintain sufficient resolution around the island. Nevertheless, the idea behind the computational grid was equal for all island locations. Hydrodynamic simulations were performed on a high-resolution grid with element sizes of approximately 15 m around the island, whereas morphological simulations were performed on a grid with element sizes of approximately 40 m to maintain feasible computational effort.

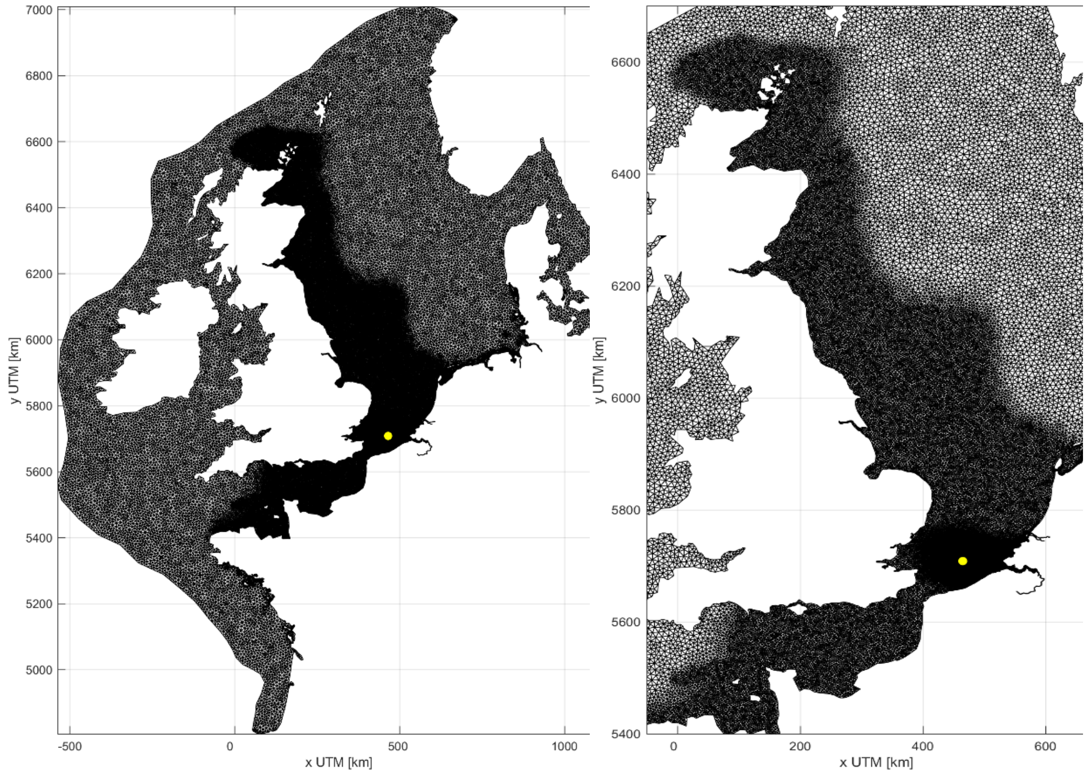


Figure 9-1: Computational grid (2D view) of FINEL North Sea flow model. The yellow dot indicates the MOG2 Island location (west).

A.5 Bathymetry

To obtain the model bathymetry, several sources are used. The bathymetry in the Irish Sea, English Channel and a large part of the North Sea is derived from the European Marine Observation and Data Network (EMODnet, 2020[6]). The Dutch model bathymetry is based on a composite bathymetry, consisting of most recent surveys by RWS and Dutch Hydrographic office. The Belgium model bathymetry is based on the combined 20 m resolution dataset available from 'Agentschap Maritieme Dienstvelening en Kust' (AMDK) last updated in 2021.

A.6 Boundary conditions and forcing

The tidal amplitudes and phases used as harmonic tidal boundary conditions are extracted from the global FES2014a[7] (32 harmonic components, 1/16° grid) world tide database. For wind and air pressure fields the CFSR dataset is used. An atmospheric pressure correction is applied on the boundary.

Additional boundary conditions are applied to accurately implement the discharge from the Rhine and Meuse River. The Eastern-Scheldt barrier is included in the model with barrier formulations including energy loss coefficients.

[6] Water depth in gridded form over whole of maritime basin on a grid of 1/8x 1/8 arc minutes which is ca 230 meter grid, see http://www.emodnet-hydrography.eu/, data update from 2020 will be used.

[7] www.aviso.altimetry.fr