Field tests with vertical perforated drain pipes used for beach protection at Southern Holmsland Barrier on the Danish North Sea Coast

First year report of 1 September 2006
Revised 20 November 2006
Issued by the project group

1. Introduction

In accordance with the agreement of 18 August 2004 between Skagen Innovation Center (SIC) and the Danish Governmental Coastal Authority (KDI) a field test with the purpose of demonstrating the efficiency of the SIC vertical drain method as a mean for coastal protecting was initiated in a meeting 24 August 2004.
The test period is three years after which a final report has to be presented. The report shall contain an evaluation of the drain system with respect to qualitative and quantitative efficiency and environmental impact, as well as a related comparison with conventional coastal protection methods.
Besides the final report yearly reports have to be presented as well as a report half a year after the start of the field test.
For the evaluation the following two experts were retained

Prof.dr.techn., dr. h.c. Hans Falk Burcharth (HFB)
Prof.dr.techn. Jørgen Fredsøe (JF)

The two experts were obliged to take part in the planning of the field tests including selection of the test location.
Besides the two experts the project group consists of

Director, engineer Poul Jakobsen, SIC
Engineer Claus Brögger, SIC
Project manager, Christian Laustrup, KDI
M. Sc. John Jensen, KDI

The present report, authored by the two experts, is the first year report, written as a stand alone report for which reason it repeats substantial parts of the first half year report of 12 October 2005.

2. Planning of the tests

Project group meetings were held in the autumn of 2004 with the objective of selecting a test size and decide the positioning of the pipes and the methods of monitoring the response of the coast.

2.1 Selection of test size

According to agreement between SIC and the Ministry of Transport a stretch of approximately 10 km on the Danish North Sea Coast should be selected for the tests.

Conditions with respect to hydrographic and geomorphological conditions should be as homogenous as possible along the stretch. Moreover, influence of man-made interventions should be as small as possible.
Two potential sites were discussed: A 15 km long stretch at Skodbjerge just south of the part of Hvide Sande, and a 7 km long stretch at Skallingen north of the town of Esbjerg.
The net-sediment transport is southwards at both site, but much larger at the Skodbjerge site. The Hvide Sande jetties north of the Skodbjerge site create leeside erosion for which reason some beach parallel detached rock structures are placed just south of the jetties. This coastal protection has been supplemented with beach nourishment and nourishment at the offshore bar approximately 600 m from the shore, cf. Fig. 1. Erosion decrease to the south so that just south of the 15 km stretch the beach is stable. Further south accretion takes place. Beach nourishment will not take place in the three years test period, but nourishment at the offshore bar will continue.

A long groin at the northern boundary of the Skallingen site creates lee side erosion. Erosion takes place over the full length of the actual stretch of coast.

KDI and JF were in favour of inspecting and most probably selecting the Skallingen site as it seems more homogeneous, and no nourishment takes place.
SIC argued that the length was too short as a 10 km stretch was needed. Moreover, SIC regarded the influence of the long groin to be to disturbing for the tests. As SIC refused to use Skallingen it was decided to use the Skodbjerge site, despite the not ideal conditions as explained.

2.2 Planning of the test

The main basis for the evaluation of the tests will be a comparison of the morphological changes in stretches with and without drain pipes.
The total length of the Skodbjerge test site was limited to approximately 11 km in order not to come too close to the beach breakwaters to the North and the accreting coast to the South.
KDI and JF preferred a split of the site in a number of relatively short stretches (say 2 km) with alternating drains and no drains. SIC could not accept this as – based on experience – they wanted longer stretches, basically a 6 km stretch with drains and a 4 km stretch without drains. However, due to the gradient in erosion along the test site this was not acceptable and HFB proposed as a minimum stretches with no pipes on both sites of the drained stretch.
A compromise as shown in Fig. 2 was found in which two stretches of 4.7 km (Rør I, chainage 4019200 - 4014500) and 0.9 km (Rør II, chainage 4011800 - 4012700) respectively were drained, and three stretches of 1.8 km (Reference I, chainage 4021000 – 4019200), 1.8 km (Reference II, chainage 4014500 – 4012700) and 1.8 km (Reference III, chainage 4011800 – 401000) respectively were left undrained.

The drains were installed in January 2005. The positions and number of the drains and time of installation during the first year are shown in Table 1. As seen from the table, drains have been added in some areas where increase in beach width made it possible.

2.3 Monitoring of the test site

2.3.1 Surveying

Profiling per 100 m of the beach including the dune front four times per year was decided as well as soundings per 200 m of the seabed within 600 m from the shoreline. The first profiling took place in January 2005 just after placement of the drains. Since then four surveys have been performed in April, July and October 2005, and January 2006. Carl Bro A/S performs the landward surveying and KDI the depth sounding.

2.3.2 Monitoring of ground water levels across the barrier spit

According to SIC the function of the drain relates to changes in the ground water flow caused by pressure equalisation in the surroundings of the drains. For this reason a comparison between pressure fields near the drains and far from the drains is of importance. The method of instrumentation is under discussion.
As it is generally accepted that ground water outflow in the beachface affects the sedimentation, it was decided in 2005 to monitor in one line the ground water table across the narrow land spit between Ringköbing Fjord and the test beach. Application for permission the establish wells was forwarded to the authorities. However, the campaign was stopped in 2006 as SIC found it not being necessary.

2.3.3 Grain size analyses

In order to check the hypothesis of SIC that the drains increase the groundwater outflow through the beachface and thereby wash out the fine beach material, it was decided to investigate if changes in the composition of the beach material take place as a result of the installation of the drains. Five borings were taken app. three month after the installation of the drains. (SIC has raised the question if this was too late compared to the rapid development in accreation observed after placement of the drains).
Grain size analyses of the samples have been made for comparison with samples to be taken later in the course of the project. Samples were taken in May 2006 but the grain size analysis has not been completed. Focus will be on changes in the amount of very fine material in near-drain regions compared to regions without drains.
The samples provide general information on the character of the beach with respect to stratification and permeability conditions.

2.3.4 Satellite images, aerial photographs, and airborne laser photogrametry

Seven sets of satellite images covering the period 9.10.2004 – 2.3.2006 have been obtained but not yet analysed. The varying quality of the images makes an analysis difficult. Airborne laser photogrametry was tried but without success. Aerial photographs have not been of a frequency and quality which allow more systematic analyses.

2.3.5 Pressure measurements in the beach

In order to get some insight regarding the physical functioning of the drain system, a field test program for measurement of water pressure variations in the beach and in the proximetry of the drains were performed in the spring of 2006.

The programme was carried out with additional consultancy from University of Copenhagen. The results of this experiment will be presented in the second year report.

3. Characteristics of the test site

3.1 Geomorphologic conditions

The test site is on the southern part of a barrier spit separating the Ringkøbing Fjord lagoon from the sea. The spit is formed by sand deposition resulting from a decrease in the rate of southwards longshore sediment transport. The natural southwards shift of the opening between the lagoon and the sea has been stopped by the construction of a permanent sluice and a lock at Hvide Sande where also a fishing port is located. The entrance is protected by jetties of which the longest to the north built in 1962 at present extends approximately 450 m from the foot of the dunes.

As to the coastal profile along the test site, the distance from the coastline at level 0.0 m (equal to mean water level) to the 6 m depth contour is approximately 650 m over the full length of the test site, i.e. an average slope of app. 1:100. This slope has remained almost constant during the last 20 years according to the profiling by KDI. The coastline has in the same period shown large fluctuations with changes in position ranging from 50 m to 100 m.

Grain size analyses of the sand in the foreshore and in the beach top layers shows medium to very coarse sand with grain diameter in the range 0.3-2.5 mm. Deeper borings show fine sand down to approximately 10-12 m below the surface. Underneath is very fine sand or silt, and in some places clay.

Several shore parallel bars, typically three, are formed along the coast. The net sediment transport in front of the test site is southwards amounting to approximately 2.1 million m^3 per year in average (ref. KDI). Most of the longshore transport takes place in the bar zones.

3.2 Hydrographic conditions

Water levels

At the coast the difference between mean high water and mean low water is 0.7-0.8 m. Storm surge caused by strong westerly gales and low pressures can give water levels of up to approximately 3.1 m above mean water level. Low water levels down to -2.0 m can occur during easterly winds.

In the Ringköbing Fjord lagoon the water level varies between -0.5 m and +0.5 m, dependent on the operation of the sluices and on the wind set-up.

A very severe storm with westerly winds of more than 26 m/s occurred 8-9 January 2005, shortly before the first survey took place in January 2005. Water levels up to 3.03 m above M.S.L. were recorded at the head of the jetties at Port of Hvide Sande. Wave set-up might have caused an even higher maximum water level at the beach face of the test site. No severe westerly storms have occurred in the period covered by the present report. The maximum water level recorded was

+1.44 m on the 26.10.2005.

Waves

The prevailing westerly winds cause quite frequently storm waves with significant wave heights in the range H_s = 3-4 m offshore in 20 m water depth, and related peak periods of approximately T_p = 10 s. During more extreme events, say return periods of 5 years or more, H_s will exceed 6 m and T_p exceed 12 s. It is not often that H_s is less than 1 m and T_p less than 5 s during westerly winds. The waves are strongly seasonal as storms occur mainly in the autumn and during the winter.

The dominating directional sector of the larger waves reaching to actual stretch of coastline is West-North West, causing the net sediment transport to be Southbound.

Typical crest levels of the bars in the nearshore zone area round 2 m below MWL, limiting the significant wave height passing the inner bar to be approximately 0.6 x (2,00 + heigh water), i.e. around 3 m during the highest storm water levels.

Fig. 3 shows the one-year (2005) statistics of significant wave height recorded by a directional waverider buoy in 15.5 m water depth offshore Nymindegab.

Shown in Fig. 3 is the wave statistics for significant waves larger than 3.0 m, which includes the storm 8-9 January, 2005.

It is seen from Fig. 3 that the angle between the coastline and the dominating incoming waves is approximately 45^{o}, thus causing a net-sediment drift in southern direction.

3.3 Former coastal changes and man-made interventions

The natural erosion (retreat of the coastline) is estimated by KDI to vary gradually from approximately 3.5 m/year just south of the Hvide Sande jetties to approximately 1.5 m/year at the southern end of the test site, calculated as averages over the years 1977-96.
The actual erosion is different due to man-made interventions. Actually the coastline has, apart from fluctuation, in average been stable over the last 5-10 years as documented by the KDI profiling of lines 5700-5810 (chainage 4010000-4021000). Table 2 lists the man-made interventions for the stretches Årgab (5 km stretch north of the test site), Havrvig (northern half part of the test site) and Skodbjerge (southern half part of the test site).

3.4 Natural coastline undulations moving along the shore

It is known that obliquely incoming waves can cause undulations in the beach-width. The scale of these undulations are typical: wavelength 1-2 km, amplitude 10-50 m, and down drift migration velocity: 50-500 m/year. Very large undulations along the Danish coast are for instance identified by KDI at Uggerby just East of Hirtshals, and at Gl. Skagen at the northern tip of Jutland. At both locations, the coast are exposed to very obliquely incoming waves. It should be noted that in the period January 1999 – April 2004, during which the coast of Gl. Skagen were surveyed as part of a field test with vertical drains, no systematically moving undulations were identified by Hans F. Burcharth.

Along the actual test site, the angle between the coastline and the dominating incoming waves is approximately 45 degrees, see Figure 3, for which reason a potential for large-scale undulations exists. Observed accretion along the shore may then stem either from the drain-system, or be due to natural coastal processes. Man-made supply of large quantities of sand by beach and bar nourishment could play a significant role as well.

In Appendix A of this report is presented an analysis of coastline undulations. However, while these undulations to a certain extend can explain the observed planform movements, they only constitute a small fraction of the observed accretion of the beach.

4. The functioning of the vertical drains

The physical explanation of the functioning of the drains is still under discussion. Appendix B presents an analysis of the effect of the SIC vertical drains in a beach with homogeneous isotropic soil conditions. The effect of stratifications observed in the actual beach are not included in the analysis. The appendix only serves as a background note for further investigations about the functioning of the drains.

5. Method of presentation of surveys

With the objective of gaining information on the development of the coast with respect to the following beach properties

- changes in position of the coastline, defined at level 0.00 corresponding to M.W.L.
- changes in position of dune foot, defined at level +4.00 m
- changes in dune, beach and shore face volumes
- average levels of beach and shore face zones
- average height of beach measured over 100 m from position of foot of dune at level +4.00 m on the January 2005 surveyed profiles.

the coastal profile was divided into four zones. The definitions shown in Figs. 4 and 5, are used in the analyses.

Based on the experience from the April 2005 and the June 2005 surveys, the definitions are adjusted compared to those used in the first half year report.

The following quantities were planned calculated from the coastal profiles and compared from survey to survey:

change in the positions of

- dune foot, Δb_1
- beach width, Δb_2
- position of coastline, $\Delta (b_1+b_2)$

changes in volume of

- dune, ΔB_1
- beach, ΔB_2
- dune + beach, $\Delta (B_1+B_2)$

- dune + beach + shoreface, $\Delta (B_1+B_2+B_3)$
- dune + beach + nearshore zone, $\Delta (B_1+B_2+B_3+B_4)$

changes in mean levels of

- beach over width b_2, ΔMNb_2
- shoreface over width b_3, ΔMNb_3
- profile surface measured over 100 m from the point of intersection with level +4.00 m in the January 2005 profile, Δ MSH.

Because the dunes over level +4.00 m were not fully surveyed in January 2006 it was not possible to calculate ΔB_1 with high accuracy, as exterpolation has to be made between the highest measured point and the January 2005 measured top of the dune front face. As a consequence Δ MSH is not so well defined. However, the bias introduced by this omission is not very significant and does not change to picture of the development of the coastal profile.

The most important results are given in the following.

6. Results of surveys January 2005 – January 2006

6.1. Changes in dune foot positions

The average changes in the dune foot position (defined at level +4.00m) for each of the defined stretches are shown in Fig. 6. A shoreward movement is observed for all stretches which means that material has been transported by the wind from the beach plane to the dunes.

6.2 Changes in coastline positions

The evolution in coast line position calculated as the changes in $b_1 + b_2$, i.e. $\Delta (b_1 + b_2)$ observed in the one-year period is shown in Fig. 7. For Ref. I and Rør I there seems to be no clear tendency as the stretches exhibit both seaward grow and retreate in coastline position. Ref. II shows retreate whereas Rør II and Ref. II show seaward grow.

Fig. 8 shows the development of values of $\Delta (b_1 + b_2)$ averaged over each stretch.

6.3 Changes in dune and beach volumes

The approximate net changes in dune and beach volumes calculated as $\Delta B_1 + \Delta B_2$ are shown in Fig. 9. The table below shows the approximate volume changes in m^3 per metre of coastline averaged over the five stretches.

Approximate average volume changes $\Delta B_1 + \Delta B_2$ from January 2005 to January 2006. Positive values are deposition.

Stretch	m^3/m coastline	Total m^3 over stretch
Ref. I	1	2.578
Rør I	44	205.998
Ref. II	-23	-41.543
Rør II	126	113.793
Ref. III	80	143.317

It is seen that significant net deposition has taken place in Rør I, Rør II and Ref. III whereas both erosion and deposition - almost equalizing each other - have taken place in Ref. I. Ref. II shows mainly erosion. The net increase in beach and dune volumes amounts to app. 424,000 m^3 in total. This volume is supplied from the sea.

Fig. 10 shows an estimation of the changes in the dune volume. The real increase in volume will be bigger, cf. the above given explanation. It is seen that substantial deposition has taken place in nearly all profiles. This is characteristic for a relative quiet period as the actual one-year period during which no significant storms occurred.

6.4 Dune, beach and nearshore volume

The changes in shore face volume ΔB_3 have been small relative to other volume changes and are not discussed further in this report. The total changes in volume, $\Delta B_1 + \Delta B_2 + \Delta B_3 + \Delta B_4$, are shown in Fig. 11. Significant increase in volume is seen in Rør II and Ref. III, whereas significant decrease is seen in Ref. II. In Rør I is seen a moderate increase in volume, and in Ref. I a moderate decrease. It should be noted that ΔB_4 is very changeable as it includes the nearshore fluctuating seabed region. Fig. 12 shows the nearshore volume changes, $\Delta B3 + \Delta B4$. By comparison with Fig. 9 it can be seen that there is not a complementary exchange in beach and nearshore volume changes.

6.5 Changes in mean level of a 100 m wide beach zone measured from position of level +4.00 m in the January 2005 profile

An estimate of the changes in the one-year mean levels, Δ MSH, which does not include the full accretion of the dune, are shown in Fig. 13. The picture is very much alike Fig. 9 showing the changes in dune and beach volumes. MSH can be regarded as an indicator of the resistance to erosion. Fig. 14 shows the initial values of MSH as per January 2005 together with the approximate one-year Δ MSH.

The initial values of MSH are not evenly distributed over the test area. Large values of MSH ≥ 2.0 m existed only near the border between Ref. II and Rør II. Values larger or equal to 1.5m were present mainly in Rør I and Ref. II.

7. Preliminary observations

In the period January 2005 to January 2006 no significant changes have taken place in the beach planform as the coastline undulations have more or less maintained their positions except that in the southern part of Rør II and the northern part of Ref. III the coastline has significantly moved seaward and there seems to be a tendency that the undulations are moving southwards. It can be observed that significant accumulation of sand has taken place within the two areas with drains, Rør I and Rør II, i.e. the beach level has been raised. The same or even stronger development is however observed in Ref. III with no drains, whereas Ref. I also with no drains exhibit both erosion and accretion. Ref. II generally shows erosion.
This observed development has taken place in a period with no severe storms and extreme high water levels since the very severe storm around 8 January 2005 occurred. At that occasion large quantities of sand was probably eroded from the beach. Usually part of this sand will be transported back to the beach in periods with milder wave climate, normally occurring in the spring and the summer. Also sand nourishment might contribute to the accretion of the beach. Actually, the migration pattern of the nourishment sand is not clear, it may go on-, off- or long-shore. However, twice as much sand has been nourished as what has been accumulated on the beach in the one-year period. The changing wave and sea level conditions cause large natural fluctuations in the beach planform and volume. Moreover, coastline undulations moving along the coast in the direction of net sand transport might contribute to these fluctuations. The effect of the drains has to be detected from such "background noise" which is not easy during a short period, even if the drains might have a significant effect. For this reason the following conclusions are of preliminary character.

8. Preliminary conclusions

During the first one year period the beach has increased its volume significantly in the two stretches where the SIC-drains have been installed. Significant increase took place already in the first half of the one year period. Out of three stretches without drains there has been significantly volume increase in one stretch, significant volume decrease in a second stretch, and balancing increase and decrease in volume in a third stretch. Although there seems to be some positive correlation between areas with beach volume increase and areas with drains, indicating a positive effect of the drains, it is too early to draw final conclusions. This is because a one year observation period is short seen in relation to the timescale of natural beach fluctuations, and theoretically based considerations has not yet explained a significant effect of the vertical drains. Moreover, because of the mild wave conditions throughout the one year period, the performance of the drained stretches after storms has not been studied. It is however obvious that the resistance to erosion has increased where significant growth in beach volume has taken place.

20 November 2006

Jørgen Fredsøe　　　　Hans F. Burcharth

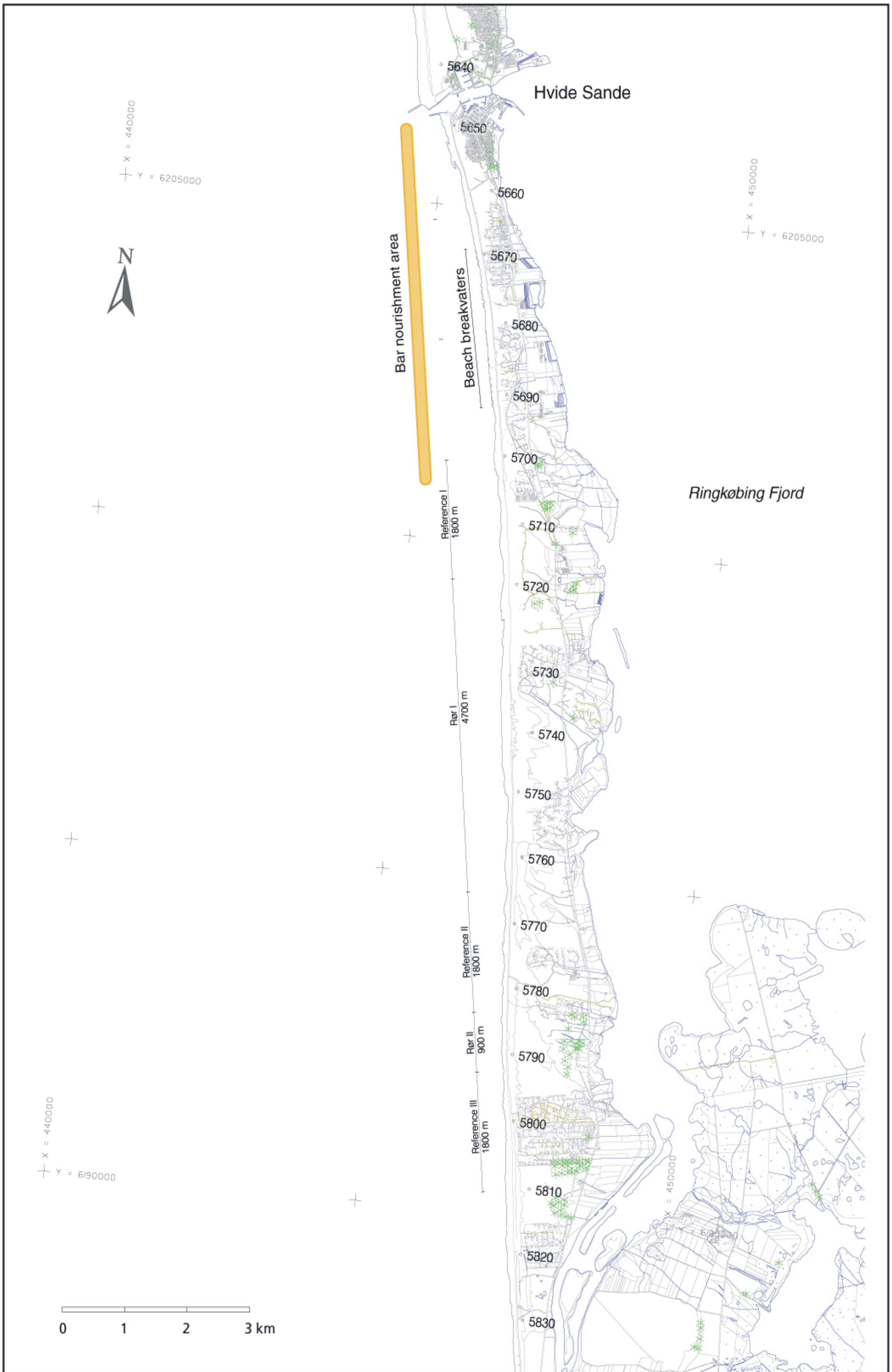
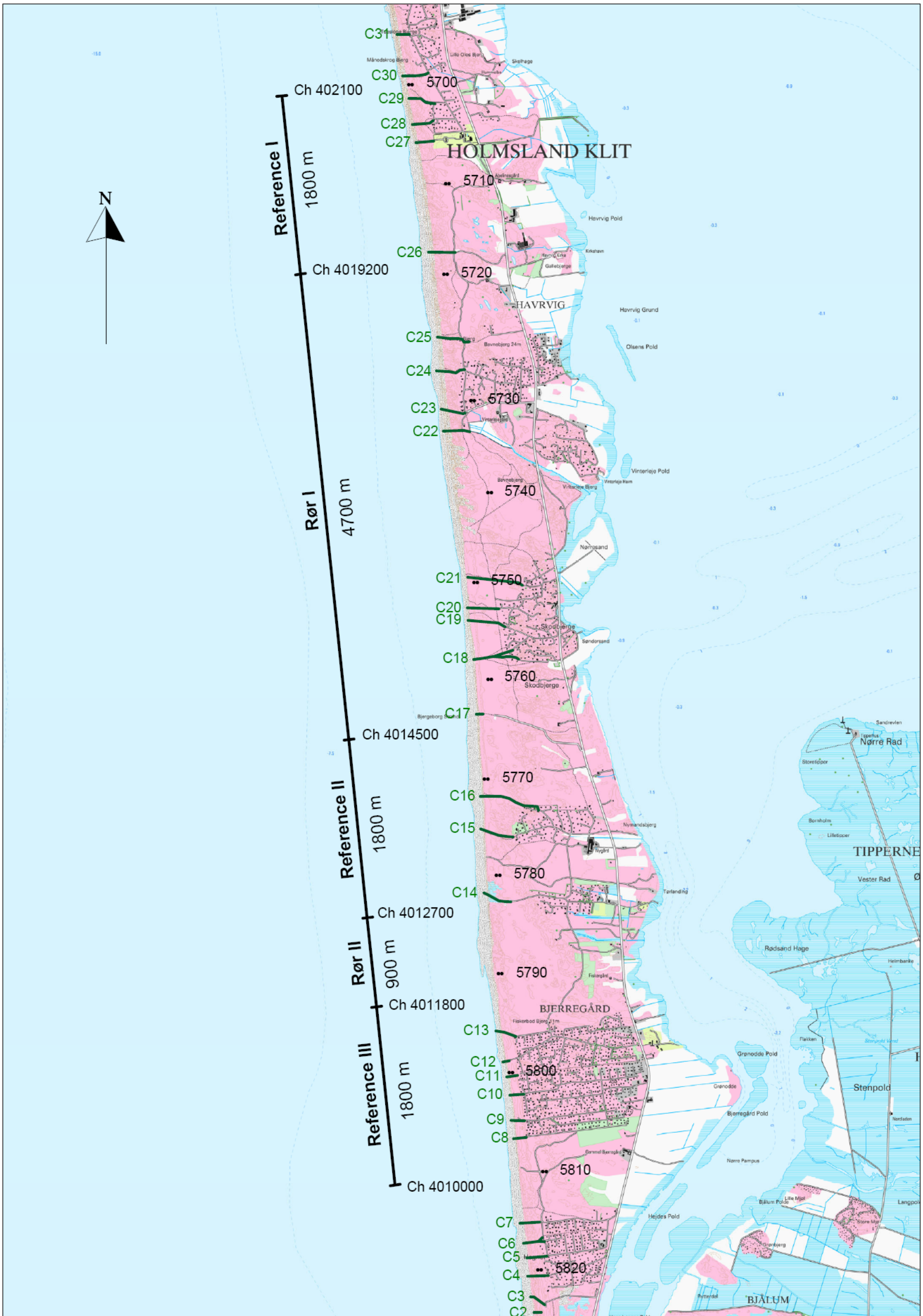
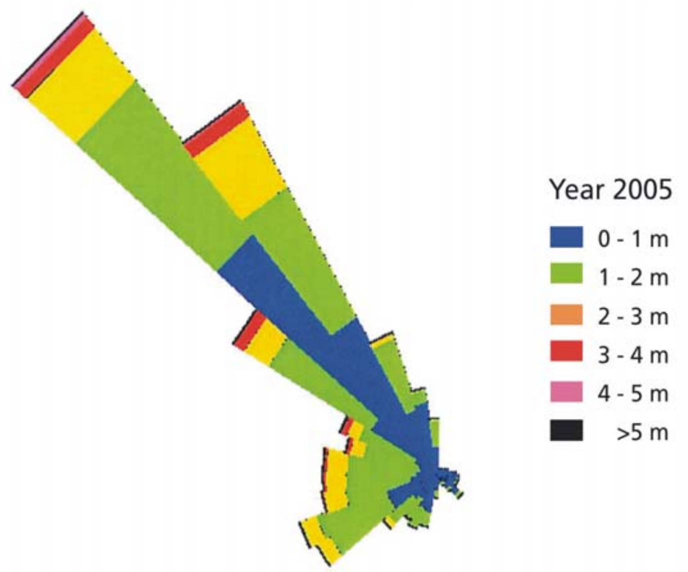


Figure 1
Bar nourishment

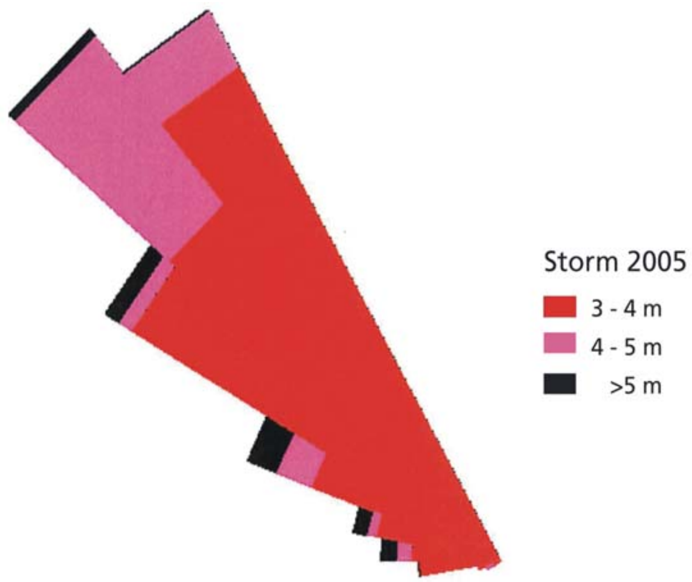
Mål: Projekt: JJ/TL/BBK Rev.:	Tegn. nr. Nr. 99 Gr. 103-659-2
Godkendt: 16.11.2006 JJ	



KYSTDIREKTORATET	Figure 2 Location of test stretches	Mål: 1:50000 Projekt: JJ/TL Rev.: 05.10.2005	Tegn. nr. Nr. 100 Gr. 103-659-2
		Godkendt: 11.05.2005	



Wave rose including all wave measurements in 2005



Wave rose for all waves larger than 3 m recorded in 2005

Fig. 3. Frequency and direction of significant wave height for 2005, recorded in 15.5 m water depth offshore Nymindegab.

28.2.06

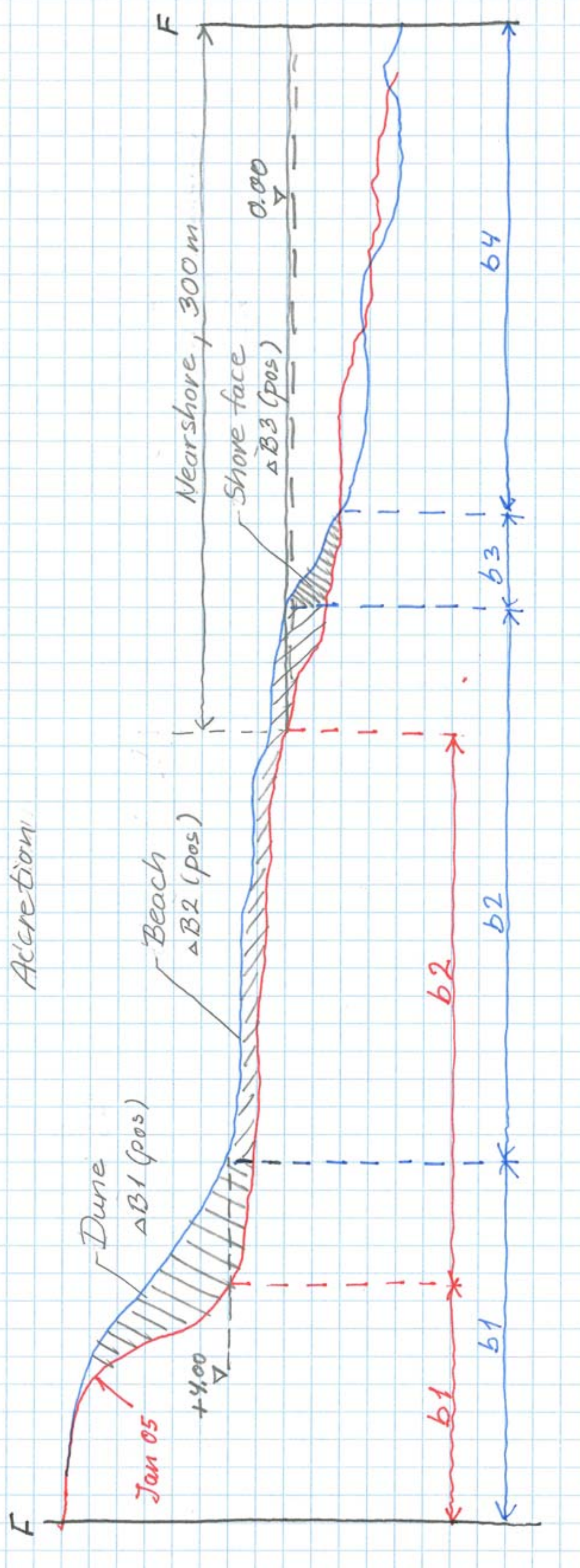


Fig. 4

Definition of geometrical parameters for the analyses of changes in coastal profiles

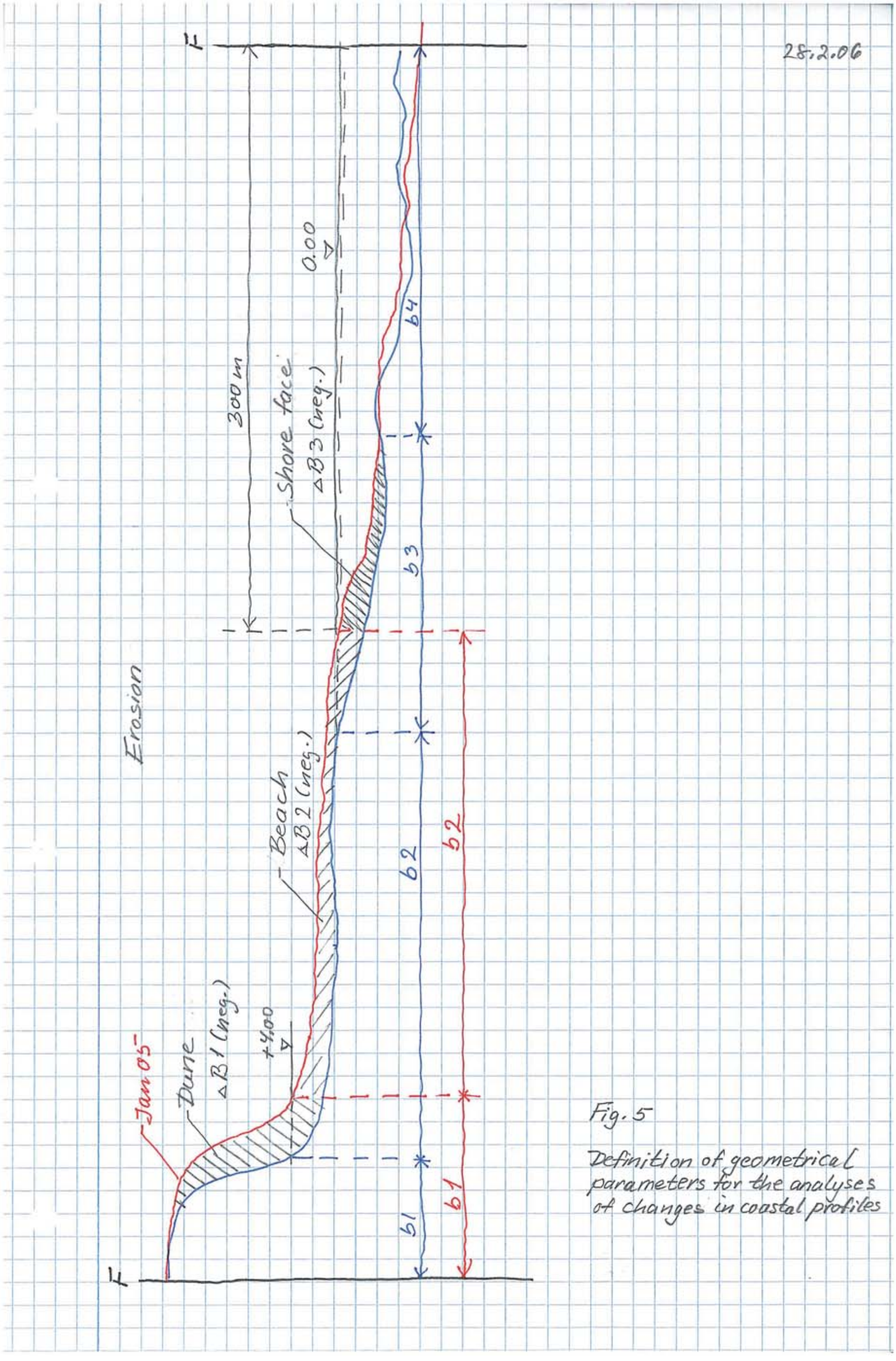


Fig. 5

Definition of geometrical parameters for the analyses of changes in coastal profiles

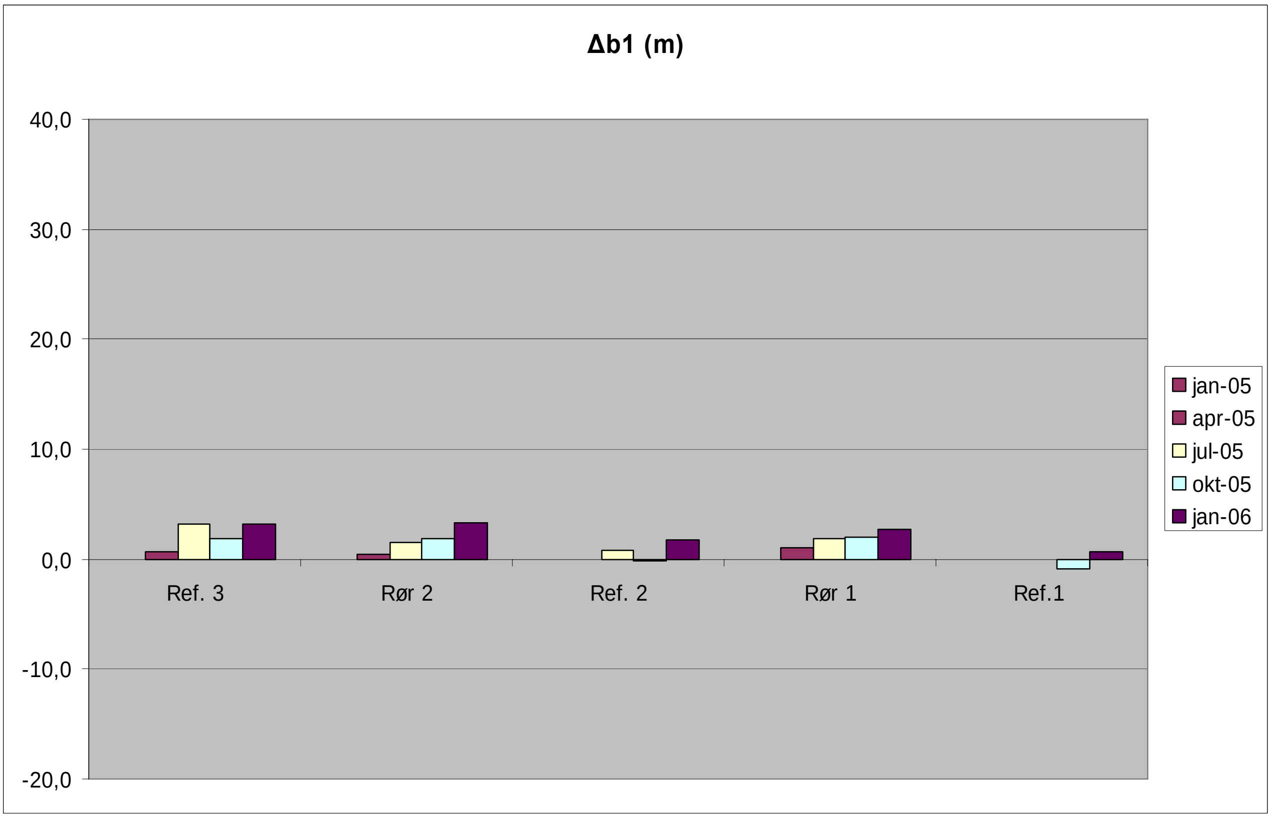


Fig. 6. Average changes in dune foot positions.

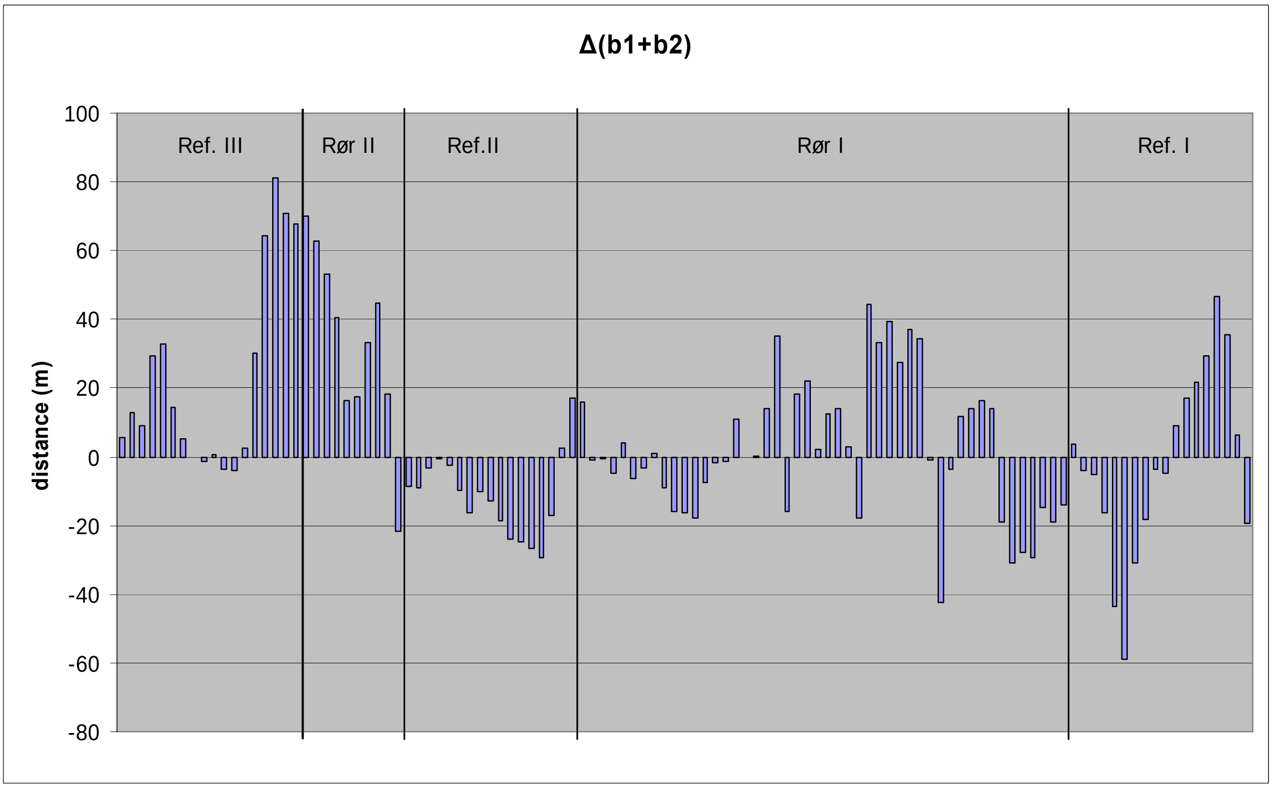


Fig. 7. Changes in coastline position, January 2005 – January 2006.

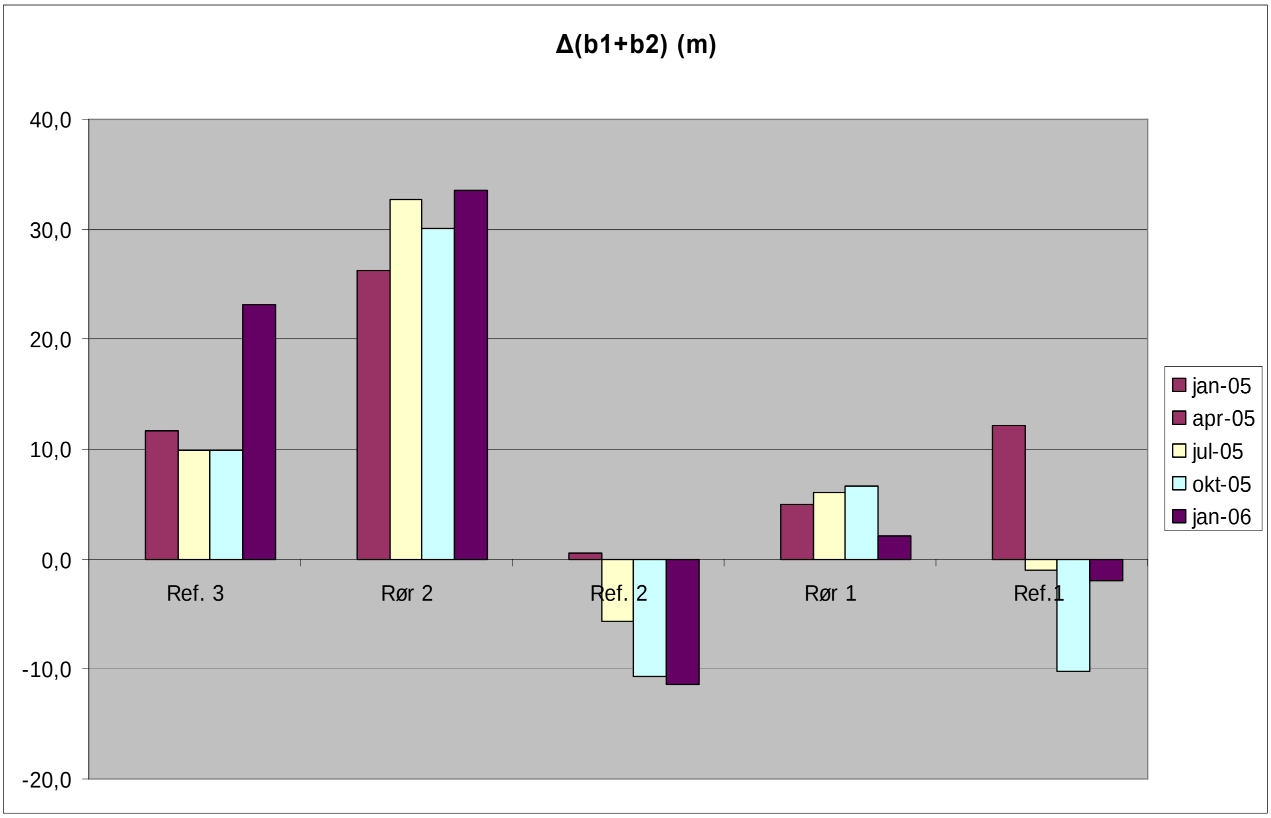


Fig. 8. Development in changes in coastline positions averaged over each defined stretch.

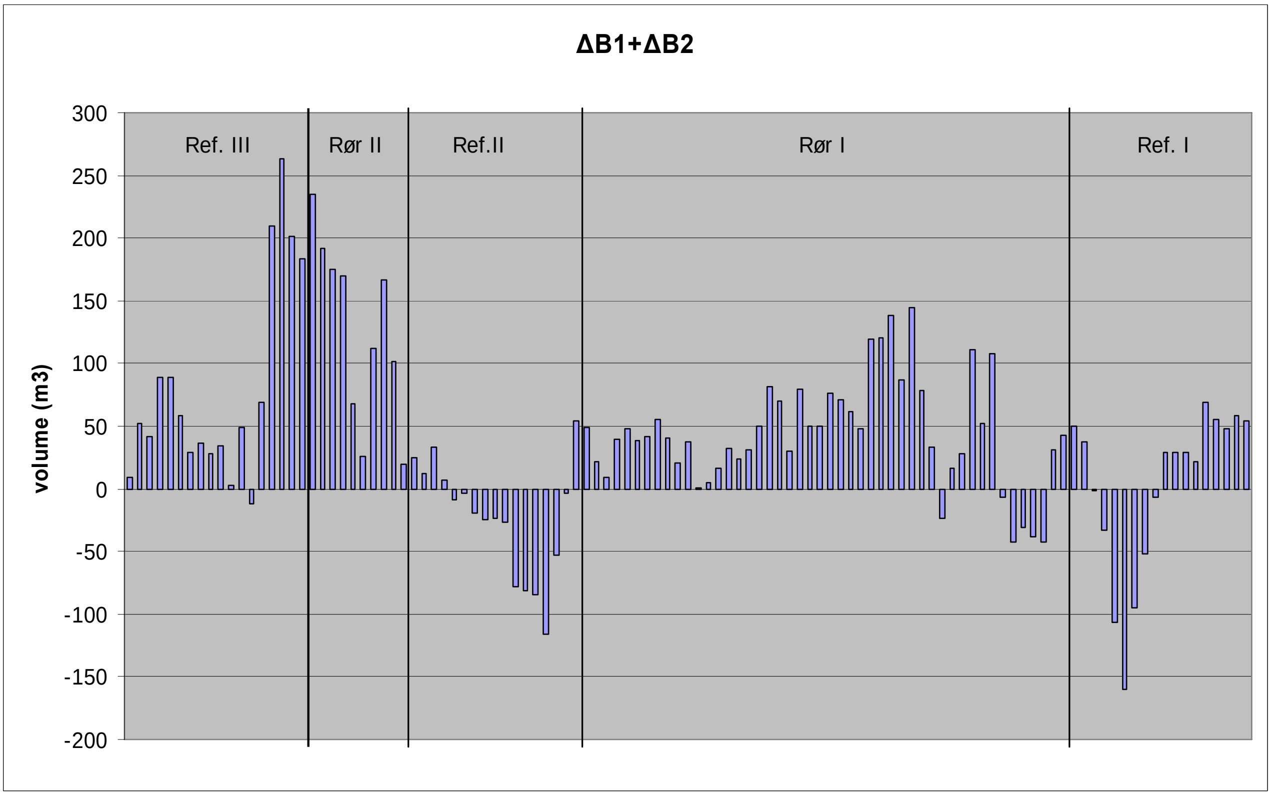


Fig. 9. Changes in volume of dune plus beach from January 2005 to January 2006.

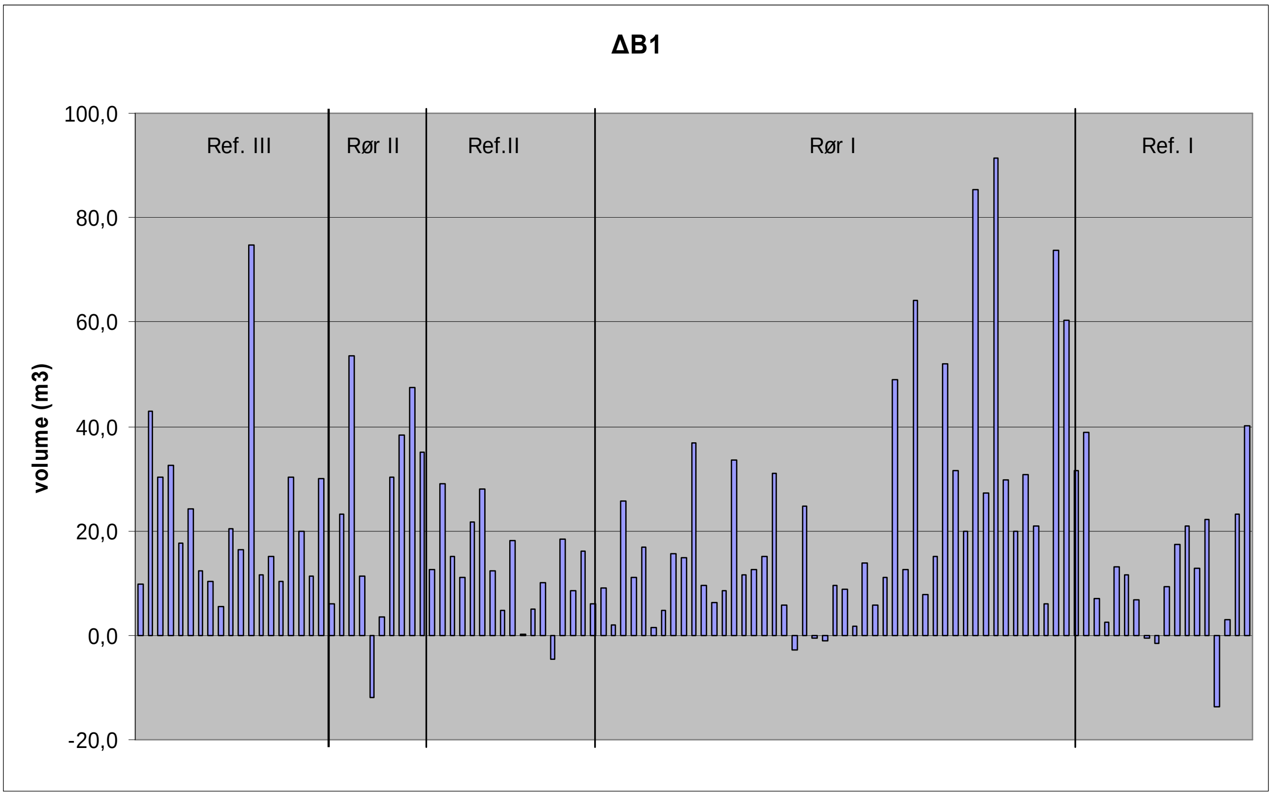


Fig. 10. Estimate of changes in dune volume in the one-year period

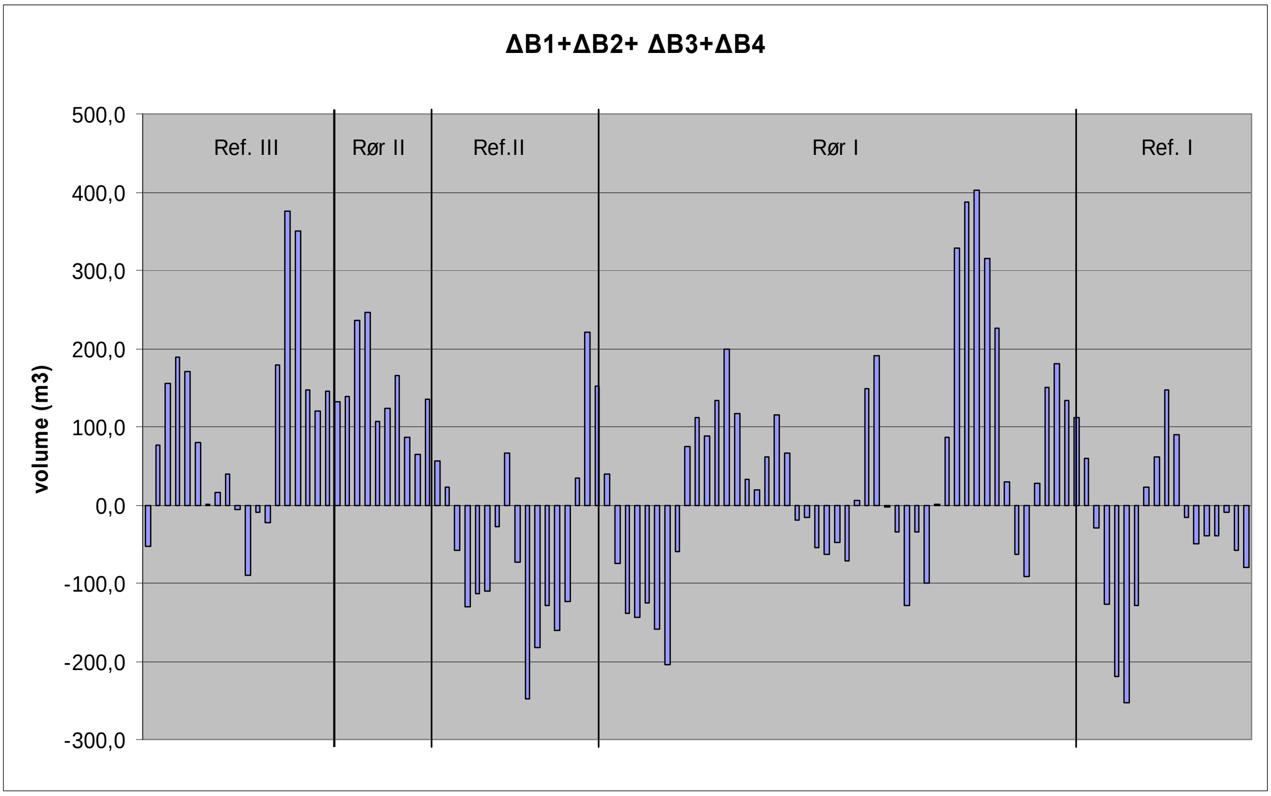


Fig. 11. Changes in total volumes of dune, beach and nearshore zone in the one-year period.

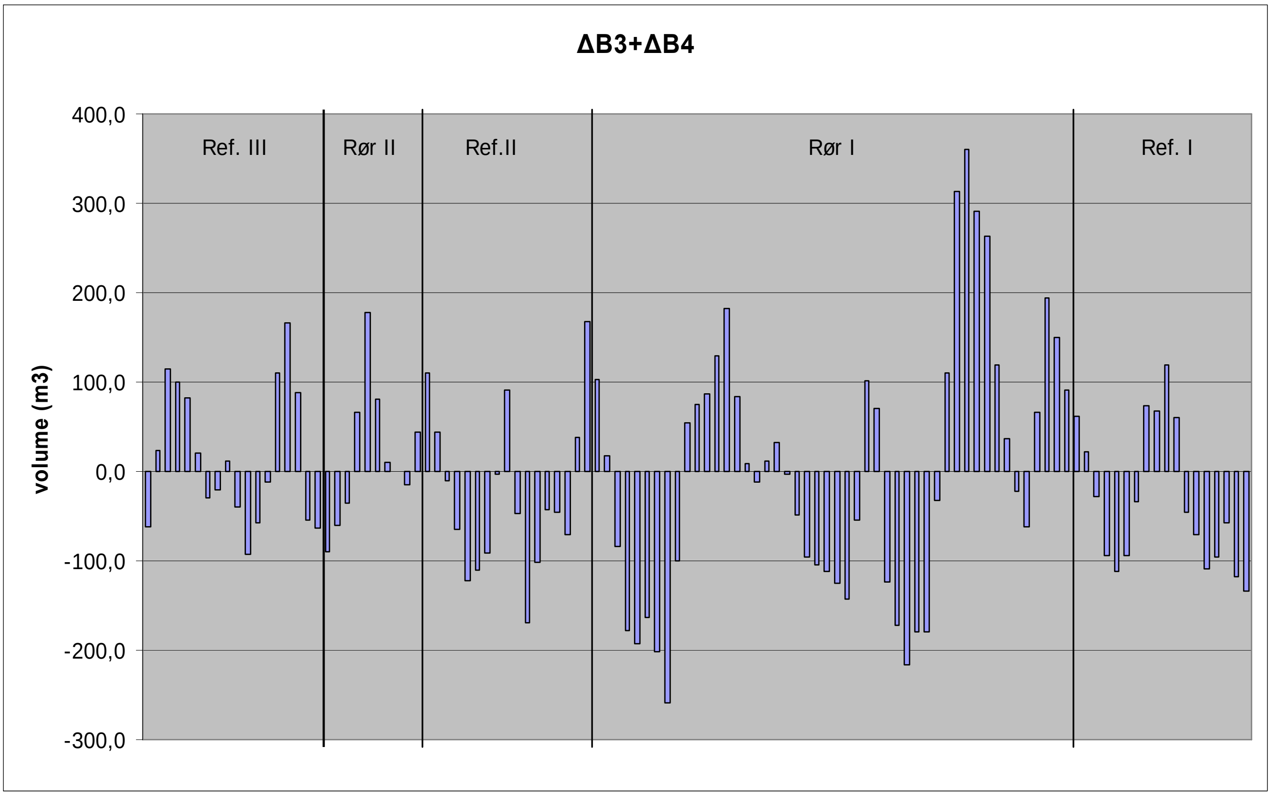


Fig. 12. Changes in volume of nearshore zone in the one-year period.

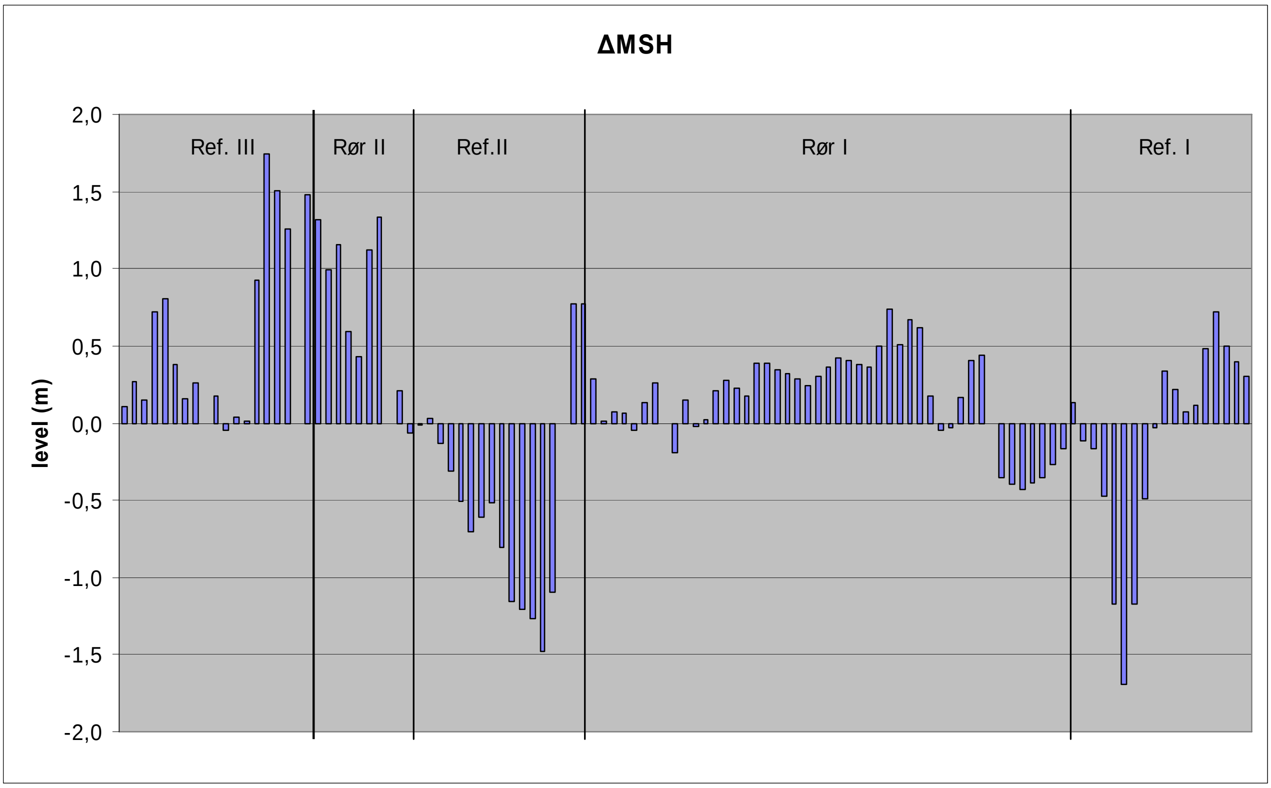


Fig. 13. Approximate changes over one year in mean level of profile surface measured over 100 m from the point of intersection with level +4.00 m in the January 2005 profile.

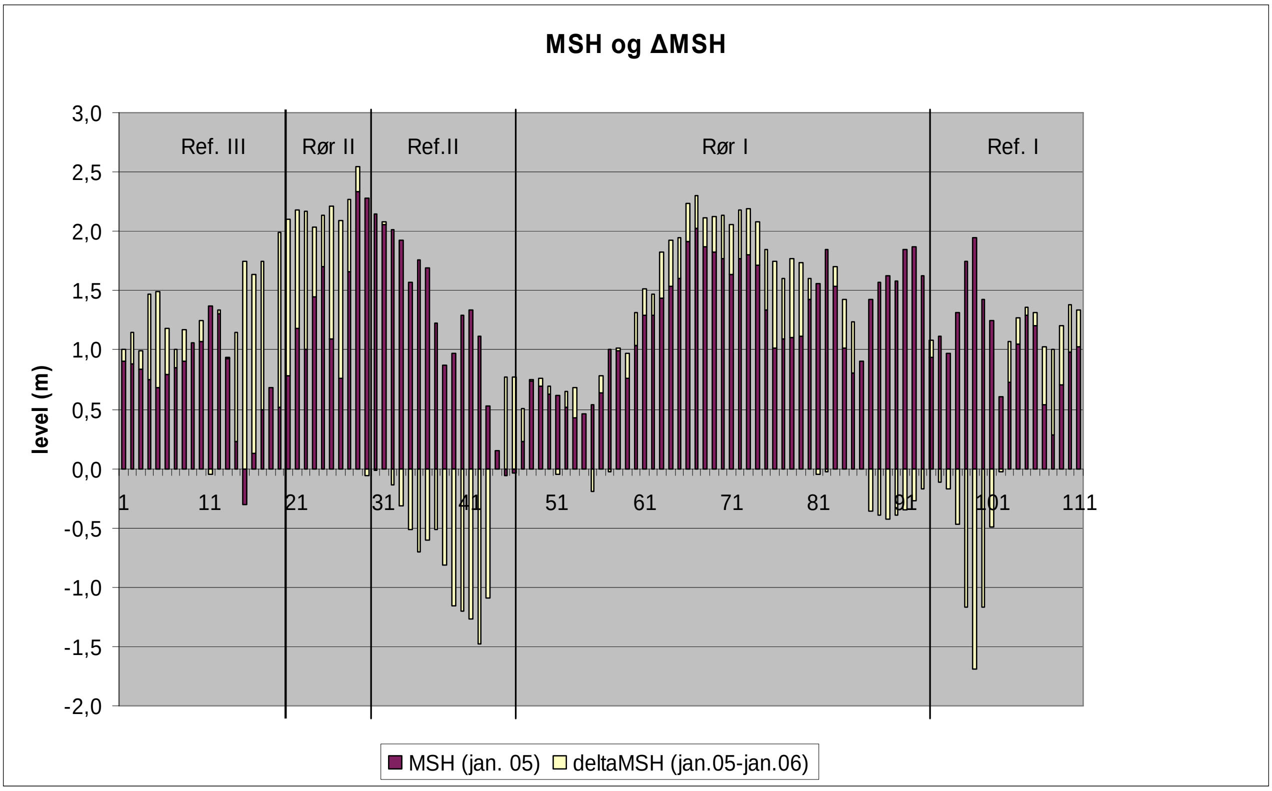


Fig. 14. Initial values of MSH (January 2005) and approximate Δ MSH over one year.

Table 1. Positions and number of drains placed.

stn.	No.	1	2	3	4	5	6	7	8	9	10	11	12
4011800		X	X	X	X	X	X	X	X	X	X	X	
4011900		X	X	X	X	X	X	X	X	X	X	X	X
4012000		X	X	X	X	X	X	X	X	X	X	X	X
4012100		X	X	X	X	X	X	X	X	X	X	X	
4012200		X	X	X	X	X	X	X	X	X	X	X	
4012300		X	X	X	X	X	X	X	X	X	X	X	X
4012400		X	X	X	X	X	X	X	X	X	X	X	
4012500		X	X	X	X	X	X	X	X	X	X	X	
4012600		X	X	X	X	X	X	X	X	X	X	X	
4012700		X	X	X	X	X	X	X	X	X	X		
	No.	1	2	3	4	5	6	7	8	9	10	11	12
4014500		X	X	X	X	X	X	X	X				
4014600		X	X	X	X	X	X	X					
4014700		X	X	X	X	X	X	X					
4014800		X	X	X	X	X	X	X	X				
4014900		X	X	X	X	X	X	X	X				
4015000		X	X	X	X	X	X	X					
4015100		X	X	X	X	X	X	X	X				
4015200		X	X	X	X	X	X	X					
4015300		X	X	X	X	X	X	X					
4015400		X	X	X	X	X	X	X					
4015500		X	X	X	X	X	X	X					
4015600		X	X	X	X	X	X	X	X				
4015700		X	X	X	X	X	X	X	X				
4015800		X	X	X	X	X	X	X	X				
4015900		X	X	X	X	X	X	X	X	X			
4016000		X	X	X	X	X	X	X	X	X			
4016100		X	X	X	X	X	X	X	X	X			
4016200		X	X	X	X	X	X	X	X	X	X	X	
4016300		X	X	X	X	X	X	X	X	X	X	X	X
4016400		X	X	X	X	X	X	X	X	X	X	X	
4016500		X	X	X	X	X	X	X	X	X	X	X	
4016600		X	X	X	X	X	X	X	X	X	X	X	
4016700		X	X	X	X	X	X	X	X	X	X	X	X
4016800		X	X	X	X	X	X	X	X	X	X	X	
4016900		X	X	X	X	X	X	X	X	X	X	X	
4017000		X	X	X	X	X	X	X	X	X	X	X	
4017100		X	X	X	X	X	X	X	X	X	X	X	
4017200		X	X	X	X	X	X	X	X	X	X	X	
4017300		X	X	X	X	X	X	X	X	X	X	X	
4017400		X	X	X	X	X	X	X	X	X	X	X	
4017500		X	X	X	X	X	X	X	X	X	X	X	
4017600		X	X	X	X	X	X	X	X	X	X	X	
4017700		X	X	X	X	X	X	X	X	X	X	X	
4017800		X	X	X	X	X	X	X	X	X	X	X	
4017900		X	X	X	X	X	X	X	X	X	X	X	
4018000		X	X	X	X	X	X	X	X	X	X	X	
4018100		X	X	X	X	X	X	X	X	X	X	X	
4018200		X	X	X	X	X	X	X	X	X	X		
4018300		X	X	X	X	X	X	X	X	X	X		
4018400		X	X	X	X	X	X	X	X	X	X	X	
4018500		X	X	X	X	X	X	X	X	X	X		
4018600		X	X	X	X	X	X	X	X	X	X		
4018700		X	X	X	X	X	X	X	X	X			
4018800		X	X	X	X	X	X	X	X	X			
4018900		X	X	X	X	X	X	X	X	X			
4019000		X	X	X	X	X	X	X	X	X			
4019100		X	X	X	X	X	X	X	X	X			
4019200		X	X	X	X	X	X	X	X	X			
	No.	1	2	3	4	5	6	7	8	9	10	11	12

PEM modules Skodbjerge

- X PEM modules 28 jan 2005
- X ADDITIONAL 28 MAR 2005
- X ADDITIONAL 06 MAY 2005
- X ADDITIONAL 05 AUG 2005
- X ADDITIONAL 20 OCT 2005
- X ADDITIONAL 21 FEB 2006

Table 2. Man-made interventions, 1977-2005

Volumes (m^3)

	Årgab					**Havrvig**			**Skodbjerge**	
	dumping at dune foot	beach nourishment	beach scraping	foreshore nourishment	bar nourishment	beach nourishment	beach scraping	foreshore nourishment	beach nourishment	beach scraping
1977	158.007									
1978	48.817			34.959						
1979	57.813			29.014						
1980	54.383			17.005						
1981	87.100									
1982	95.342									
1983	84.656									
1984	89.002		21.726							
1985	119.288		17.704	18.491						
1986	85.816		21.604	29.927						
1987	97.542		9.384	25.900						
1988	173.960		750	44.864						26.997
1989	165.361			41.336			4.410			21.182
1990	187.306			7.100			4.418			21.222
1991	177.766			1.318			4.084			24.422
1992	197.907			3.855		21.099			115.669	
1993	82.333	208.099		2.955		152.115	108.904			81.128
1994	60.602	148.455	13.395	1.591		214.945	51.288		82.345	25.123
1995	35.528	184.655	23.848	33.136			58.969			
1996	18.288	395.811		1.973		185.946	11.131			79.873
1997	12.534	187.718	19.001	2.618			36.565			42.875
1998	36.095	504.742		382		326.358	43.637			57.680
1999	17.480	388.036				228.020	8.010	200.255	154.110	41.624
2000	60.256	519.733		10.800		218.080	13.075			56.060
2001	14.342	429.572					4.634			60.900
2002		628.317					12.540			17.188
2003	28.706	527.925			2.632		20.239			42.907
2004		73.900	11.443		600.041		3.951			15.061
2005					200.419					
Total	2.246.230	4.196.963	138.855	307.224	803.092	1.346.563	385.855	200.255	352.124	614.242

Appendix A

ANALYSIS OF COASTLINE UNDULATIONS ALONG THE TEST SITE

From Figure 3 in the report it is evident that the sediment drift is in the southern direction. Based on the actual wave climate the CERC-formula predicts an annual rate of around 2 million cubic metre. By inspection of satellite-photos, large-scale undulations can be identified, but their behavior (change of shape and migration) is quite stochastic and not so easy to identify during the relative short time of period of the present experiment.

Undulations have been observed at the location of the experiment also before the SIC vertical drain experiment was started, so the presence of undulations cannot only be due to the implementation of the drains. Figures A1 and A2 show the measured longshore variation in beach width in May 2000 (yellow), August 2002 (blue plus brown) and September 2005 (blue plus dark blue). Also fits with polynomial are included in the figures. First of all, undulations can be detected from this figure. Secondly, they seem to migrate in the downdrift (southern) direction, around 1000-1300 metres during the 5 years. The wavelength of the very large undulations is around 6 km, and it is observed that the undulation which in year 2000 had its peak in “rør 1” now has become wider, while the other undulation, which was located on the border between “ref 2” and “rør 2”, now has become more narrow.

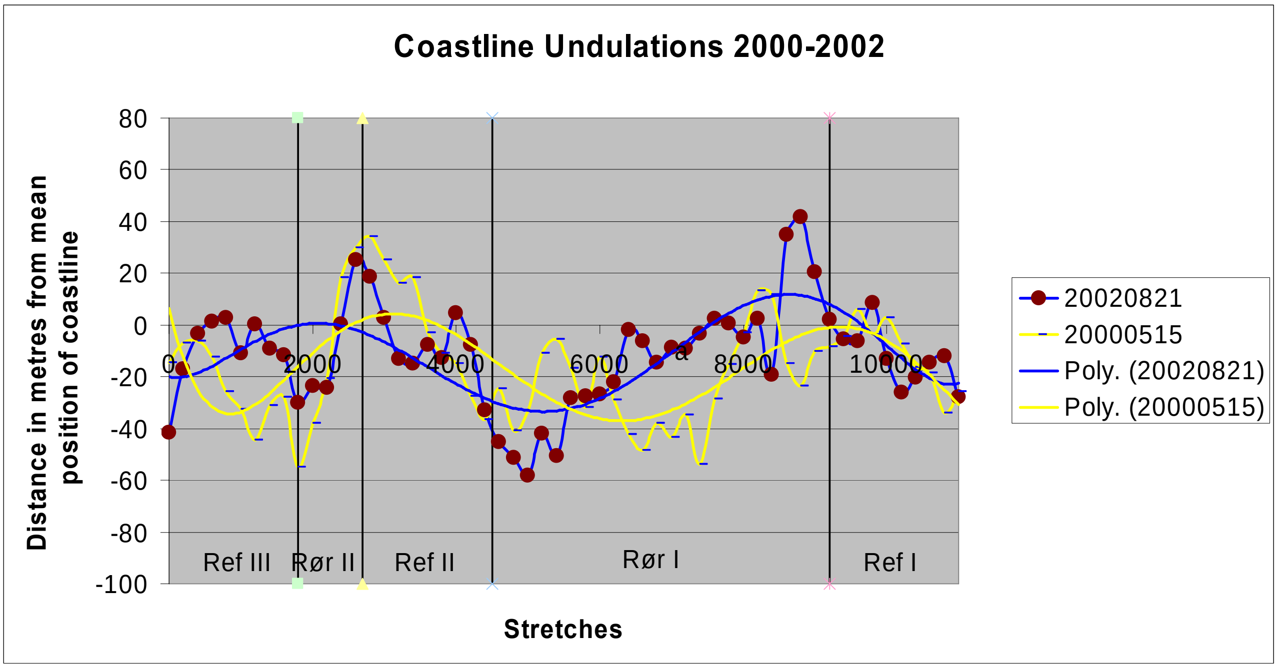


Figure A1: Variation in beach width from 2000-2002 (Produced by KDI).

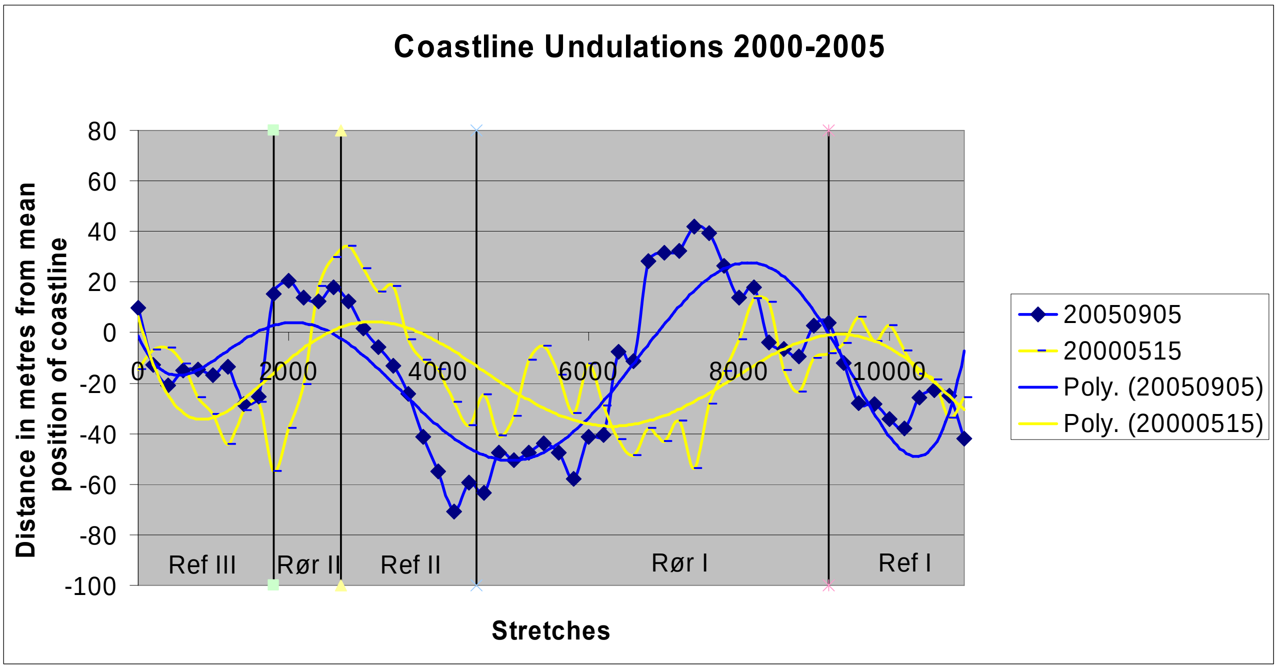


Figure A2: Variation in beach width from 2000-2005 (Produced by KDI).

It is assumed that the migration of the undulations will cause a rhythmic pattern of erosion and deposition along the coast as sketched in figure A3.

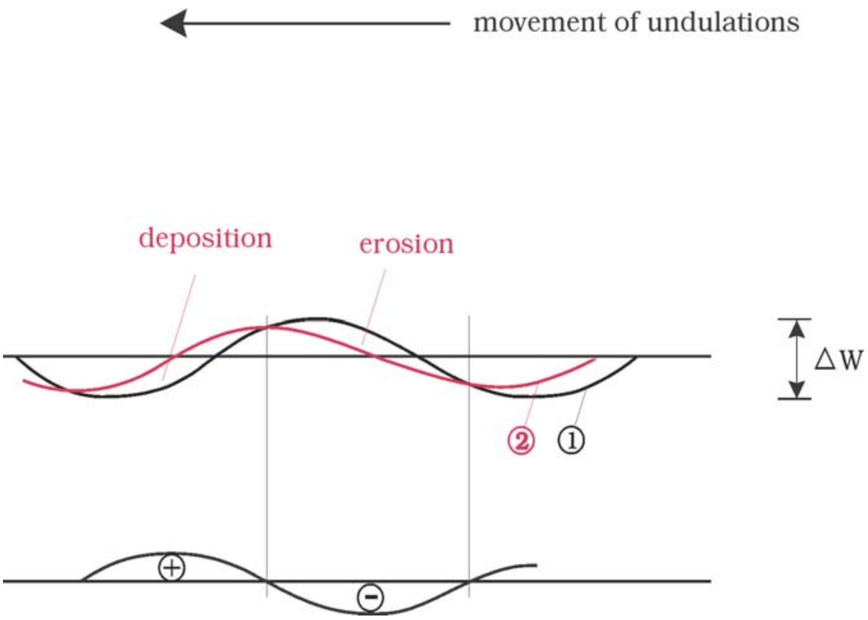


Figure A3: Erosion and deposition pattern caused by migrating undulations. Position 2 is to a later time than position 1.

The local variation in sediment transport q along the undulations with the shape h=h (x) is given by

$$\frac{\partial q}{\partial x} = -T \frac{\partial h}{\partial t}$$

where T is the average thickness of the beach and x a coast parallel coordinate positive in the direction of q.

If we assume the undulations migrate with a steady shape and a migration velocity a, we have

$h = h(x - at)$ and $\frac{\partial h}{\partial t} = -a\frac{\partial h}{\partial x}$

so

$$\frac{\partial q}{\partial x} = aT\frac{\partial h}{\partial x}$$

If we take a=250 m/year and T=2m, the accretion of the beach will be 100 cbm/year on a location, where the beach widens 10 meter over a 50 meter long distance. This is not unusual at the test site.

The average transport in one “longshore wave” is

$$q = \frac{1}{2}a\Delta WT$$

where a is the velocity of the undulation and ΔW the biggest difference in the beach width.

As an example, let a=250 m/year, T=2 m and ΔW =80 m. This gives an average transport equal 20000cbm/year due to the motion of an undulation.

A picture like that sketched in Figure A3 can to a certain extend be identified in the measurements. Figures A4 and A5 show the difference in beach width along the site developed during the first six months (January to July, 2005). The pattern of erosion and deposition is quite patchy due to a variety of different undulations, but the tendency is like that sketched in Figure A3.

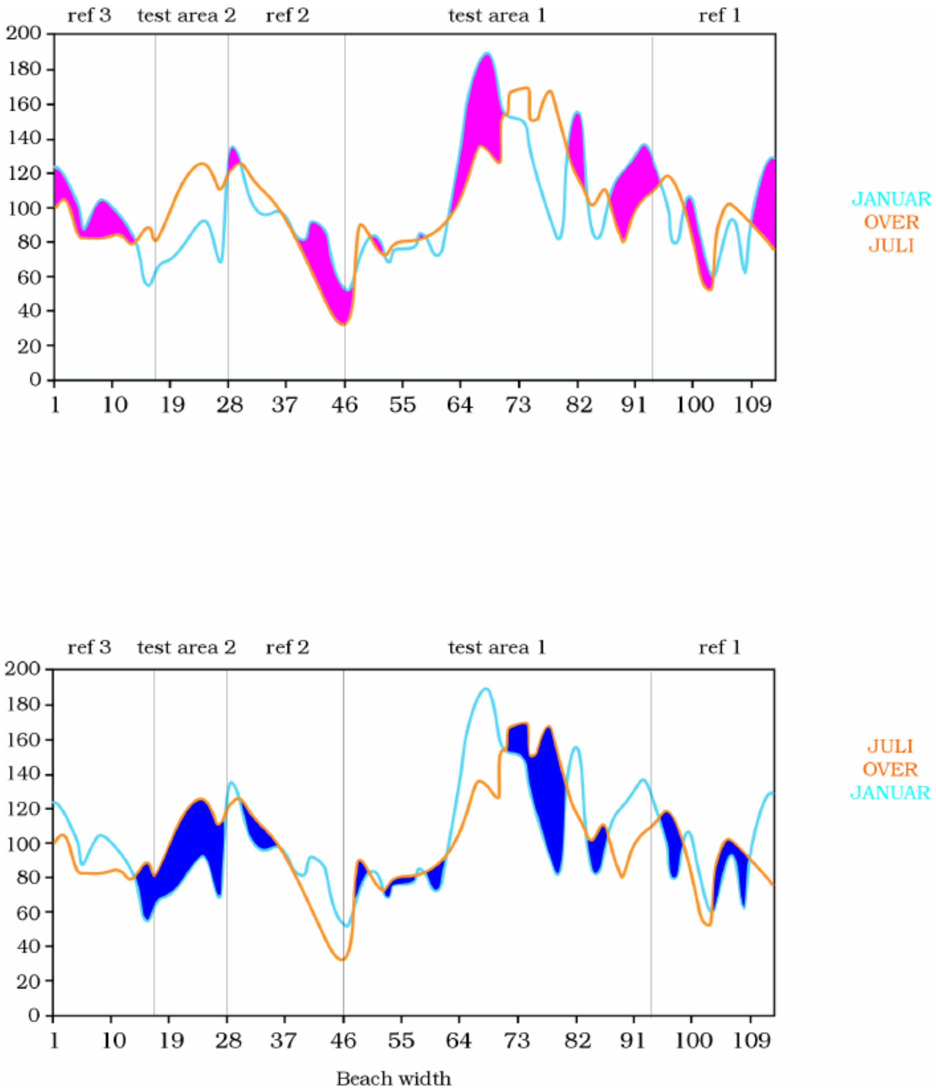


Figure A4: Variation in beach width from January 2005 to July 2005. Pink: erosion. Blue: accresion.

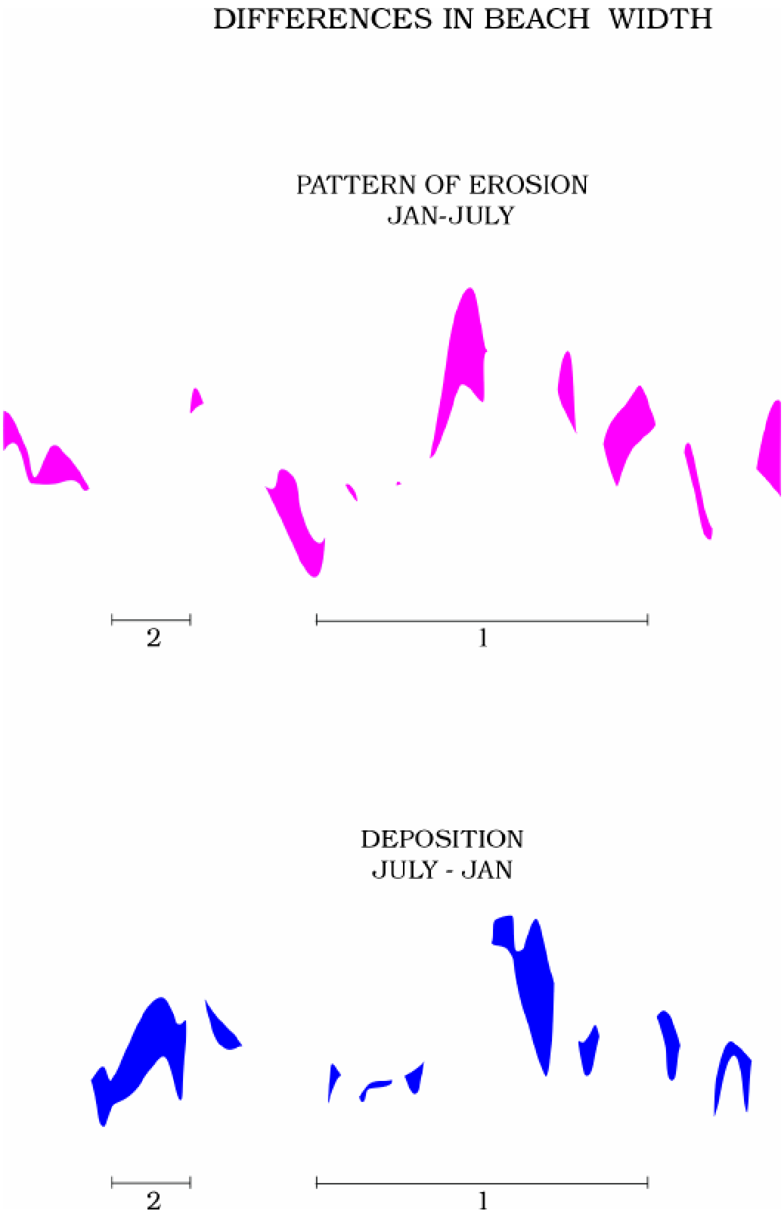


Figure A5. Pattern of erosion and deposition identified from January 2005 to July 2005.

Fig. A5 clearly illustrate, like Fig. A4, that the area of erosion is not that different from the area of deposition, and everything occur independently of the location of the drains, at least in the large test area “Rør 1”.

General observations from satellite-photos June 7 2005 and comparison with measured changes in coastline position (beach width).

Figures A6, A7 and A8 depict the satellite image along the test stretches. From these it is easy to get a visual feeling of the undulations shown in Figure A1.

Figures A9 and A10 show the measured changes in the coastline position during the first year of the test: Figure A9 shows the changes from January 2005 to April and July 2005 (Second and third surway), while figure A10 shows the change from January 2005 to January 2006.
North of reference 1, figure 4: The beach is quite narrow, and it seems like it has become even narrower during the last 12 months.

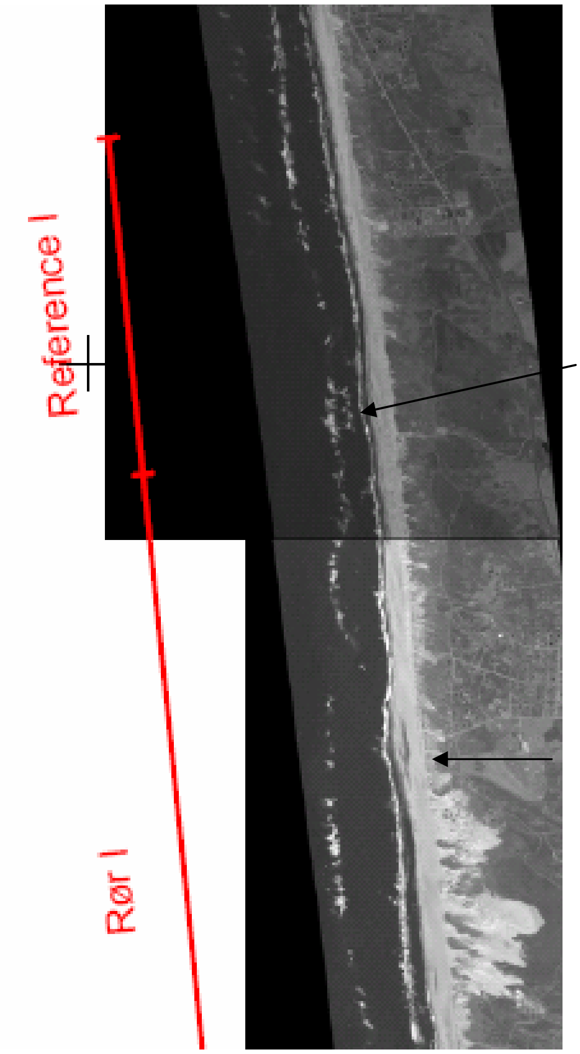


Figure A6: Satellite photo 7.6.2005 of the Northern part of the test site. The black arrows indicate pronounced peaks in the alongshore undulations.

Reference 1: at least one undulation can be identified in this part of the coast, see Figure A6, the upper arrow. The top of this undulation is on its way to move into “Rør 1” during the test period. This will lead to a loss in “Ref 1” (see the arrow to the right in Figure A10) and a gain in “Rør 1”. This latter cannot be identified in Figure A10.

Rør 1: In addition to the undulation mentioned above, another undulation can be found in this area, see the lower black arrow in Figure A6. This undulation does also move, and can be identified at the middle arrow in Figure A10. Because it still is contained within the area, only a small flux of sediment is expected to be transferred by the moving undulation from this area to the downdrift "Reference 2" area.

Reference 2: A very distinct undulation is observed at the border between "Reference 2" and "Rør 2", see the white arrow, Figures A7 and A10.

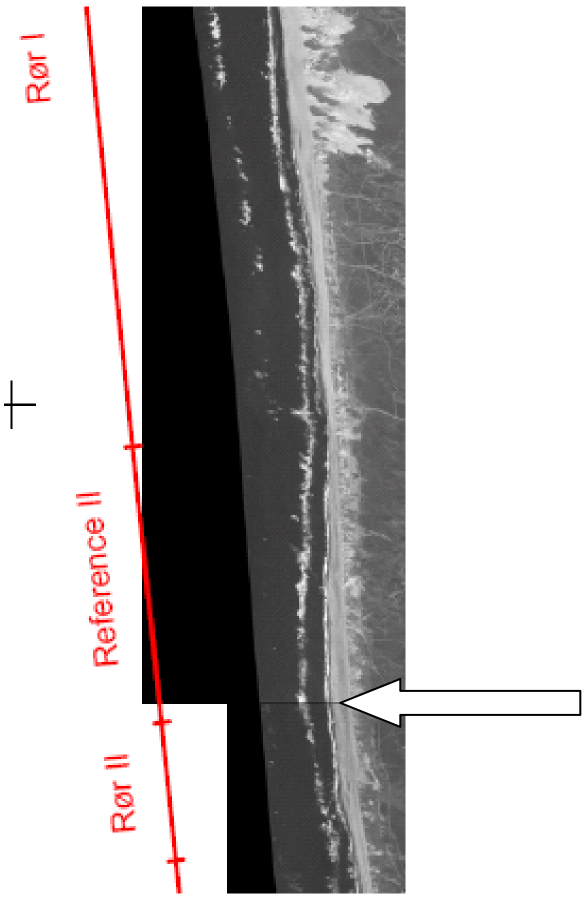


Figure A7: Satellite photo 7.6.2005 of the middle part of the test site. The white arrow indicates the peak in an alongshore undulation.

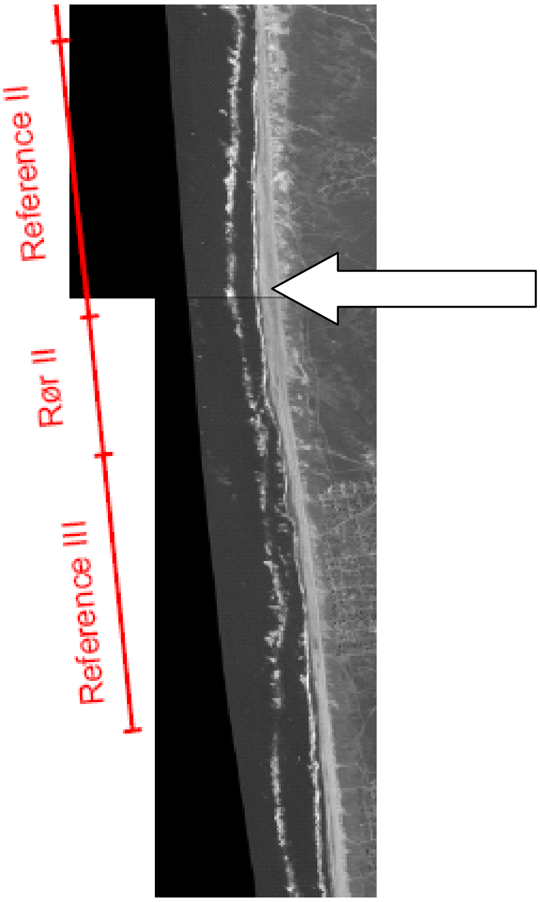


Figure A8: Satellite photo 7.6.2005 of the southern part of the test site. The white arrow indicates the peak in an alongshore undulation.

Rør 2 and Reference 3: No significant undulations are found here. It seems like the beach widens in the southern direction, indicating the existence of another undulation just south of the test site.

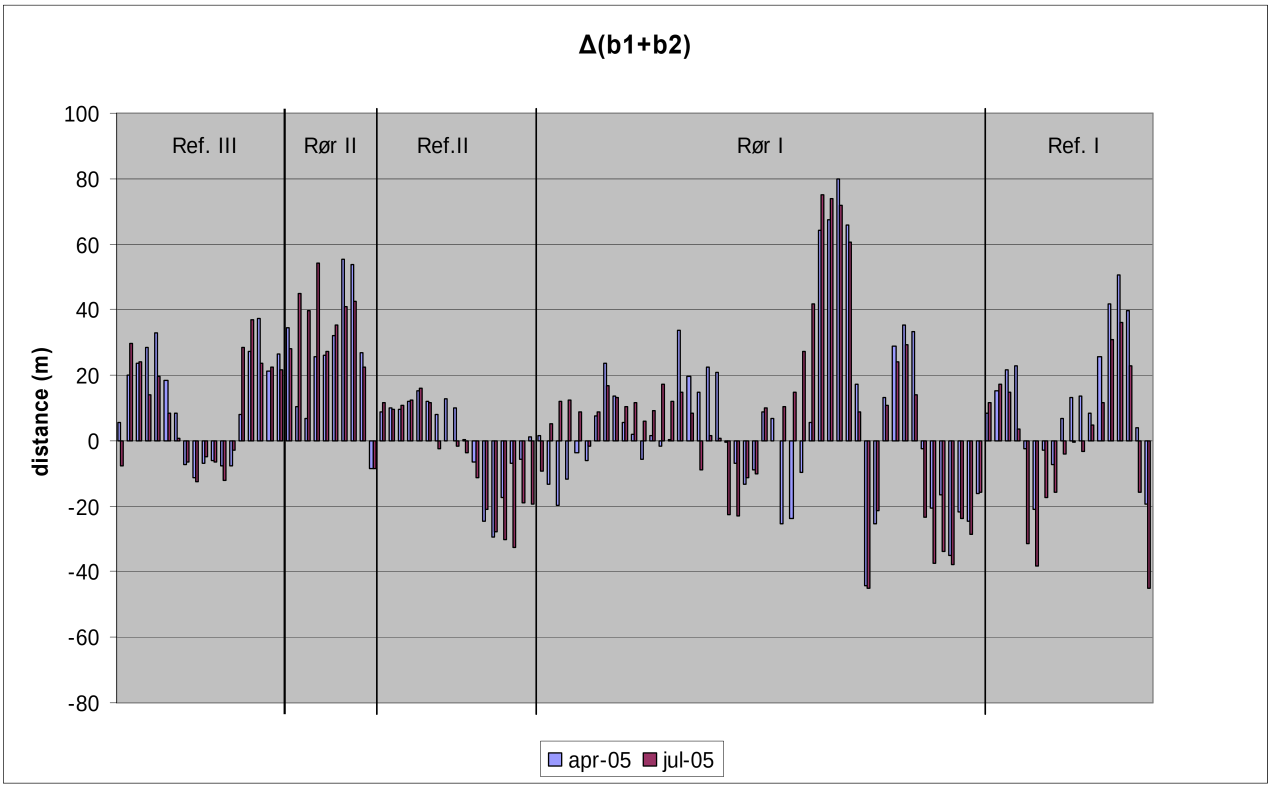


Figure A9: Changes in coastline position from January 2005 to April 2005 (blue) and from January 2005 to July 2005 (purple).

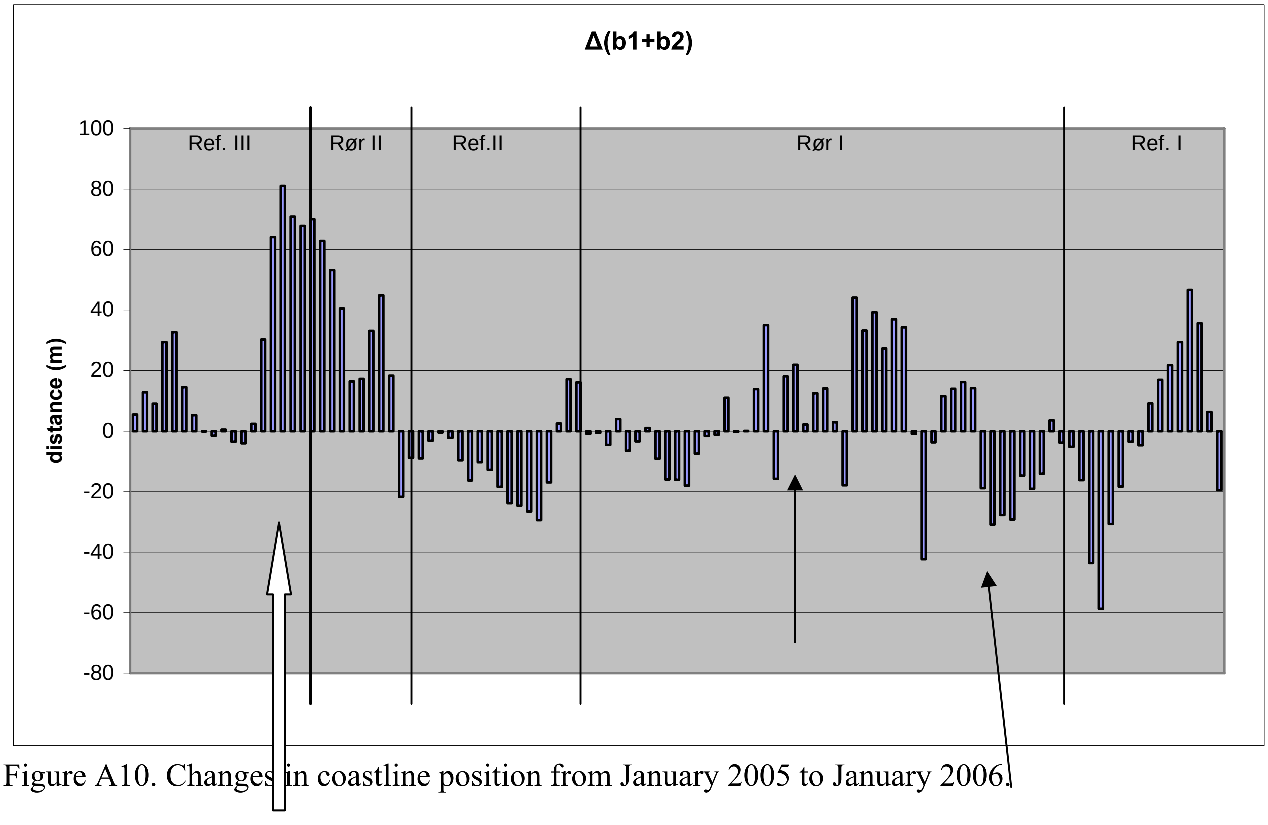


Figure A10. Changes in coastline position from January 2005 to January 2006.

APPENDIX B

THE FUNCTIONING OF THE SIC VERTICAL DRAINS

It has been discussed very much – and the discussion is still going on – how the functioning of the tubes are.
The main idea is, that the water table will decrease faster together with the falling water level in the sea in relation to tide and storm surge.
This effect is due to vertical drainage by the tubes.

Let us consider Figure B1, which shows the groundwater flow in the sand during falling sea level. If there is no freshwater supply from land, the flow pattern in the sand is like that sketched in the figure.
Lets consider the pressure conditions at tube I and II:

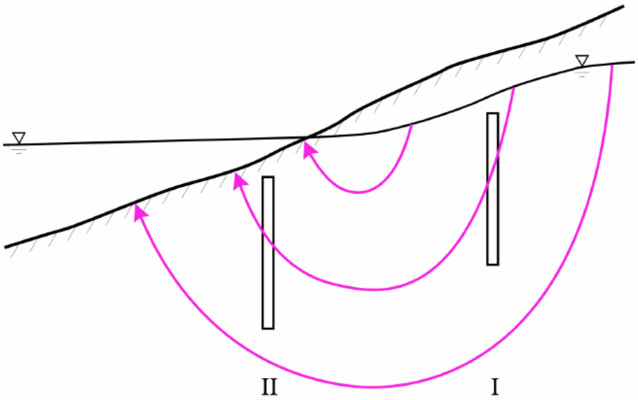


Figure B1: Ground water flow pattern in the beach during falling sea level.

At I, the flow is directed down, and it is easier to flow through the tube than outside in the surrounding soil: in the tube there are nearly no flow resistance, and with small flow velocities, the pressure within the tube can be taken to be hydrostatic.
In the soil you need an excess pressure gradient (in this case negative) to force the flow through the soil, where there is a considerable flow resistance (the Darcy law).

This is illustrated by the schematic pressure distribution in Figure B2. The continuity equation for the tube requires (in a quasi-steady flow) that the flow into the tube equals the flow out. This requirement determines the water level within the tube relative to the water level just outside in the soil. This difference is called Δz (see Figure B2). In the upper part of the tube (from z_0 to z_1 +Δz) the water pressure in the soil is larger than the pressure in the tube. This will cause a flow into the tube. In the lower part of the tube, the things are opposite: here the pressure is largest within the tube, and there will be a flow form the tube to the soil.

This shortcut through the tube of the near-tube flow will increase the vertical drainage.

The question is how much.

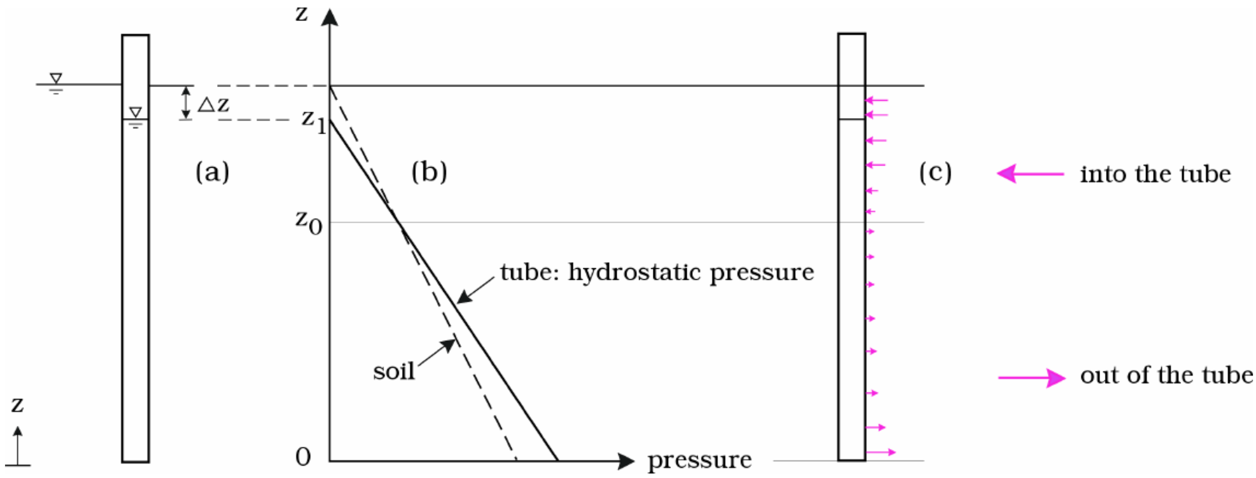


Figure B2.: Pressure distribution along a tube, and the resulting flow pattern to and from the tube located at position I (Figure B1) during falling sea level.

Let us consider a well-sorted beach without any kinds of stratification in the sand or water (salt water – fresh water). Let the permeability coefficient be k=0.005 m/sec (corresponding to 1mm sand). Without the tubes a typical lowering-velocity of the water table in the beach (forces by falling sea water level) will be

V= 1m/(3600sec/hour)/6hours)

or

V~5E(-5) m/sec =0.05 mm/sec.

This corresponds to a lowering of the water table in the beach equal 1 meter in 6 hours.

The hydraulic gradient, i, to cause this flow is given by

i=V/k = 0.01

Over 2m (the length of the tubes – this is actually exaggurated since there are only slots in the lower 1 meter of the tubes) this corresponds to 2 cm loss in energy head =Δz

The next question is how much water will flow through the tube with Δz=2cm.

To answer this a simple experiment at the Technical University of Denmark (DTU), in which the tube was placed in sand as shown in Figure B3, and the flow through the tube was measured.

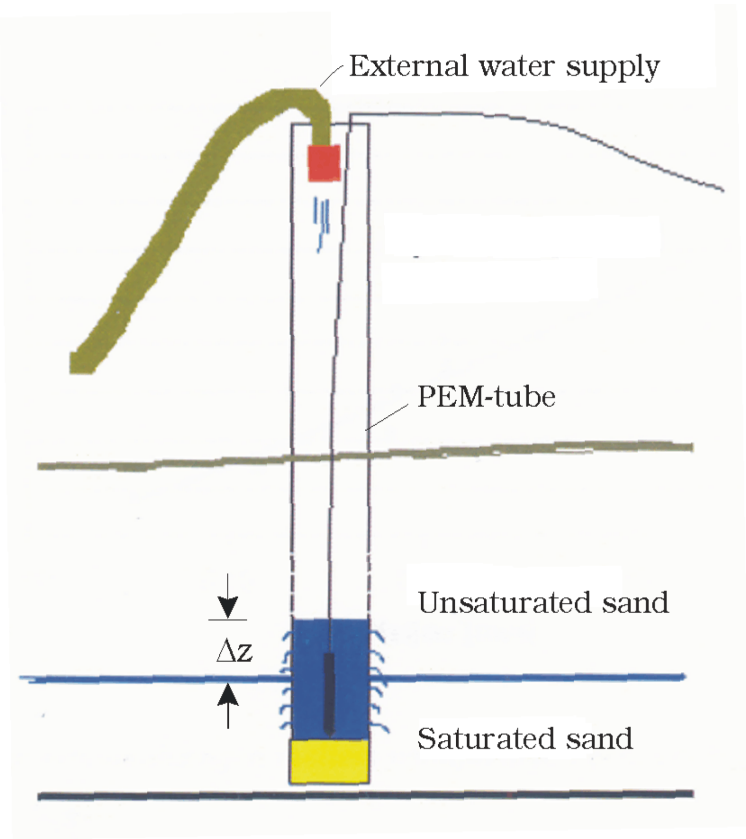


Figure B3: Set-up to determine the flow through the tube. The sand size is about 0.4 mm

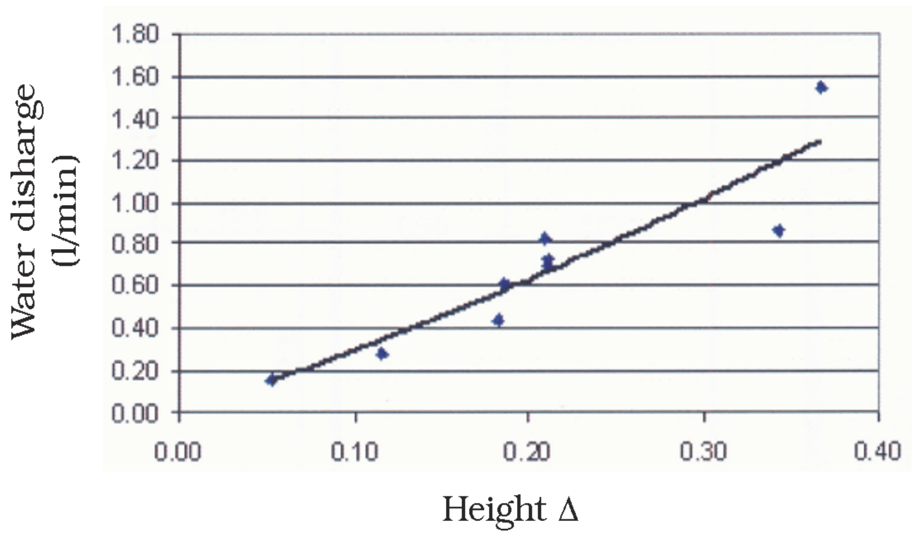


Figure B4: Relation in between Δz and flow discharge through the tube (diameter 6 cm)

With an overheight Δz= 20 cm, the discharge is around 0.6 l/minute (see figure B4), so for smaller heads like Δz= 2 cm, the flow rate is around 0.06 l/minute. This corresponds to a flow velocity of

V (tube)= 0.00006 cbm/minute/(pi*0.03*0.03) = 0.35 mm/s

This flow velocity within the tube is approximately 7 times higher than outside the tube.

The drained area around the tube is approximately a circle with a radius of 5 meter (since the mutual distance in between the tubes is 10 m), so the area to be drained is

A (drained)= 80 sqm.

The area of the tube is

A (tube)=0.0028 sqm= 3.5 E (-5) A (drained) (0.03 per thousand)

So even with a higher flow velocity in the tube (a factor 7), the impact on drainage will only be 7*0.03 per thousand= 0.21 per thousand increased drainage capacity.

In Table B1 is given the impact of different sand sizes in the beach on the drain capacity of a tube.

Table B1. Influence of sand grain size on drainage.

d (10) in mm	k in (m/s)	Hydraulic gradient i	Δz in m	V (tube) in mm/s	Improved drainage in promille
0.05	3.75E(-5)	1.33	2.66	6.5	0.65
0.1	1.5E(-5)	0.33	0.66	1.6	0.16
0.2	6E(-5)	0.083	0.17	0.41	0.04
0.4	4.68E(-4)	0.0208	0.042	0.103	0.01
0.8	1.17E(-4)	0.0052	0.0104	0.0256	0.0025

Lundgren /1/ suggests k to depend on d (10) (10% of the sediment is finer than this size, d given in mm) in the following way:

k=0.0125 d (10)**2

This expression has been used in Table B1 in which all other parameters are those used above. For the flow through the tube, Figure B4 is applied. Actually, when changing the sediment size, this experiment should be repeated with the corresponding sand size. In this case, the flow through the tube would be smaller for fine sediment, and larger for the coarse. Hence the drainage improvement would be smaller for the fine sand and larger for the coarse.
It is seen that the improved drainage of an area around each tube is only improved with less than 1 per thousand, even for a beach with a lot of fines. (Please note that Δz in case of fine sand becomes larger than the length of the tubes, which of course is not possible)

Let us finally return to Figure B1 and consider the tube II which is located out in the water where the flow is directed upwards. In this case the arguments put forward above are exactly the same, and the flow directed upwards outside the tubes will be reduced only with less than 1 per thousand, or much less than required to get any kind of stabilizing effects on the sediment grains moving on the seabed. (This would correspond to a change in tidal range from 1 meter to 1.001 meter)

Effect of stratification in the beach on the functioning.

Permeable layers:
It has been suggested by SIC, that the functioning of the tubes is due to the connection to different permeable layers by the tubes, see Figure B5. It is slightly difficult to see why these layers not anyway will contribute to improved drainage of the beach, even without the tubes. At least, the geometry of these layers must be very special in order to guide the water flow in the right direction – down to the sea. An example is sketched in Figure B6.

Further, it can be questioned if naturally depositet highly permeable layers will exist in a beach: Usually, the voids in horizontal layers of coarse material, will be filled with finer sediment dropping down from the deposits above the coarse layer.

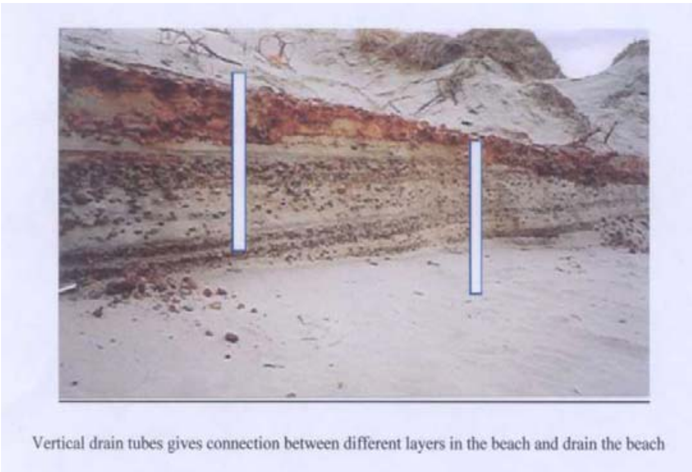


Figure B5: Photo of stratified depositions at Gl. Skagen. An interpretation given by SIC about the functioning of the drain-system is implemented in the photo.

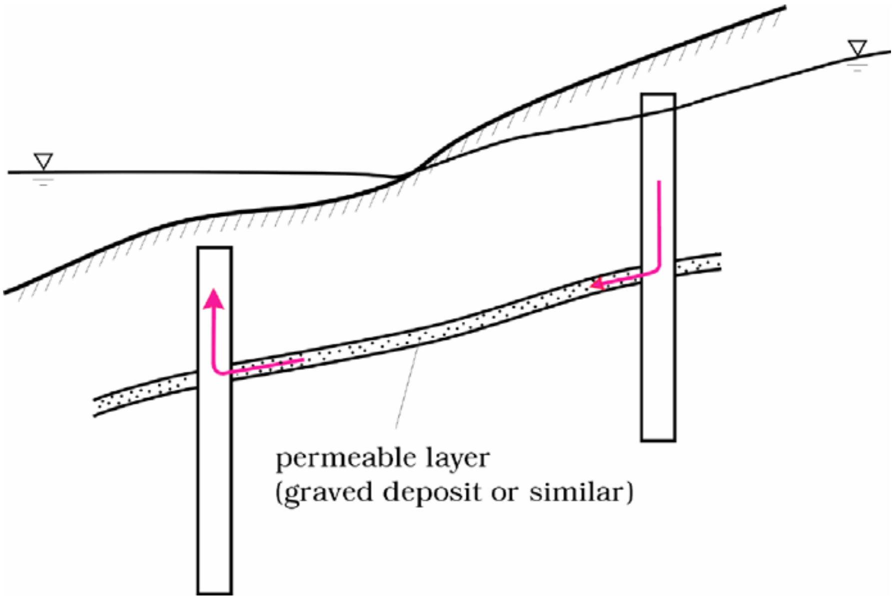


Figure B6: An example on a situation, where the vertical drain tubes might be helpful.

Impermeable layers.
If we go to the limit, where impermeable layers are present in the beach, see Figure B7, the tubes are not able to drain sufficient water anyway, since there is an upper limit of flow through the tubes as shown in Figure B4.

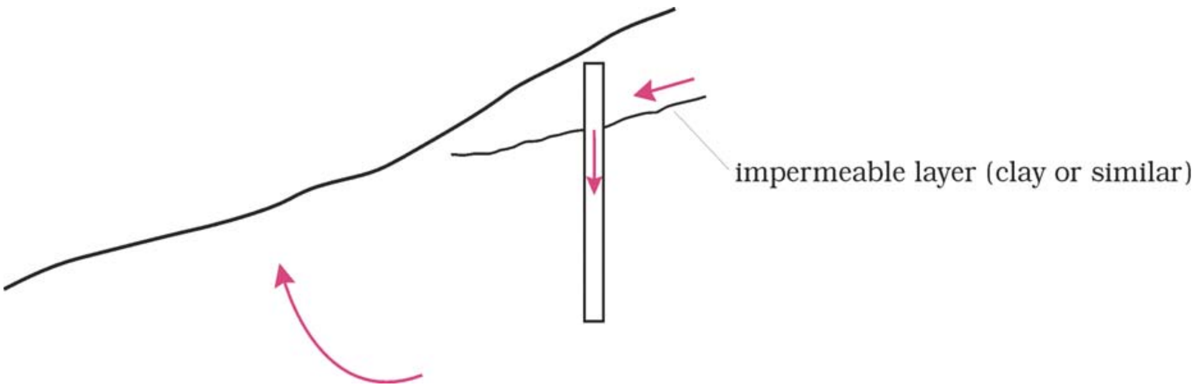


Figure B7: An example of flow through an impermeable layer conducted by the tubes.

/1/Lundgren and Brinch Hansen: Geoteknik, Teknisk Forlag, Copenhagen 1965.