EXERCISE BREAKWATER DESIGN
CASE 2025

1 INTRODUCTION

The 2025 breakwater design exercise for the units CIEM4220 and CIEM3210 will concern the Fehmarnbelt Fixed Link project between Denmark and Germany. The Fehmarnbelt is a strait in the western Baltic Sea, located between the German island of Fehmarn (near the town of Puttgarden) and the Danish island of Lolland (near the town of Rodbyhavn), at approximate geographical coordinates 54.583°N, 11.280°E, see Figure 1.

Figure 1 Project location

In its current state, Figure 2, the area is exposed to wave action from the Baltic Sea, while the ongoing construction of the immersed tunnel requires the development of temporary and permanent marine structures, including work harbours and protective breakwaters.

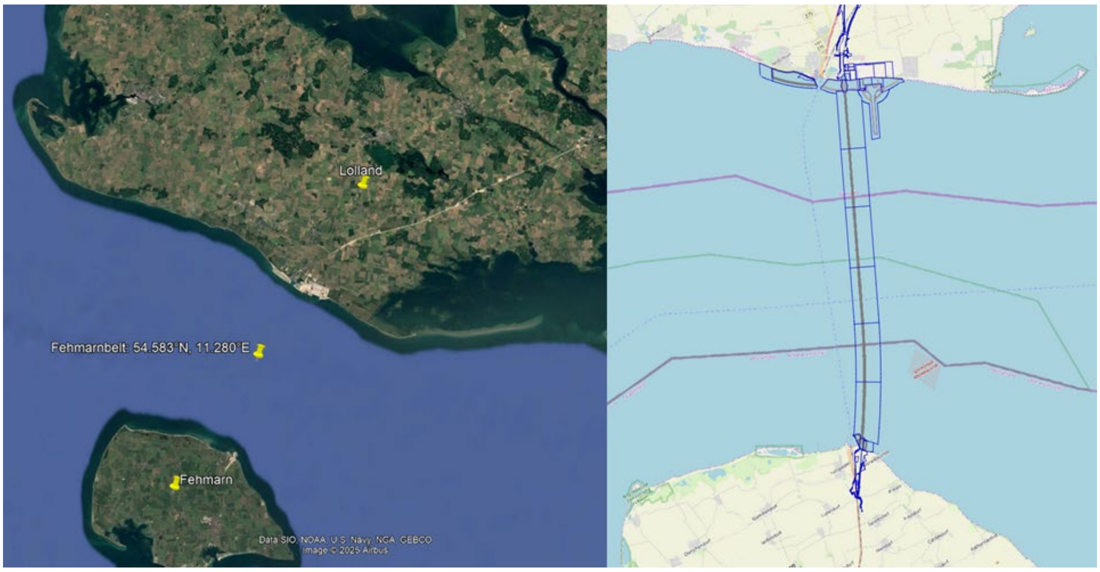

Figure 2 Present situation and general project layout

Figure 3 shows a conceptual layout of the coastal structures (breakwater and shoreline protection) and the bathymetry in the vicinity of the tunnel alignment and construction zones. On the Danish side (Lolland), the harbour breakwater extends to the south and is approximately 700 m long (red line in Figure 3), protecting a temporary working port that supports the casting and launching of immersed tunnel elements. Moreover, to facilitate the working activities and provide storage space, three reclaimed areas (purple, green and violet areas in Figure 3) will be developed on both the eastern and western sides of the harbour. On the German side (Fehmarn), the northern breakwater is approximately 520 m, providing shelter for marine logistics and limiting sediment transport into the port basin. Through the development of the tunnel trench, the dredged material trench will be used in part to create sheltered working areas. Therefore, part of the breakwater will be used as shoreline protection while the easternmost part will retain its detached breakwater functioning. The reclaimed areas are considered part of the design domain and can be assumed to be filled with quarry run and other coarse material from dredging.

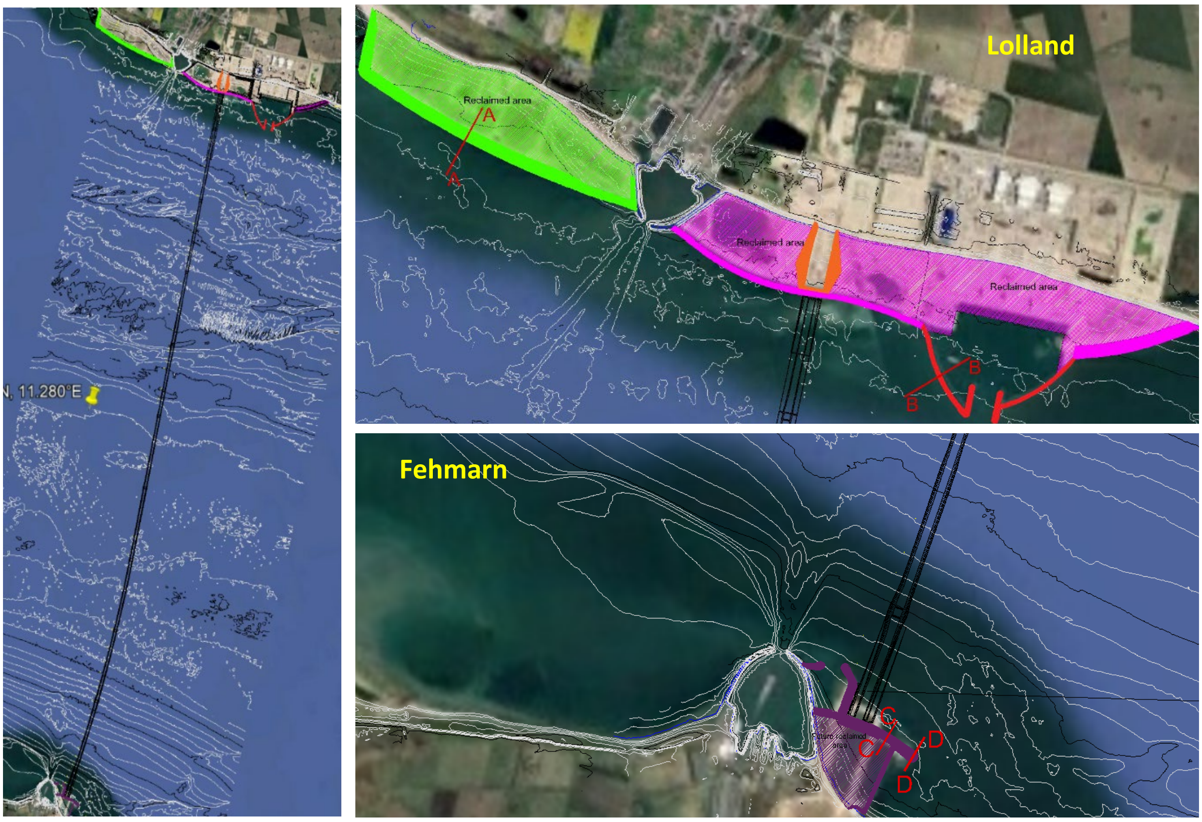

Figure 3 Project layout. The superposition of the bathymetry and satellite image is not precise and is only provided for illustrative purposes. During the design phase, the bathymetry as provided in the CAD file should be considered the official reference.

The harbour breakwater on Lolland must be designed to reduce wave transmission to the sheltered area, ensuring safe berthing and working conditions for the equipment and vessels used in tunnel element transport during operational conditions. Overtopping and wave transmission during extreme design conditions should be minimised to protect onshore equipment and the berthed working vessels. The breakwater on Fehmarn should ensure safe working conditions along the crest of the breakwater for moving work machinery during operational conditions. During extreme design conditions, operational activities may be halted, but the structural stability of the breakwater must be guaranteed.

Your assignment is to make a conceptual design for a section of the breakwater or shoreline protection. We have modified some of the boundary conditions. Hence, your assignment is based on the real project, but it is not exactly the same.

2 BOUNDARY CONDITIONS

2.1 Wave conditions

We have performed a Peak-over-Threshold (PoT) and Extreme Value Analysis (EVA) for the location presented in Figure 4. Water level and Significant Wave Height (H_{m0}) EVA were performed for both directional and omnidirectional data; the results are provided in the appendix for the extraction point P2. You can use this information to determine your own design conditions. Note that you will still need to do some analysis on your own; for example, you must decide which return period to apply, which corresponding wave period as well as the possible effects of the shallow area in front of the breakwaters, but you can do that on the basis of the information provided here and the bathymetry. You do not have to conduct your own PoT and EVA analysis. However, you are allowed to do so if you wish and can find the available data.

An overview of the extraction points locations, along the tunnel and near the sites, is given in Figure 4.

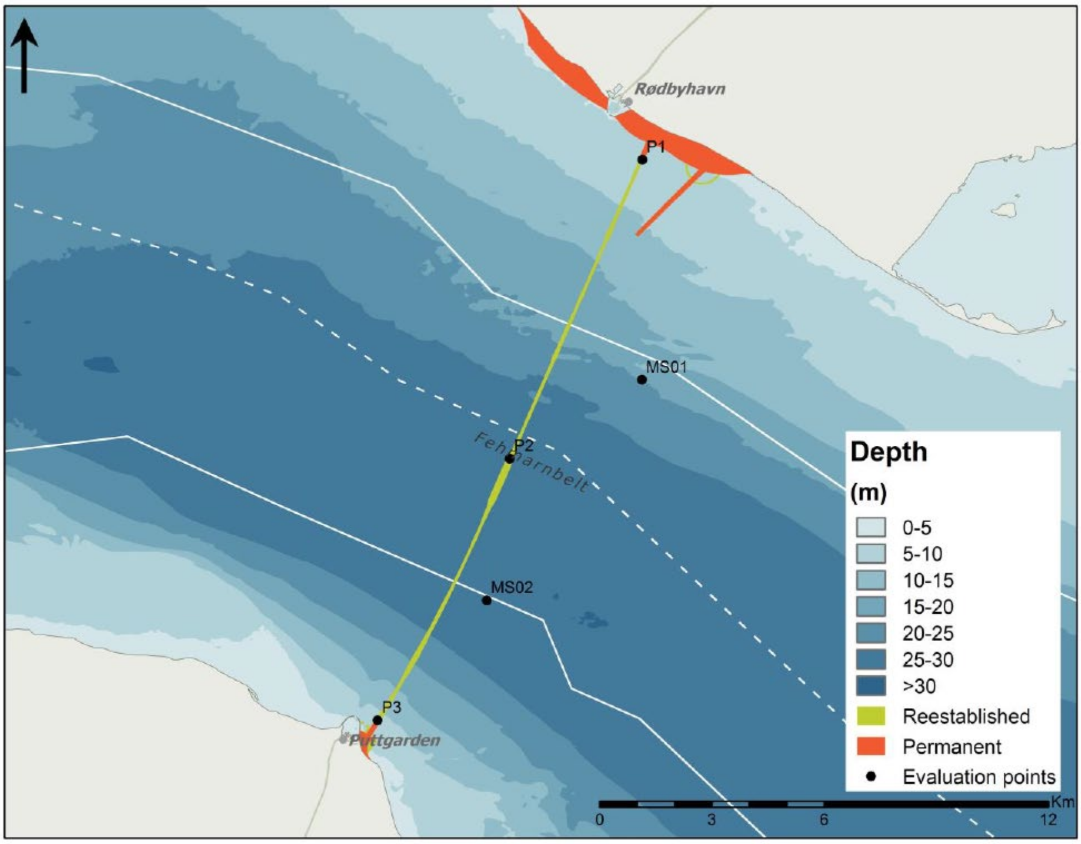

Figure 4 Location of the extraction points

2.2 Meteorological background to water depth, wave heights and their correlation

The Fehmarnbelt Fixed Link project involves two coastal locations: Rødbyhavn (Denmark) and Puttgarden (Germany). These two shorelines behave differently in terms of extreme water levels due to both geographical and meteorological factors. Water level records and analyses were performed using long-term datasets at Rødbyhavn (1955–2012) and Marienleuchte, near Puttgarden (with records from 1872). A significant finding is that water level extremes, both high and low, are not symmetric between the two sides of the Belt.

At Rødbyhavn, extremes are typically larger than at Puttgarden. This difference is largely attributed to the Coriolis effect: easterly storms generate higher water levels on the Danish coast and lower levels on the German coast, while westerly winds do the reverse. This directional asymmetry leads to amplified water level excursions at Rødbyhavn compared to Marienleuchte/Puttgarden.

Additionally, the Baltic Sea system behaves like a lake basin in terms of water level set-up and set-down. For westerly winds, water is blown into the main basin leading to a set-down at the project site. For easterly winds the effect is reversed leading to set-up at the project site. The most extreme low water levels, such as the event in December 1999, are associated with strong westerly winds causing a significant outflow of water from the western Baltic. As a result, the correlation between extreme wave heights and extreme water levels is complicated at this site. As a first-order estimate, you can assume that extreme waves from southerly or westerly directions are associated with extreme low water levels of the same return period, while extreme waves from northerly or easterly directions are associated with extreme high water levels of the same return period. This is, however, an oversimplification. For a better estimate, please refer to the scatter plots in Figure 6. These provide a more detailed correlation between wave heights and water levels for the various wave directions. A complete analysis would require you to calculate the *joint* probability of occurrence of all these combinations (those are the coloured isolines on the plots), but that is outside the scope of this assignment. You can simplify your analysis to (1) choosing an appropriate extreme wave height according to your selected return period, and (2) finding an associated water level that corresponds to this wave height using the information in the scatter plots.

In summary, both shorelines of the Fehmarnbelt must be treated individually due to their differing responses to storm events. Moreover, the occurrence of negative water level extremes due to basin-wide oscillations in the Baltic Sea represents a key design challenge for the Fixed Link.

Water depth information can be found in the available CAD bathymetry (*Fehmarn Belt - Case Study - Bathymetry.dwg*). The local vertical reference level is called FCSVR10 (Fehmarnbelt Coordinate System Vertical Reference 2010) and is applied for both the German and Danish coasts. The mean sea level (MSL) is actually +0.00 m FCSVR10.

This is a microtidal area, where tidal variations generally do not exceed ±0.10 m. The designer is responsible for properly accounting for the forecast Sea Level Rise within the design life of the structures.

2.2.1 Extreme water levels at Rødbyhavn

An integrated analysis of extreme total (tide + meteorological) high water levels at Rødbyhavn was conducted by merging observed data (1955–2012) with historical storm records, including significant events such as the 1872 and 1760 storms. Two different statistical populations are identified: one for frequent events (water levels below 1.5 m), which are well captured by observations, and another for rare, extreme events (above 1.5 m), informed by historical data. An exponential distribution is used for the lower-level events, while a Weibull distribution is applied to the more extreme levels. The results are presented in Table 1 and Figure 5.

Table 1 Extreme high water level at Rødbyhavn. L_B: Lower bound; B_E: Best estimate; U_B: Upper bound.

Return period [years]	Water level [m FCSVR10]		
	L_B (5%)	B_E	U_B (95%)
1	1.08	1.08	1.09
10	1.39	1.47	1.54
50	1.82	1.98	2.24
100	2.01	2.21	2.54
1000	2.58	2.92	3.50
10000	3.08	3.55	4.39

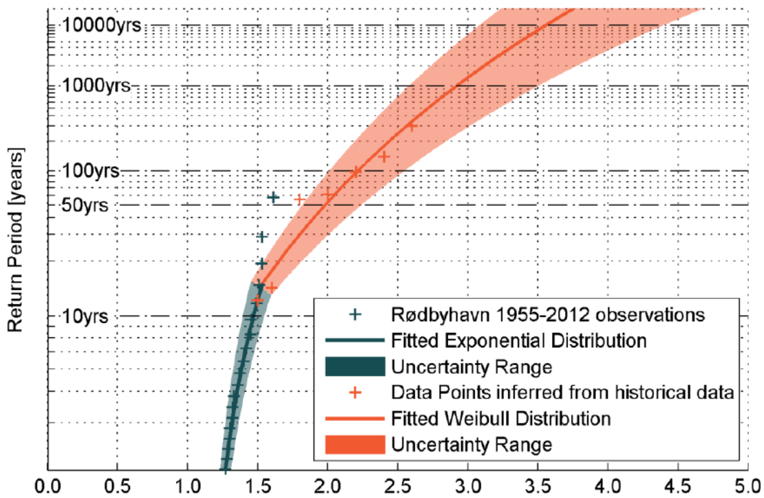

Figure 5 Extreme high water level at Rødbyhavn 90% confidence limits.

Extreme low water levels at Rødbyhavn are caused by strong westerly winds that push water out of the western Baltic Sea. Although such winds are common, only particularly intense events lead to significant drops in sea level, such as the -1.24 m FCSVR10 recorded during the December 1999 storm. Due to the limited data available (1992–2012), this analysis also took into account the longer records from nearby Gedser, which include historical extremes. A Gumbel distribution was fitted to annual minima to estimate return levels, and the uncertainty of the estimate was assessed using a bootstrap resampling procedure. The results are presented in Table 2 and Figure 6.

Table 2 Extreme low water level at Rødbyhavn

Return period [years]	Water level [m DVR90]		
	L_B (5%)	B_E	U_B (95%)
1	-0.97	-1.04	-1.14
10	-1.34	-1.55	-1.72
50	-1.59	-1.93	-2.18
100	-1.70	-2.08	-2.38
1000	-2.04	-2.61	-3.02
10000	-2.38	-3.13	-3.66

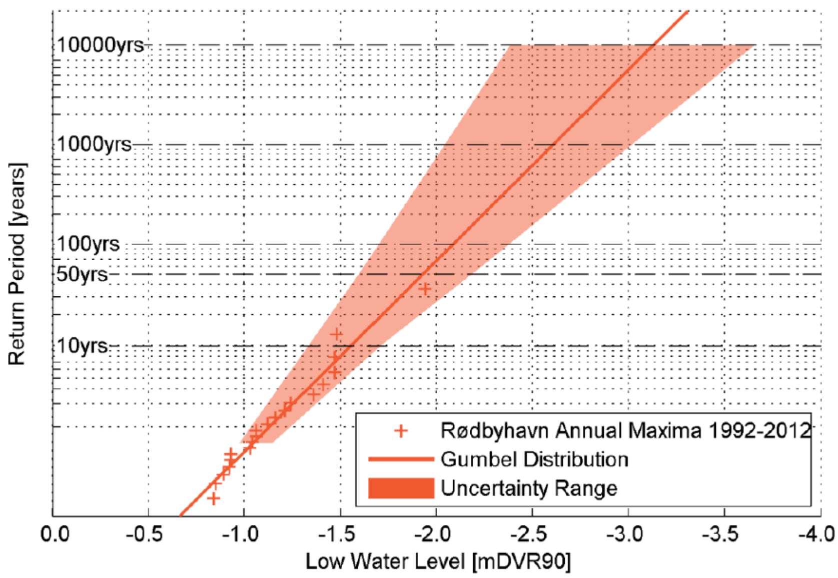

Figure 6 Extreme low water level at Rødbyhavn and 90% confidence limits.

2.2.2 Extreme water levels on the German Coast

Due to the limited and low-quality data available at Marienleuchte (near Puttgarden) from August 2007 to November 2008, a full extreme value analysis for the German side of the Fehmarnbelt could not be performed. However, a comparison between simultaneous water level measurements at Rødbyhavn (Denmark) and Marienleuchte (Germany) showed that extreme water level variations (both high and low) are typically about 10% greater at Rødbyhavn. This difference is attributed to the hydrodynamics of the Fehmarnbelt, including the Coriolis effect. During high-water events, easterly winds push water westward, causing setup on the Danish coast and setdown on the German side. Conversely, low water events driven by westerly winds produce the opposite effect. As a result, it is recommended to apply a correction factor of ±0.1 m to estimate water levels at Puttgarden, using the more complete data from Rødbyhavn.

A comparison of the simultaneous observed water levels at Rødbyhavn and Marienleuchte is presented in Figure 7 and can be used to apply the correction factor.

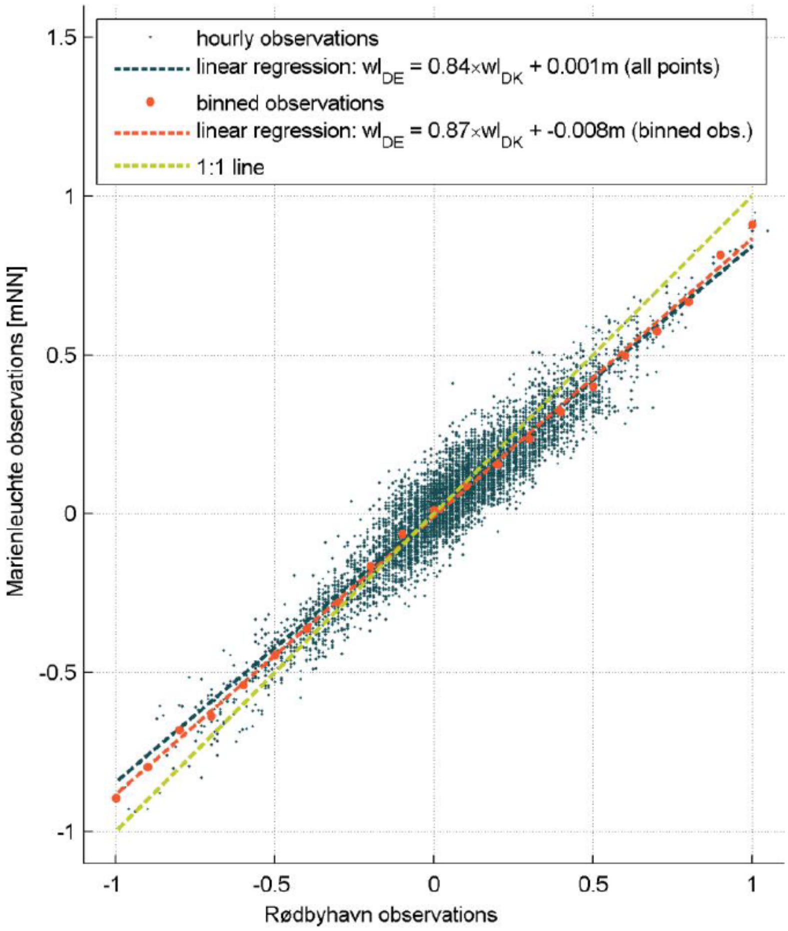

Figure 7 Comparison of observed water levels (FCSVR10) at Rødbyhavn and Marienleuchte, Jan. – Nov. 2008.

2.3 Nearshore wave conditions and water depth

The provided design wave conditions are given for a water depth of 22 m (P2); you will need to create your own wave propagation. Moreover, the wind intensity and direction are also provided in Table 3.

Table 3Extreme estimate of U_{10}

P2	Direction								Omni		
T_R [years]	N	NE	E	SE	S	SW	W	NW	BE	LB	UB
1	13.3	14.2	15.7	15.2	15.0	18.4	20.4	17.3	21.0	20.4	21.7
10	17.8	17.6	19.0	17.2	18.5	23.6	24.7	21.6	25.6	24.0	26.5
50	21.5	21.3	21.1	22.0	22.6	26.3	27.5	26.2	29.2	26.2	32.2
100	23.2	23.0	22.8	23.6	24.2	27.7	28.8	27.6	30.4	27.2	33.8
1000	28.0	27.9	27.7	28.4	28.9	31.9	32.8	31.8	34.3	29.8	38.8
10000	32.2	32.1	31.9	32.5	32.9	35.6	36.4	35.5	37.8	32.2	43.2

2.4 Geotechnical boundary conditions

You can assume that the bearing capacity of the subsoil is sufficient to carry the breakwater without any deformations or settlements. A geotechnical stability assessment is not part of your assignment. The natural bottom material can be assumed to be sand.

3 ASSIGNMENT DETAILS

3.1 Section to be designed

Both breakwater and coastal protection structure are required for the realisation of the immersed tunnel. The required structures are both temporary and permanent, including work harbours and protective breakwaters. Among these structures we have identified 4 sections that will be designed in the assignment. You will have to design one of these depending on your group number. The 4 sections are shown in Figure 8.

- **Section A (Lolland side)**: is the trunk section of the structure protecting the reclamation behind. During the working period, the reclaimed area will be used to store working machinery and tools, while after the conclusion of the work, this area will be used for a commercial area expansion.
- **Section B (Lolland side):** This is the trunk section of the breakwater that will be built to protect the work harbour, located in relatively deep water. The breakwater is designed to ensure acceptable working conditions inside the basin during operational conditions and to provide safe berthing points during extreme events throughout the project's operational period. The internal agitation within the harbour basin will result solely from wave transmission through the breakwater, with no significant penetration occurring at the port entrance.
- **Section C (German side):** is the trunk section protecting the future reclaimed area, while preliminary serving as main passage for the working machinery during the initial phase. At the end of the work there will be reclaimed land behind it for a future commercial area expansion.
- **Section D (German side)**: is the roundhead section of the future breakwater for Puttgarden harbour, while preliminary serving as the main passage for the working machinery during the initial phase. At the end of the work there will not be reclaimed land behind it.

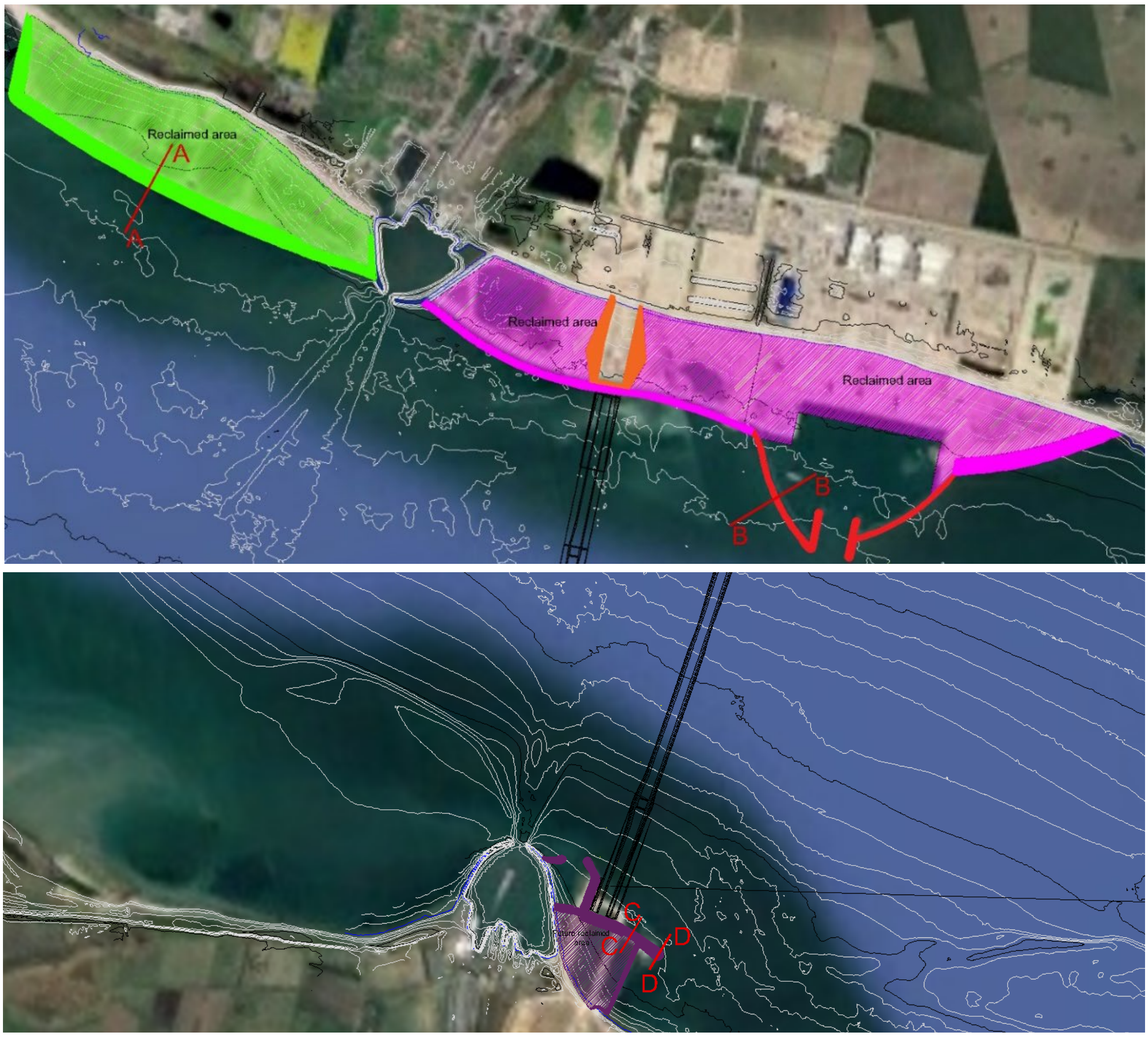

Figure 1: Sections to be designed

You must derive your own design criteria for all the relevant failure modes

3.2 *Lifetime and breakwater type*

You will need a specification of the design lifetime of the breakwater in order to select your design return period. This is either 25 or 75 years, depending on your group number. The duration of the work can be estimated as 7 years. You will have to design a breakwater of any of the following types, depending again on your group number, see Table 3.

Table 4 Group design specification

Design life	**25**				**75**			
Section	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**
Statically stable rock breakwater	**HE1**		**HOS8**			**HOS2**	**HOS9**	**HOS6**
Single layer concrete elements		**HE4**		**HE6**	**HE2**			**HOS4**
Double layer concrete elements		**HE8**		**HOS5**		**HE3**		**HE5**
Block revetment	**HE7**		**HOS3**		**HOS1**		**HOS7**	

- For Sections A and C, you should provide the drawing of your cross-section and the reclaimed land. Moreover, the construction method(s) and sequence should take into account the presence of the reclaimed land.

3.3 Assignment requirements

Your assignment is to make a conceptual design for the assigned section. We have changed some of the boundary conditions. **So, your assignment is based on the real project, but the conditions and requirements are not exactly the same!**

After the exercise is completed, two members of the consortium, responsible for the marine works (Boskalis and Van Oord) will deliver a guest lecture about the design and construction of the real project; you will then see how it was actually designed and constructed. The presentation is scheduled for early afternoon on **Friday 27th June**, the exact time will be announced on Brightspace.

3.4 Deadline

HOS – CIEM4220: 24-6-2025 at 18:00. The reports should be sent to a.antonini@tudelft.nl and b.hofland@tudelft.nl. Please put all the group members in Cc and clearly specify whether you are HOS or HE students.

HE – CIEM3210: 20-6-2025 at 23:59. The reports should be sent to a.antonini@tudelft.nl and b.hofland@tudelft.nl. Please put all the group members in Cc and clearly specify whether you are HOS or HE students.

HE students will need to present the design work on 25-6-2025. The presentations will be held in two parallel sessions during the afternoon. Your attendance is compulsory for the entire session, not just for your own presentation. The presentation schedule for each group will be provided later in Brightspace and communicated during the lecture. You are expected to actively contribute to the discussions about the designs presented by the other groups.

3.5 Further details

Other details related to the exercise, the steps you need to take, the questions you need to answer, the deliverables you need to produce, the assessment criteria, the time schedule, and the organisation can be found in the "General description" document.

4 ACKNOWLEDGEMENTS

This exercise is based on the Fehmarnbelt Fixed Link project, which is under execution by the Joint Venture composed of Van Oord and Boskalis. We wish to thank them for allowing this case to be presented and for providing valuable information.

5 APPENDIX

5.1 Wave Point 2

- Data period: 1/2/1994 – 31/01/2012 - Declustering time 36 hours - n. event/year 3.5 - Water depth 29 m - Weibull distribution - Bootstrap confidence interval 2000 realisations										B_E: Best Estimate L_B: 5% Lower Bound U_B: 95% Upper Bound		
P2		**Mean Wave Direction**								**Omnidirectional**		
TR [years]	**Parameters**	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**	**B_E**	**$L_{B\ (5\%)}$**	**$U_{B\ (95\%)}$**
TR = 1	**Hm0 [m]**	**0.8**	**0.8**	**1.5**	**1.8**	**1.4**	**1.3**	**2.5**	**1.7**	**2.5**	**2.4**	**2.6**
	Tp [s]	3.5	3.2	5.3	5.5	5.0	4.7	6.3	5.4			
	Tm-1,0 [s]	3.1	2.9	4.8	5.0	4.5	4.3	5.7	4.9			
TR = 10	**Hm0 [m]**	**1.2**	**1.1**	**1.9**	**2.2**	**1.9**	**1.8**	**3.3**	**2.1**	**3.3**	**3.0**	**3.5**
	Tp [s]	4.1	3.7	5.8	6.0	5.6	5.2	6.9	5.9			
	Tm-1,0 [s]	3.7	3.3	5.2	5.4	5.1	4.7	6.2	5.3			
TR = 50	**Hm0 [m]**	**2.0**	**1.8**	**2.3**	**2.8**	**2.4**	**2.6**	**3.8**	**3.2**	**3.8**	**3.4**	**4.3**
	Tp [s]	5.0	4.5	6.2	6.6	6.1	5.7	7.3	6.7			
	Tm-1,0 [s]	4.5	4.0	5.6	6.0	5.5	5.2	6.6	6.1			
TR = 100	**Hm0 [m]**	**2.2**	**2.0**	**2.5**	**3.0**	**2.6**	**2.7**	**4.0**	**3.4**	**4.1**	**3.6**	**4.6**
	Tp [s]	5.2	4.6	6.5	6.8	6.3	5.8	7.5	6.9			
	Tm-1,0 [s]	4.7	4.2	5.8	6.2	5.7	5.3	6.7	6.2			
TR=1000	**Hm0 [m]**	**2.7**	**2.5**	**3.2**	**3.8**	**3.2**	**3.3**	**4.7**	**4.0**	**4.7**	**4.0**	**5.5**
	Tp [s]	5.7	5.1	7.1	7.5	6.9	6.1	7.9	7.3			
	Tm-1,0 [s]	5.2	4.6	6.4	6.7	6.2	5.5	7.1	6.6			
TR=10000	**Hm0 [m]**	**3.2**	**3.0**	**3.8**	**4.5**	**3.8**	**3.7**	**5.3**	**4.6**	**5.4**	**4.4**	**6.3**
	Tp [s]	6.1	5.5	7.7	8.0	7.3	6.4	8.3	7.7			
	Tm-1,0 [s]	5.5	4.9	6.9	7.2	6.6	5.7	7.4	6.9			

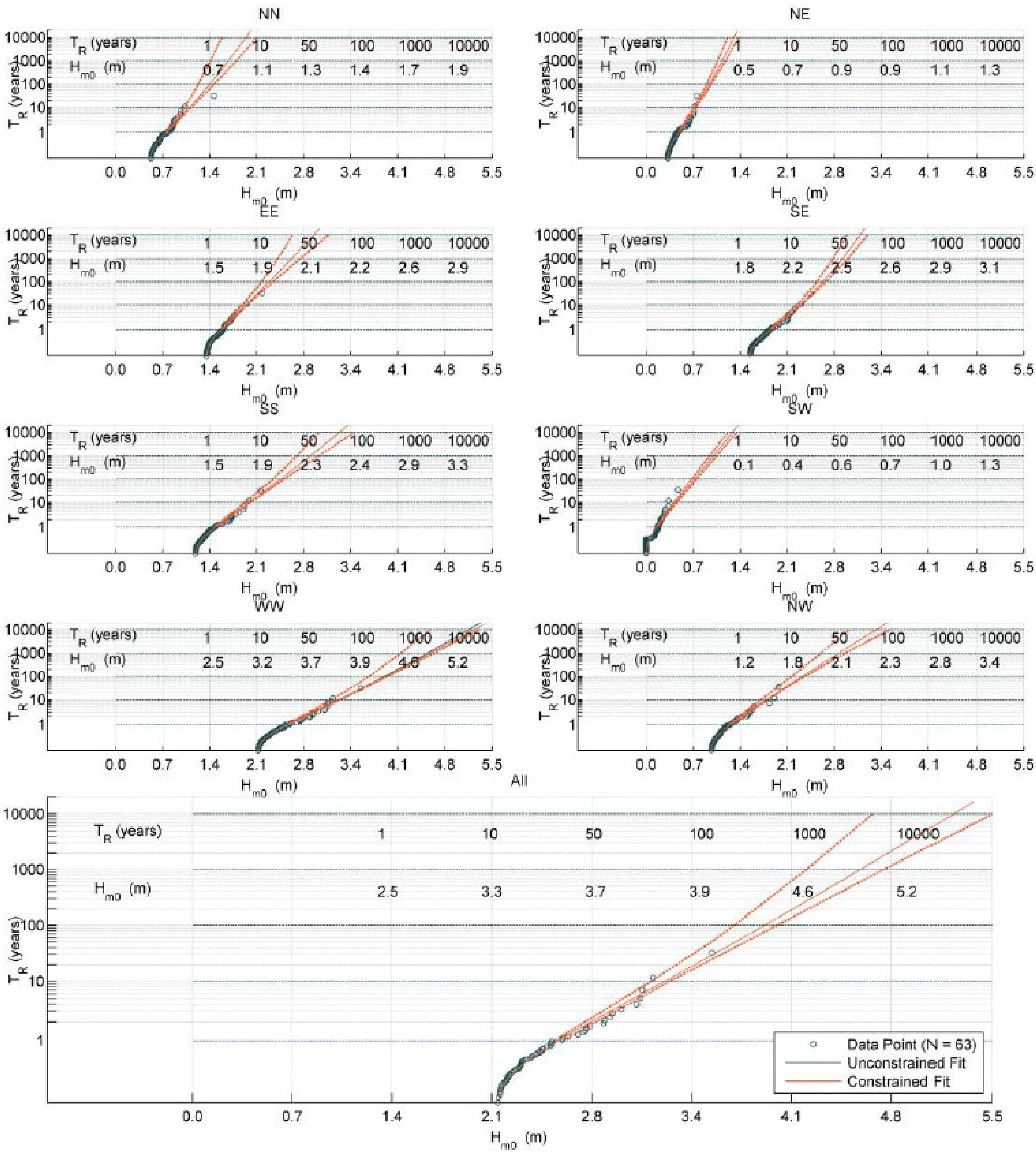

Figure 2 Extreme value distributions, Conf. interval 32 – 68 %

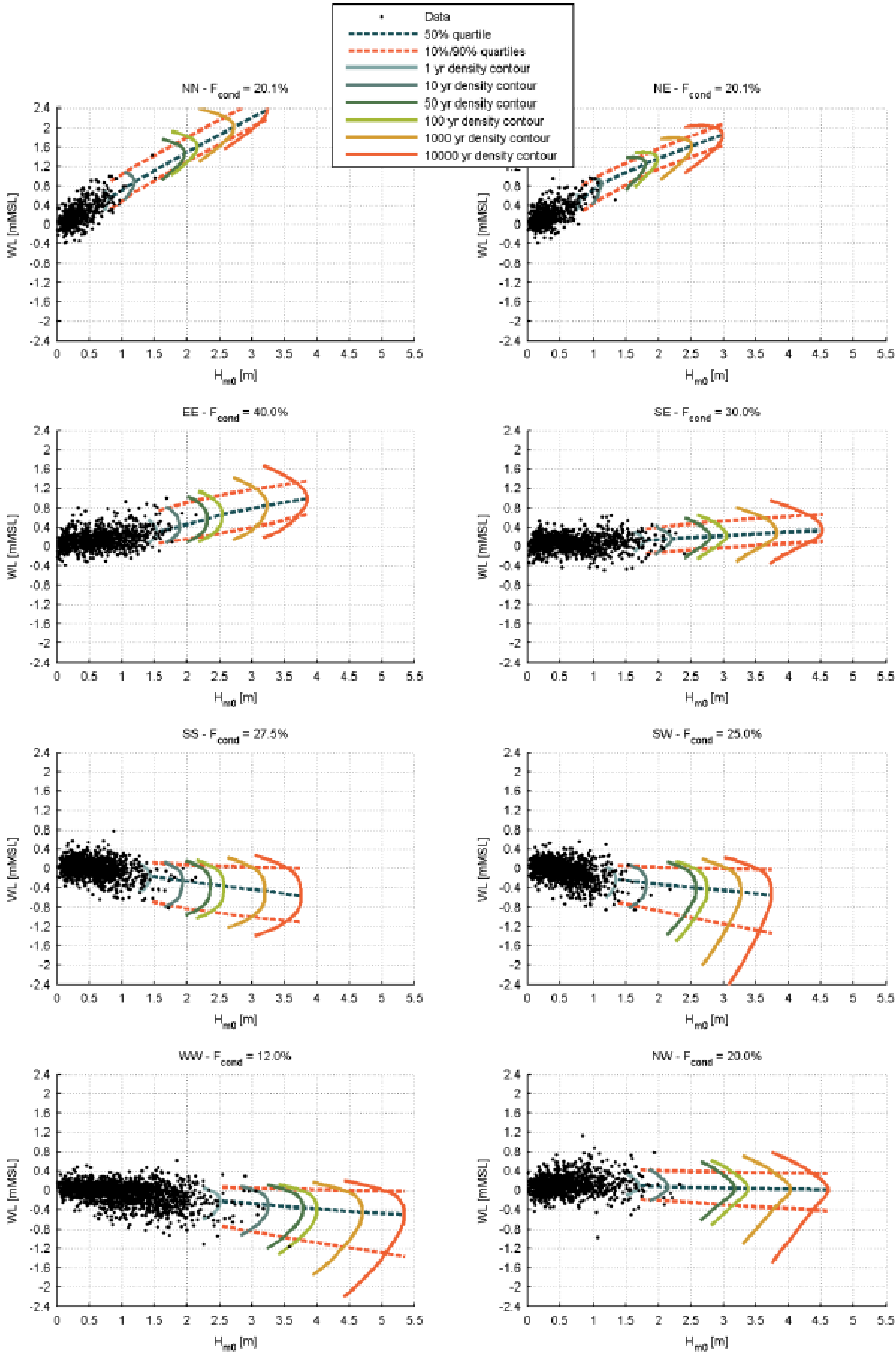

Figure 8 Joint occurrence analysis results – P2 directional H_{m0} vs associated water levels