Wave conditions at the Danish study site locations

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In the DELOS delivery no. 12 for WP2.5 "Prototype observations in Denmark" the Danish study site locations were described with respect to geometrical layout, materials and hydrodynamic conditions (waves, tide/water level variations, currents and sediment transport). In the report only rough estimates for the wave heights (typical and maximum) were given at the Danish study sites *Lønstrup* and *Skagen*. The purpose of this note is to give a more detailed description of the normal wave climate at the breakwater locations. At the study locations ecological field investigations have been carried out by the Danish DELOS partner BIAU. This subsequent description and the parameters given in the delivery no. 12 are used in the study of correlations between hydrodynamic conditions and ecology. The intension is to compare the sites with respect to the physical exposure of the ecological organisms caused by waves.

1 Introduction

A wave height calculation based on fetch limitations, wind speeds and wind directions is carried out at deep water depth for the two sites. The transformation in wave height distribution from deep water to shallow water is calculated by the point model proposed by Battjes and Gronendijk, 2000. Battjes and Gronendijks model is developed for wave height distributions on shallow foreshores, and it takes account for water depth and foreshore slope. The given significant wave heights are incident significant wave heights. The wave heights does therefore not include influences of reflections from structures and beach.

Strong on-shore winds in connection with low-pressures create high water levels by the coast and thereby higher waves. The rise in water level, called *storm surge*, is more than +0.8m occurring approximately 4 times per year. During the storms the maximum wave height is increased with approximately 0.5m by the structures. It is estimated that there will be set-up due to wind and low pressure in approximately 1% of the time. Very strong on-shore storms can create storm-surge up to +1.5m above MSL, and off-shore winds can give water levels -1.0m below MSL. These events hardly ever occur. The rare events are not included in the present calculation, as the focus of this report only is on the normal wave climate.

The tides at Skagen and Lønstrup have some influence on the water depth and thereby at the waves. The mean low water level to mean high water level at springs are approximately 0.3m. However, in general the change in water level is small compared to the total water depth, and the waves will therefore only be slightly smaller during low tide and slightly higher during high tide. The following calculation of waves does not take the influence of tide into account. If the tide was taken into account a slight increase in significant wave heights at both study sites can be expected.

2 Water depth and bottom slope

The following figures are from the delivery no. 12.

2.1 Lønstrup

The steepness of the bottom slope is approx. 1:150 (see Figure 1) and the water depth on the offshore side of the breakwaters is according to Figure 2 approximately 1m. It is clear that the breakwaters are built in very shallow water, and that the largest waves therefore are depth limited.

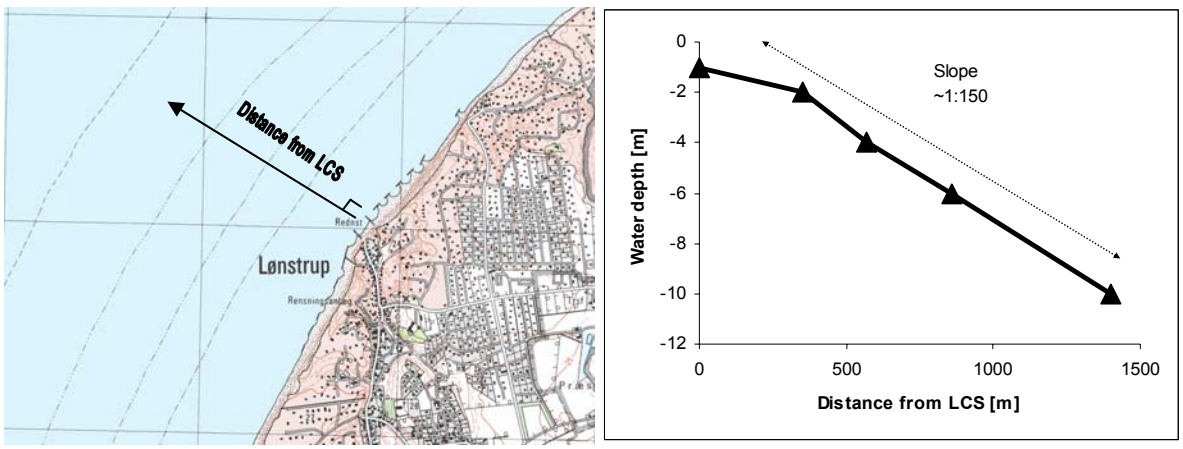

Figure 1 Bottom topography at Lønstrup (left: one square on the map = 1km^2)

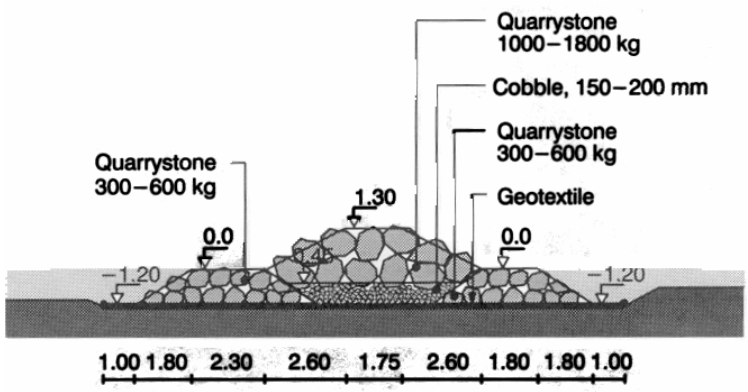

Figure 2 Cross-section of breakwaters at Lønstrup (Laustrup & Madsen, 1994)

2.2 Skagen

The water depth on the offshore facing side is approximately 1m, and the steepness of the bottom slope is approx. 1:100 close to the breakwaters (up to approx. 500m from the beach), see Figure 3 and Figure 4.

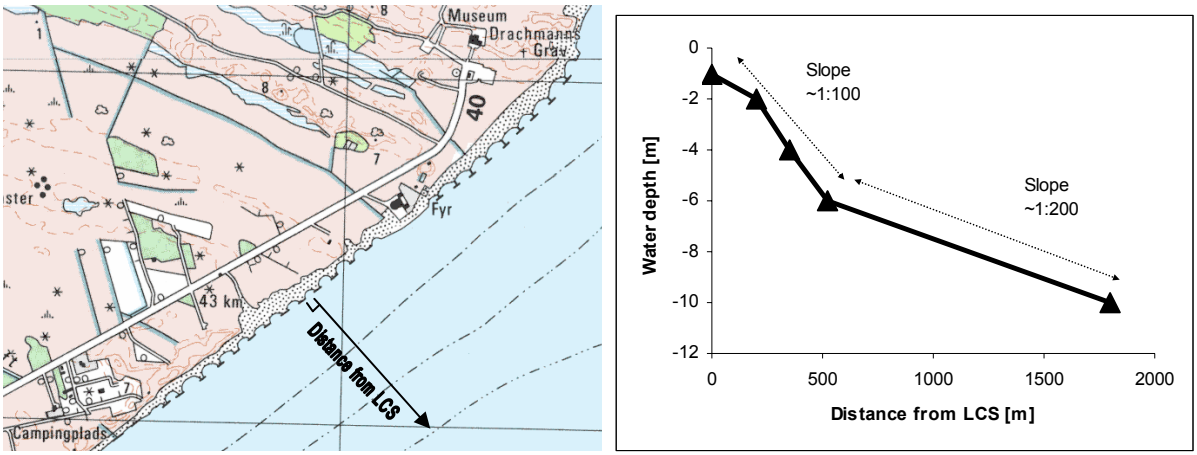

Figure 3 Bottom topography Skagen (left: one square on the map = 1km^2)

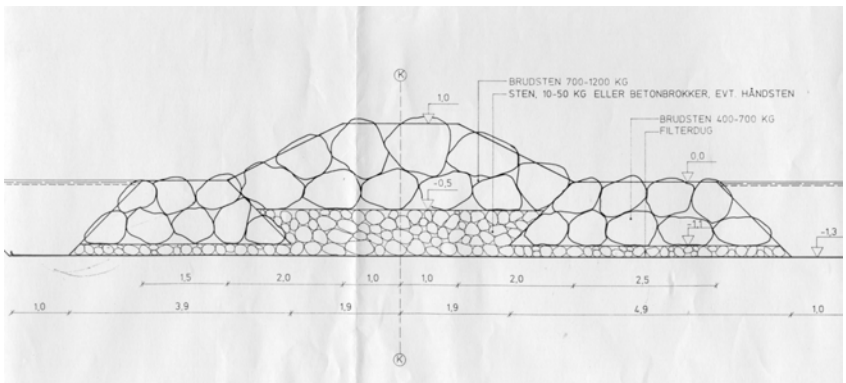

Figure 4 Typical cross-section of Skagen breakwaters

3 Wind speeds and directions

Distributions of wind speed and wind directions for each month in the year can be found in Frydendahl, 1971. Data are given for a number of recorded stations (usually data have been observed from light houses).

In Lundtang Petersen et al, 1980, a method based on a standard set of wind frequencies for the whole Denmark is given. A set of correction factors depending on height and surface roughness (type of landscape) is used to calculate the wind speeds at a given location.

3.1 Lønstrup

At Hirtshals Fyr winds have been observed in the period 1931-1960 (missing Oct. 1943 - May 1945) at the height 27m above sea level. Lønstrup is located very close to Hirtshals, and the Hirtshals data can therefore be used for Lønstrup. In Figure 5 (left) it is seen that the directional distribution according to Lundtang 1980 and Frydendahl 1971 are the same. It is also clear that the winds are mainly coming from the West (W) and South West (SW).

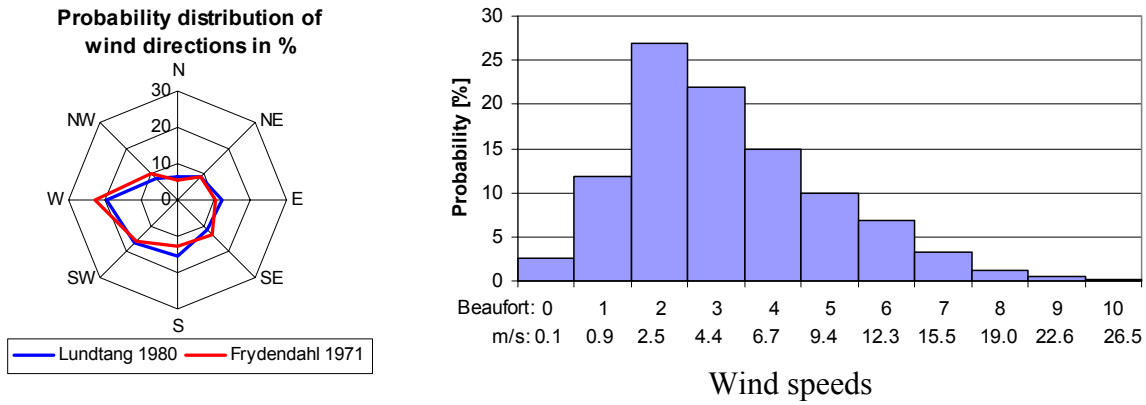

Figure 5 Distribution of wind at Lønstrup. Directions (left), and speed (right, according to Frydendahl 1971).

Winds coming from N, NW, W, and SW will produce waves at Lønstrup, which will refract and hit the coast perpendicular. It is assumed that winds from the other directions only will produce very small waves.

3.2 Skagen

At Skagen the wind speed distribution from Hirtshals is used to ensure consistency. The directional distribution according to Frydendahl, 1991 for Hirtshals is compared to a calculated distribution by the method in Lundtang Petersen et al, 1980. In Figure 6 it is seen that the two distributions are the same.

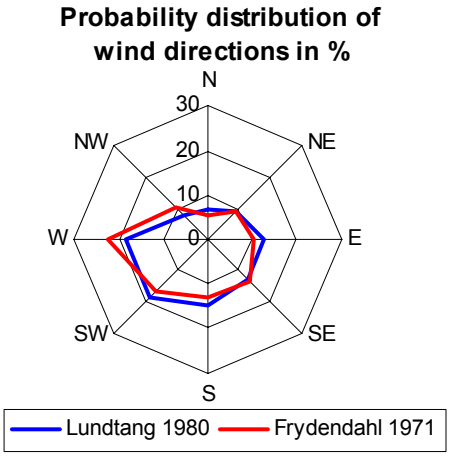

Figure 6 Directional distribution of wind at Skagen.

4 Fetch limited wave heights at *deep water*

Lønstrup is located on the West coast and Skagen on the East coast of Denmark, see Figure 7. At Lønstrup waves coming from the West can travel and grow over the long distance from England. For Skagen the waves can only travel and grow over the short distance to Sweden. The most frequent (and strong) winds are also coming from Western directions, see Figure 5. Under normal wave conditions the waves at Lønstrup will therefore be larger than at Skagen.

Figure 7 Illustration of fetch limitations

For Lønstrup the fetch for waves coming from N and NW is approximately 150km, and from W and SW the fetch is approximately 700km.
For Skagen the fetch for waves coming from E is 75km. For SE and NE the fetch is approximately 150km. Waves coming from S will refract and hit the structures and are therefore also be included. To the South of Skagen are small islands and the mainland is also causing shelter from the waves. The fetch for South is therefore chosen as 75km.

The method given in SPM, 1984 allows for calculation of fetch limited waves from given wind speeds.

4.1 Lønstrup

The wind distributions given in Figure 5 are used together with the fetch, and the wave heights in deep water offshore Lønstrup is calculated for fetch limited waves. In Table 1 it is seen that the calculated wave heights for wind speeds up to 4 on the Beaufort scale does not depend on the fetch. This is because the sea is fully arisen, meaning that the waves have reached an equilibrium state in which energy input from the wind is exactly balanced by energy loss.

Wind speeds		N (Fetch 150km)		NW (Fetch 150km)		W (Fetch 700km)		SW (Fetch 700km)	
Beaufort	m/s	Prob. [%]	H_{m0} [m]	Prob. [%]	H_{m0} [m]	Prob. [%]	H_{m0} [m]	Prob. [%]	H_{m0} [m]
0	0.1	0.31	0.00	0.31	0.00	0.31	0.00	0.31	0.00
1	0.9	0.90	0.01	0.90	0.01	1.20	0.01	1.50	0.01
2	2.45	1.40	0.08	1.60	0.08	3.80	0.08	4.80	0.08
3	4.4	1.10	0.34	1.70	0.34	4.80	0.34	4.50	0.34
4	6.7	0.70	0.95	1.40	0.95	4.20	0.95	2.70	0.95
5	9.35	0.50	1.84	1.40	1.84	3.40	2.15	1.50	2.15
6	12.3	0.30	2.58	1.30	2.58	2.60	4.22	0.70	4.22
7	15.5	0.20	3.43	0.80	3.43	1.30	7.42	0.30	7.42
8	18.95	0.10	4.40	0.40	4.40	0.50	9.50	0.10	9.50
9	22.6	0.00	5.46	0.20	5.46	0.20	11.79	0.00	11.79
10	26.45	0.01	6.62	0.01	6.62	0.02	14.31	0.02	14.31

Table 1 Wave heights and probability at Lønstrup for winds coming in different directions.

4.2 Skagen

The same procedure is adopted as for Lønstrup giving the result in Table 2.

Wind speeds		NE (Fetch 150km)		E (Fetch 75km)		SE (Fetch 150km)		S (Fetch 75km)	
Beaufort	m/s	Prob. [%]	H_{m0} [m]	Prob. [%]	H_{m0} [m]	Prob. [%]	H_{m0} [m]	Prob. [%]	H_{m0} [m]
0	0.1	0.31	0.00	0.31	0.00	0.31	0.00	0.31	0.00
1	0.9	1.20	0.01	1.40	0.01	2.50	0.01	2.40	0.01
2	2.45	2.40	0.08	3.20	0.08	5.00	0.08	4.70	0.08
3	4.4	2.00	0.34	2.20	0.34	2.80	0.34	2.80	0.34
4	6.7	1.30	0.95	1.50	0.87	1.50	0.95	1.60	0.87
5	9.35	0.90	1.84	0.90	1.30	0.70	1.84	0.70	1.30
6	12.3	0.60	2.58	0.50	1.83	0.30	2.58	0.30	1.83
7	15.5	0.30	3.43	0.20	2.43	0.20	3.43	0.10	2.43
8	18.95	0.10	4.40	0.10	3.11	0.00	4.40	0.00	3.11
9	22.6	0.00	5.46	0.00	3.86	0.00	5.46	0.00	3.86
10	26.45	0.00	6.62	0.00	4.68	0.00	6.62	0.00	4.68

Table 2 Wave heights and probability at Skagen for winds coming in different directions.

5 Wave heights at the breakwater locations

The transformation in wave height distribution from deep water to shallow water is calculated by the point model proposed by Battjes and Gronendijk, 2000. Significant wave heights cannot be larger than 0.6 multiplied by the water depth due to depth limitations. Large significant wave heights have therefore been replaced by 0.6 multiplied by the water depth.

The Battjes and Gronendijk model have been applied on the results in Table 1 and Table 2 and the results have been grouped in ranges of wave heights 0-0.1m, 0.1-0.55m, and depth limited significant wave heights, see Table 3. For winds coming over the main land (indicated as *other directions* in Table 3 and Figure 8) the wave heights close to the coast are assumed to be small and are therefore put in the range 0-0.1m.

Significant wave height Hs [m]	Skagen Prob. [%]	Lønstrup Prob. [%]
0-0.1m, other dir.	54.4	45.7
0.0-0.1m	24.1	17.4
0.1-0.55m	9.8	12.1
0.6m (depth limited)	11.8	24.9

Table 3 Significant wave height distribution at the breakwater locations.

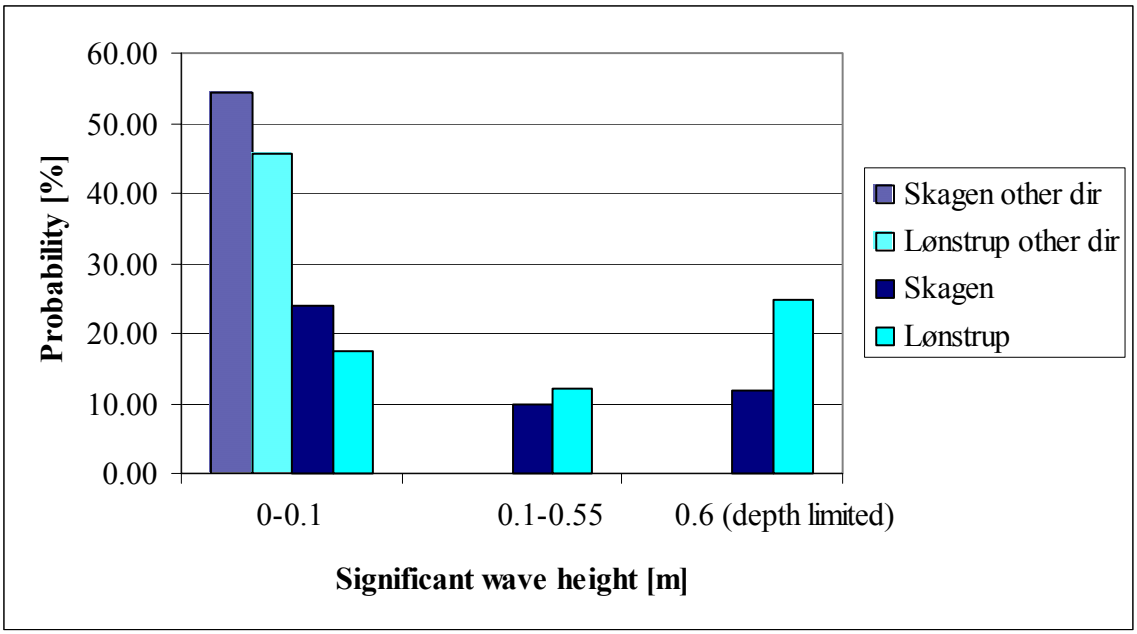

Figure 8 Comparison of wave climate at Lønstrup and Skagen

From Figure 8 it is clear that the wave heights at Lønstrup generally are larger than at Skagen. The values in Table 3 can be used as an estimate of the differences in the normal wave climate at the two sites.

6 References

Battjes, J.A. and Groenendijk, H.W. (2000). Wave height distribution on shallow foreshores, Journal of Coastal Engineering, Vol. 40, pp 161-182.

Frydendahl, Knud (1971). The Climate of Denmark in Wind – standardnormals 1931-60, Danish Meteorological Institute. (In Danish and English).

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Lundtang Petersen, Erik, Troen, Ib and Frandsen, Sten (1980). Vindatlas for Danmark, RISØ. (In Danish).

SPM (1984). Shore Protection Manual. U.S. Army Coastal Engineering Research Center.