Trafikudvalget (2. samling)
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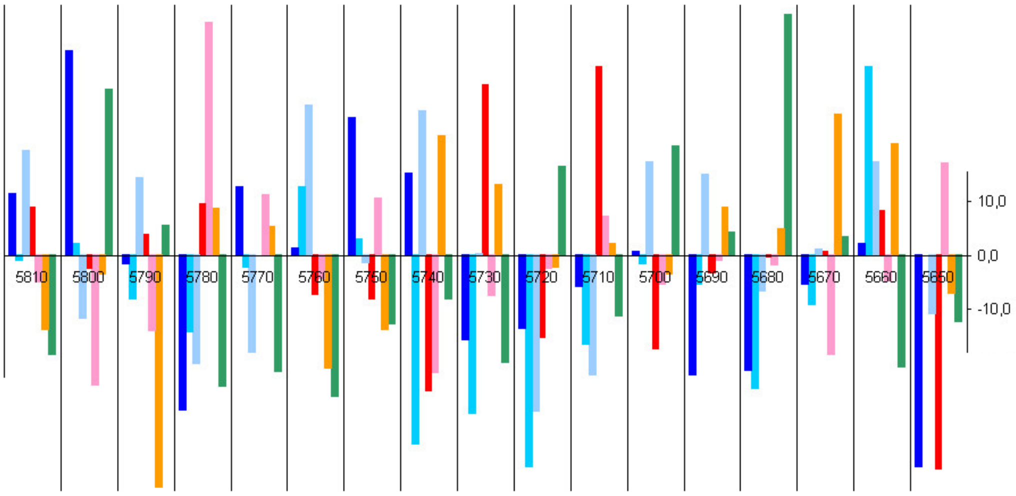
Offentligt

Report on field tests with the PEM-system at the West Coast of Jutland 2005-2008.



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Preface.

A new invention is always interesting. How does it work, is it worth to go on with, will it be profitable.
An invention which works is usually not difficult to explain how it works. An invention that does not work is sometimes much more difficult to explain why it don't work. An example is Perpetual Motion Machine. Where is the breach in the setup? Physical laws tell us that it should not work.
If you test the Perpetual Mobile, you will immediately realize that it doesn't work because you will get no surplus of energy. That can easily be tested.

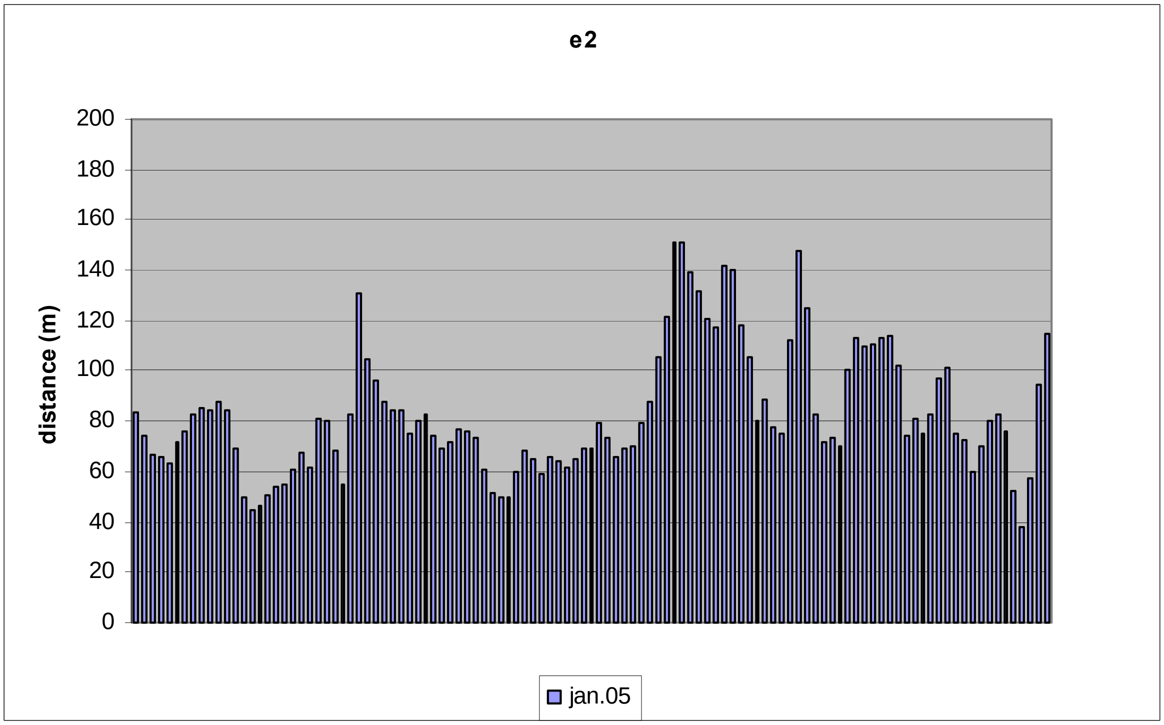
This report is about passive vertical drains. There have been earlier attempts to drain the beach. These drains have primarily been active drains that require a pump to transport the water further away from the drain. This system has had some success, the active drains collect sand, but on a very exposed coast it does not work as a coastal protection measure: the sand berm is simply too small to resist a large storm and the collected sand will disappear during a very short period of time in the beginning of a storm.

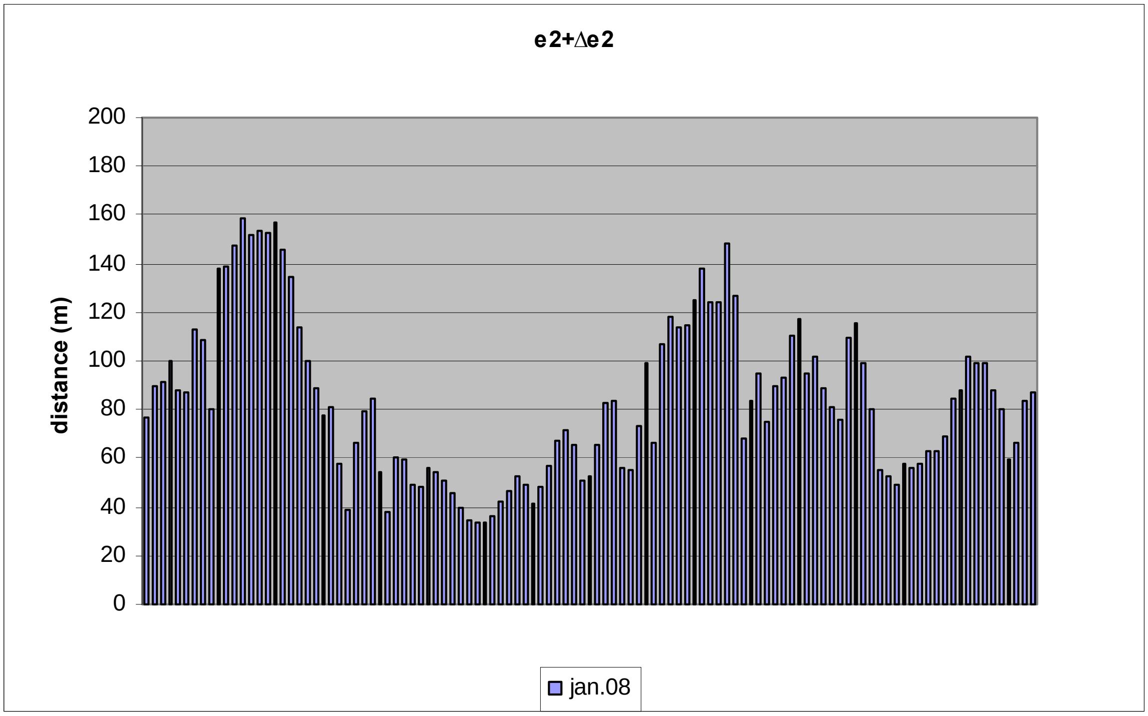
In a passive drain you do not pump the water further away but leave it to nature. Like the Perpetual Mobile also here physical laws suggest that any possible effect is negligible at best. But you never know whether something has been overlooked!

The drains have been tested on a very exposed North Sea coast for a period of three years.
Given that the natural spatial and temporal variability in the coastal profile is large, three years is too short. The beach responds to weather conditions by eroding during large waves and depositing during more calm weather. You have breaches occurring in the dunes and a very dynamic multiple bar system in front of the beach. In order to stabilize the coast you further have beach nourishment of around 600.000 cubic meters per year just north of the test stretch.

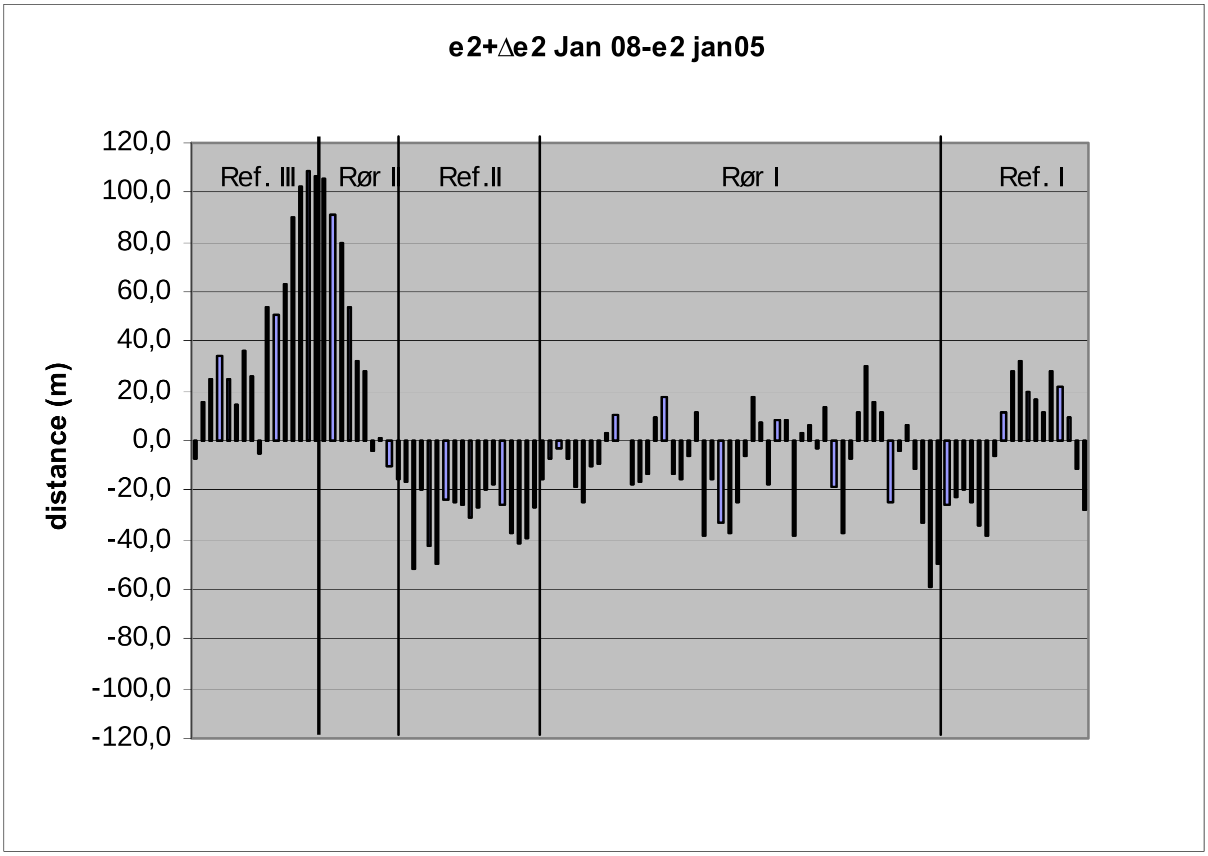
You also know that the impact from the system is weak, since you cannot observe any local accumulation around the tubes.

To make a definitive conclusion on such a test requires in the best case observations in decades of years.





Blind test: long shore variation in beach width before and after the test. Where are the tubes implemented into the beach? (Answer: see next page).



Changes in beach width during the three years test. The locations of the tubes are indicated by the vertical lines:
“Rør”: tube covered. “Ref”: no tubes.

LIST OF CONTENT.

Chapter 1: Dansk sammenfatning og konklusion.

Chapter 2: Introduction.

Chapter 3: Selection and description of the site.

Chapter 4: Description of the PEM-system.

Chapter 5: The functioning of the tubes.

Chapter 6: Description of the tests.

Chapter 7: Changes in dune volume and dune position: tables and graphs.

Chapter 8: Changes in beach volume and beach position: tables and graphs.

Chapter 9: Changes in offshore volume: tables and graphs.

Chapter 10: Morphodynamic fingerprints.

Chapter 11: Discussion of the observed results.

Chapter 12: English Summary and Conclusions.

Chapter 13: SICs egne forklaringer (in Danish).

Appendices:

1: Field test (Written by SIC).
2: Evaluation of the field tests (Written by Peter Engesgaard, KU)
3: Numerical modeling of the ground water flow (Written by Peter Engesgaard, KU)
4: Undulations alongshore (Written by JF)

Chapter 1 Dansk sammenfatning og konklusion:

I August 2004 blev det besluttet i Transportministeriet at der skulle laves et storskala forsøg på den jyske vestkyst for at identificere PEM-systemets evne til at sikre en kyst.

PEM står for Pressure Equalization Method, og består af lodrette rør, der er hule indvendig. I det rør, denne ekspert har fået udleveret, er den indre diameter er 6 cm, rørene er ca. 160 cm lange, de har slidser, der ca. er 0,2 mm tykke på den nederste halve del af røret. Andre versioner har lidt forskellig længde og diameter. Den øverste del af røret er lukket bortset fra et lille luftfilter øverst på toppen. Hele røret er vist til venstre i figuren nedenunder, slidserne til højre.

Figur 1.1. Foto af rør.

Rørene er placeret i rækker vinkelret på stranden. Der er 100 meter mellem hver række, og den indbyrdes afstand mellem rørene i rækken er 10 meter, så på en 80-100 meter bred strand står der c 8-10 rør i en række.

Den udvalgte strækning blev et 11 km langt område på Holmslands tange mellem Nymindegab og Hvide Sande, se kortet figur 2. Sandtransporten langs kysten er her i sydlig retning, og årligt transporteres der mere end 2 millioner kubikmeter sand mod syd af bølger og strøm langs kysten.

På grund af molerne ved Hvide Sande (nord for kortet, figur 2) blokeres sandtransporten her delvist, hvorfor der sandfodres, så man kompenserer for den manglende tilførsel. Årligt sandfodrer man ca. 600.000 kubikmeter syd for Hvide Sande.

Figure 2
Location of test stretches

Mål: 1:50000
Projekt: JJ/TL
Rev.: 05.10.2005

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Nr. 100
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1. Hvordan fungerer rørene?

1.1: Nærfeltet.

Det første man spørger sig selv er naturligvis hvordan rørene fungerer. Det kan *ikke* være noget med at ventilere luft, eller prikke hul i sandet, for det er jo i forvejen fyldt med luftfyldte porer, så sand kan populært sagt "ånde". Dette kan man jo forvisse sig om ved at hælde en spand vand ned i stranden, vandet forsvinder normalt ned i sandet med det samme. Så man kan hurtigt konkludere, at det ikke har noget med luft at gøre. Altså må det have noget med vand at gøre, der må strømme vand gennem røret, hvis ikke, ja så har rørene ingen virkning.

Vandets strømning.

Hvor kommer vandet fra, og hvor løber det hen?
I en strand kommer vandet dels fra havet (normalt saltvand), og dels fra land. Sidstnævnte er grundvand, der strømmer ud i havet, og dette stammer fra nedbør og er som regel fersk. Mængden af grundvand der strømmer ud i stranden afhænger af forskellige faktorer, af hvilke baglandets størrelse og højdekurver samt tilstedeværelse af grøfter og vandløb er nogle af de vigtigste. Mængden af saltvand, der strømmer ind fra havet afhænger mest af tidevand: jo højere tidevand, jo mere pumpes ind og ud af stranden. Der kan også komme vand ind i forbindelse med kraftig blæst, der stuver vandet op ude i havet. Endelig vil almindelig bølgeslag også medføre vand ind og ud af stranden. Sidstnævnte påvirkning er dog af betydelig mere lokal karakter end tidevand, der fylder stranden op mange meter ind fra strandlinien.

Hvad betyder vandet i stranden for sandets bevægelse?
Der er almindelig enighed om at en vandfyldt strand ikke pålejres samme mængde sand som en veldrænet strand. Dette hænger sammen med, at det vand der transporteres ind mod land i bølgeopskyllet i en drænet strand kan sive ned i strandplanet og herved aflejre sandet på stranden. Er stranden derimod u-drænet ryger der lige så meget vand tilbage i tilbageskyllet, som der transporters ind i opskyllet, og herved bliver det aflejrede sand taget med til havs igen. Mekanismen antages dog ikke for at være særlig væsentlig i forhold til en anden mekanisme: der transporteres betydeligt mere sand ind på kysten fordi bølgen bryder i opløbet, og i dette urolige vand kan der transportere meget sand ind. I tilbageløbet er vandet mere roligt, hvorfor der transporteres mindre med tilbage.

En anden mekanisme kan stamme fra det tilløbende grundvand fra baglandet: dette pibler ud i en smal zone tæt ved vandlinien og kan gøre sandet mere udsat for bølgeerosion. Kan denne zone gøres bredere, bliver denne effekt nedsat.
Spørgsmålet er så, om rørene vil medvirke til at strømningen i stranden bliver så anderledes, at det får en ændret effekt på sandtransporten. Den første helt absolutte betingelse herfor er, at der foregår en betydelig strømning gennem rørene, ellers ændrer man jo ikke på strømningen udenfor røret på nær meget lokalt.

Så når man skal undersøge rørenes virkning er det oplagt at undersøge hvor hurtigt vandet strømmer gennem røret. Dette kan man gøre ude i naturen, men man kan også gøre det i laboratoriet eller ved hjælp af en computermodel. De to sidstnævnte ting er lette nok at gøre, og begge kom ud med det resultat at man ikke kan forvente hastigheder i røret større end maksimalt 0.5 cm/sekund eller 30 cm/minut. Dette er meget små hastigheder, og meget mindre end hvis man forbandt røret med en pumpe, der hele tiden kunne tømme røret for vand. Sidstnævnte kalder man et aktivt dræn. Men PEM-systemet er et såkaldt passivt dræn, hvor det er naturens egne kræfter, der skal sørge for strømningen gennem røret. I naturen dannes disse strømninger af forskelle i tryk, og disse forefindes ganske rigtigt omkring et rør, hvor mekanismen er den simple, at vandet strømmer lettere gennem røret end udenfor, hvor der er sand og derfor modstand mod strømningen. Desværre kan vandet ikke strømme ret langt gennem røret, højst 80 cm (nemlig længden af den perforerede del af røret), hvorefter det skal ud af røret igen og her møder vandet igen modstand mod sin bevægelse, da det nu igen skal strømme videre gennem sandet. Dette er en af årsagerne til, at vandet strømmer så langsomt gennem røret. En anden er den lidt mere tekniske, at når vandstanden i stranden er faldende (fra høj- til lavvande) er det lettere for vandet simpelthen at synke lodret ned i stranden gennem sandet frem for først at strømme hen til røret og så tilbage igen, svarende til at ”gå over åen efter vand”.

Man kan tænke sig andre muligheder for at rørene har en funktion, f.eks. at røret munder ud i permeable lag, så vandet fra røret lettere kan strømme ud. Dette er ganske rigtigt, men i dette tilfælde behøver stranden ikke rør for at blive drænet, da de permeable lag i sig selv virker som et stort dræn.

Så vi står tilbage med den kendsgerning, at vandet i røret strømmer med mindre end 30 cm per minut, svarende til at der kan strømme højst 0.8 liter gennem røret i minuttet.

Hvor meget saltvand pumper tidevandet ind per minut?

På 6 timer stiger tidevandet på pågældende lokalitet ca. trekvart meter, og antager vi at tidevandet fyldet stranden op 30 meter ind fra strandlinien strømmer der ca. 2 kubikmeter per time per meters bredde af kysten når tidevandet stiger kraftigst, svarende til 33 liter /minut, altså ca. 40 gange så meget, som der strømmer gennem røret.

Nu står der flere rør i hver række. Hvert rør er gravet ned i stranden, så toppen er dækket med ca. 30 cm sand. De yderste rør står med toppen ikke langt over middel hav niveau, mens rørene nærmest klitten står flere meter højere. Der er derfor ikke strømning i alle rørene samtidigt så længe vi kun ser på tidevand, så den totale dræningseffekt fra en rørrække er maksimalt ca. 2 liter/minut, svarende til 2-3 aktive rør. Afstanden mellem hver rørrække er 100 meter, så pr 100 meter strand drænes der stadig kun 2 liter/minut. Men der strømmer 33 liter tidevand ind per meter pr minut eller 3300 liter tidevand ind per 100 meter per minut, altså mere end 1500 gange så meget. Så rørenes dræningseffekt er i dette tilfælde en godt en halv promille.

Populært sagt svarer dette til at man reducerer tidevandet fra 0.75 meter til 74,93 cm. Alene langs forsøgsstrækningen aftager tidevandet fra syd mod nord med 5 centimeter.

Tilstrømmende grundvand.

Vender vi os nu mod grundvandet er spørgsmålet om dette hurtigere bliver drænet væk af rørene, og derved mindsker ”ferskvandstrykket”. På lokaliteten hvor vi arbejder er der desværre ikke noget reelt ferskvandstryk, da vi opererer på den smalle tange (1-2 km bred) mellem hav og fjord. Vi skønner at der i den våde del af året strømmer ca. 1 kubikmeter ferskvand ud i stranden pr dag, altså mindre end 10 procent af tidevandsudstrømningen. Computermodellen siger da også at udsivningshastigheden af det ferske vand i strandplanen er nærmest er upåvirket af rørenes tilstedeværelse.

Kan man se dræningen?
En ting er at vi ikke teoretisk kan påvise nogen drænende virkning. Men derfor kan det vel godt virke. Næste trin er: kan man se dræningseffekten på vandspejlet tæt på rørene? Det mest oplagte vil være at kigge i det område, hvor bølgerne skyller op på stranden. Dette er et vigtigt område, for det er her sandet skal fanges. Her er der en zone, nedenfor hvilken sandet er vandmættet (blank) mens den højere oppe er mat, fordi vandet her er sivet ned i stranden. Man kan på stranden følge denne mættede zones forløb langs stranden. Kigger man nu på denne zones forløb når man passerer en rørrække skulle man tro, at denne zone indikerede et lavere vandspejl ved at bøje ned mod havet nær rækken da der jo her skulle være dræning. Men et sådant forløb er aldrig konstateret, tværtimod kan man se den vandfyldte linie forløbe totalt uforstyrret gennem en række. Dette er en særdeles stærk indikation på, at rørene ikke har nogen som helst indflydelse på vandets bevægelse i stranden.

Sandets ophobning.

Det er altså ikke muligt at identificere nogen effekt på vandets strømning. Næste trin er så at se på aflejringen af sand. Det mest oplagte her er igen, at kigge på om der ophobes sand omkring de enkelte rør. I nogle af de tidligere projekter stak rørene op over sandoverfladen, men med det nuværende koncept er de gravet helt ned i stranden, så man skal vide på forhånd, hvor rørene er. Et generelt visuelt blik over stranden indikerer ikke nogen lokal ophobning hverken omkring de enkelte rør eller om de enkelte rørrækker. Fotoet nedenfor viser en rørrække, der stikker op over stranden. Grunden til de stikker op skyldes at der har været erosion siden de blev sat ned i stranden, men billedet illustrerer klart at stranden overhovedet ikke bemærker rørene. Dette er ikke et enkelteksempel: man kan generelt overhovedet ikke se sandet hobe sig op lokalt om rørene. Denne ekspert har kørt langs strækningen i alt 14-15 gange under forsøget, og har aldrig observeret lokale sandpuder omkring rørene.
Hvorfor skulle man det? Hvis der er en drænende virkning skal vandet strømme hen til rørene. Dette kræver et fald på grundvandsspejlet i stranden hen mod røret, ellers strømmer vandet ikke derhen. Derfor skal vandstanden lokalt være lavere ved rørene end længere væk. Dette kaldes en sænkningstragt, og den aftager hurtigt væk fra rørene. Da dræningen er langt kraftigst lokal må der også opsamles mest sand lokalt. Men det gør der ikke. Dette er ikke blot en stærk indikation, nej det er nærmest et 100 % bevis for at rørene ikke har nogen virkning. I forsøgets første måneder ophobede der sig i gennemsnit cirka 25 kubikmeter sand pr meter strand. Dette er helt sædvanligt efter en hård vinter, se beskrivelsen ”erosion og aflejring” nedenfor. Hvis disse mængder sand er forårsaget af rørene svarer det til, at hver rørrække har ansvaret for en ophobning lig med 25gange 100 meter (afstand mellem 2 rørrækker) eller 2500 kubikmeter sand. Dette er et større bjerg af sand opsamlet af hver række rør, og det burde helt sikkert have givet sig udslag i at

stranden blev både højere (adskillige meter) og betydeligt bredere omkring hver række. På sigt bliver en sådan ophobning naturligvis glattet ud, men hvis man dumper 100 lastvogns læs sand på stranden kan man altså se det mere end nogle få timer efter at det er anbragt der.

Stranden synes ikke at bemærke rørene, men…

…..går uforstyrret igennem.

Man burde forvente noget lignende disse natur-skabte udbulinger, der også kan forekomme på forsøgsstrækningen.

Figur1. 3: Stranden er lokalt upåvirket af rørenes tilstedeværelse.

Såfremt rørene holder på sandet i blot rimelig stor skala, forekommer det denne ekspert *fuldstændigt ubegribeligt*, at sandet ikke ophober sig lokalt i nærheden af rørene eller rørrækkerne – mellem hvilke der er hele 100 meter.

1.2. Storskala forsøget:

Som beskrevet ovenfor kan man ikke se nogen virkning helt lokalt, så vi skal undersøge systemet i en større skala. SIC blev lovet en stor sammenhængende strækning på kysten. Spørgsmålet er naturligvis: hvad skal vi kigge efter, hvor og i hvilken skala?

Vi skal vel først og fremmest se efter om stranden bliver stærkere eller svagere. Men sammenlignet med hvad? Det bedste ville være at have 2 identiske strande, udsat for samme vind, bølger og strøm, og have rør i den ene og ingen rør i den anden. Men det har vi ikke, da forholdene langs kysten varierer. Derfor må vi sammenligne strandens opførsel efter at rørene er sat i stranden med den samme strands opførsel tidligere. Herudover kan vi på stranden tilføje nogen såkaldte *reference områder*, hvor der ikke er rør, og vurdere om disse områder skiller sig ud fra *rør-områderne*. Disse 2 typer områder er vist i figur 2. Da SIC ønskede et langt sammenhængende rørområde, er de forskellige områder desværre ikke lige lange. De ændringer der observeres skal så adskilles i de ændringer, der er forårsaget af rørene og dem, der er forårsaget af naturlige variationer. Da der imidlertid ikke er noget tydeligt lokalt aftryk af rørene, bliver vi hurtigt begrænset til at sige: kan de observerede ændringer anses for at være indenfor rammerne af de naturlige variationer, der altid foregår på en kyst, eller er det der foregår så specielt, at rørene må have en effekt.

For at forstå en sådan analyse er det vigtigt at kende til en kysts adfærd som kort beskrevet i det følgende.

Erosion og aflejring.
Langs den jyske vestkyst er der visse steder erosion, andre steder aflejring (fremrykning af kysten). Disse 2 størrelser er tids-midlede værdier over mange år, og på en kyststrækning, der f.eks. generelt rykker frem, kan der godt i nogle år ske en erosion, d.v.s. tilbagerykning. Dette skyldes, at erosion/aflejring afhænger af bølge, strøm og vandspejls forhold, samt tilførselen af sand.

Når man taler om erosion/aflejring af en kyst, vil man visuelt altid forholde sig til om *stranden* vokser eller bliver eroderet. Stranden er dog kun en del af det samlede system, idet der også sker store ændringer af bunden udenfor vandlinien, og det er vigtigt at betragte det samlede system. Herudover sker der også vindtransport af sand fra strand til klit.

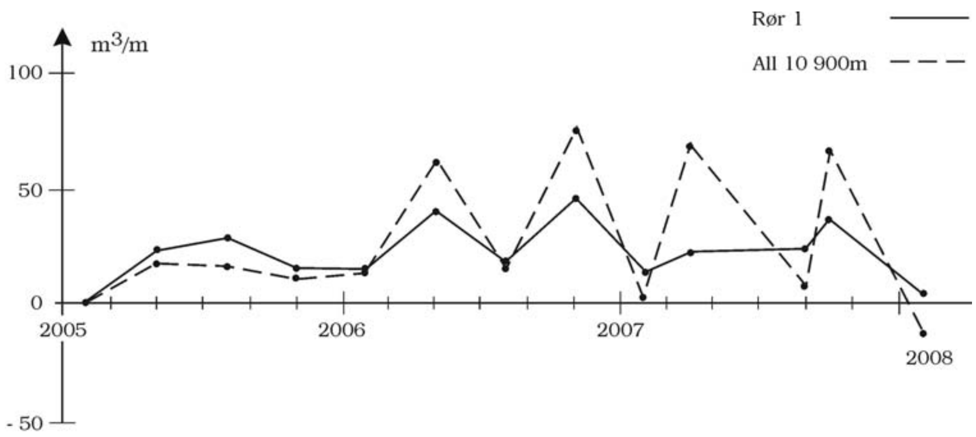
Under en stor storm eroderes en strand generelt. Da storme er hyppigst om vinteren kaldes stormprofiler også vinterprofil. Erosionen skyldes først og fremmest at brydende og brudte bølger transporterer sand i en retning væk fra kysten. Under en storm gnaves der derfor af stranden - specielt hvis vandstanden er høj - og sandet transporteres et stykke væk fra kysten. Ofte kan man også iagttage, at revlerne samtidigt bevæger sig en smule væk fra kysten.

I mildere vejr-perioder er bølgerne mindre, og kan derfor nå helt ind til stranden, før de bryder. I disse perioder transporteres sandet ind mod kysten af bølgerne, men mængden af sand der transporteres af disse mindre bølger, er langt mindre pr. dag end den udadrettede transport fra stormbølgerne. De mindre bølger regenerer altså stranden (sommerprofil), men det kan tage meget lang tid, specielt efter en kraftig storm som den vi havde den 8. og 9. januar 2005, få uger før rørene blev sat i stranden.

En storm kan altså skabe et reservoir af sand ude i vandet, der kan bruges til at genopbygge stranden på et senere tidspunkt.

Herudover skal det nævnes, at der også sker variationer i sandtransporten på langs af kysten forårsaget af en kraftig ”bølge-genereret” strøm, der igen forårsages af bølgers brydning. Strøm gennem et hestehul i revlen er et eksempel på en bølgegeneret strøm. Bølgerne bryder normalt på revlerne, og er der hul i revlen kan bølgerne her nå helt ind til stranden før de bryder, og herved forårsage lokalt større angreb på stranden. Generelt betyder revlernes opførsel således meget for strandens udseende.

Klitterne er også en vigtig del af stranden: vinden transporterer sand fra stranden ind mod klitterne. Er klitterne høje vil sandet normalt transporteres langs klitfoden. Kommer der en åbning i klitten vil vinden koncentreres her og transportere sand længere ind mod land.



Figur 1.4. Variation i strandvolumenet gennem de tre forsøgs år.

Figur 1.4 ovenfor viser noget om strandens bevægelse. Målingerne er en del af det nuværende forsøg, og viser hvorledes mængden af sand i stranden varierer hen gennem de tre år. Vi begynder i januar 2005, lige efter en stor storm 8. og 9. januar 2005. Den fuldt optrukne linie viser hvor meget sand, der siden januar 2005 har lagt til i et område kaldet rør 1 som beskrives nedenfor, men som er et 4700 meter langt sammenhængende område med rør i.
Den stiplede linie viser den tilsvarende variation midlet over hele forsøgsområdet, d.v.s. alle områder med og uden rør. Med en bredde af stranden på 100 meter viser figuren at stranden vokser og aftager i højden med typiske størrelser på en halv meter fra måling til måling.

Kontrol kasserne:

Kysten er med ca. 3 måneders mellemrum målt op i linier på tværs af kysten, på strand og klit med 100 meters mellemrum, og ude i vandet med 200 meters mellemrum. Herved er man i stand til at beregne hvor meget sand der ligger i stranden og i kystprofilet. Vi definerede stranden som et 100 meter bredt bælte, der starter i klitfoden, defineret som kote +4.00 meter over havets middel niveau. Figur 1.4 viser variationen i strand volumenet foran det store rørområde 1. Da målingerne som sagt er foretaget med 100 meters mellemrum langs stranden, så vi ser på ændringer der er af en skala på mindst 200 meter eller mere på langs af stranden.
Tallene bag den fuldt optrukne linie i figuren er vist i tabel 1.1.

Dato *Måned. år*	*04.05*	*07.05*	*10.05*	*01.06*	*04.06*	*07.06*	*10.06*	*01.07*	*04.07*	*08.07*	*09.07*	*01.08*
Strækning	m^3/m	m^3/m	m^3/m	m^3/m	m^3/m	m^3/m	m^3/m	m^3/m	m^3/m	m^3/m	m^3/m	m^3/m
Ref. I	13,4	2,6	-12,2	-11,5	-6,9	-18,2		-32,5	24,4	-12,8	38,3	-36,3
Rør I	22,3	28,8	17,5	16,7	39,9	18,5	43,2	11,5	21,1	21,3	34,5	0,3
Ref. II	-9,5	-32,2	-42,3	-54,6	-41,3	-64,7		-104,8		-150,3		-163,8
Rør II	45,0	58,3	68,1	93,3	91,7	87,3	99,9	37,5	184,6	27,2	206,7	-25,7
Ref. III	25,2	29,3	38,2	54,4	93,2	81,5	118,2	104,3	188,0	113,0	139,2	114,8
Middel, total	18,5	17,9	11,4	14,2	60,4	16,2	74,1	4,0	68,2	4,9	66,8	-14,5

Tabel 1.1: ophobet sand siden januar 2005 på de forskellige strækninger, angivet som kubikmeter per meter strand langs kysten. Dividerer man tallene med 100 får man hvor meget stranden hæver eller sænker sig i højden.

Desværre er figur 3 en altafgørende figur, der viser at et sådant forsøg på at vurdere rørenes funktion er umulig.
Hvis vi går ind på figur 1.4 – eller tabel 1.1- opdager vi, at havde forsøget kun varet tre måneder, ja så ville konklusionen være, at der foran rørene i det lange rørområde kaldet rør1 var opsamlet 22 kubikmeter sand på 3 måneder pr m langs kysten. Dette ville så være resultatet, der skulle fremgå af den første halvårsrapport, som SIC fik indføjet i

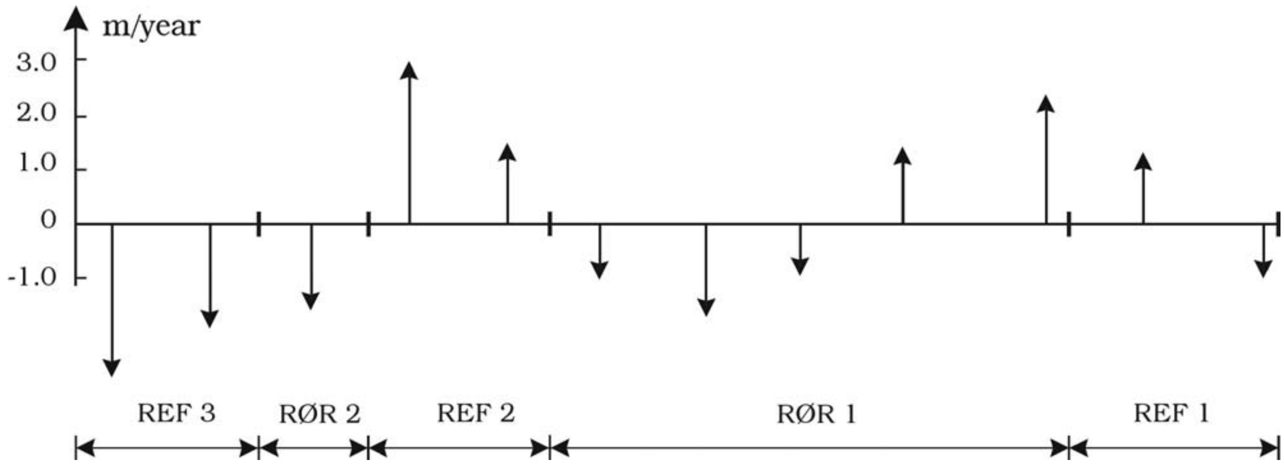
kontrakten skulle laves, selv om forsøget knapt var begyndt. 1-års rapporten ville derimod sige at rørene havde samlet 17 kubikmeter sand, og var forsøget stoppet f.eks. september 2007 var resultatet stadig positivt: +34 kubikmeter (men nu opsamlet over knapt 3 år), men da forsøget stoppede jan 08, ja så sluttede vi af med et rundt nul hvad angår kasseregnskabet om strand volumenet.

De store variationer skyldes blandt andet ovennævnte vinter- og sommerprofiler. Problemet er nøjagtigt lige så svært som at måle middeltemperaturændringerne her på kloden. Man stikker ikke bare et termometer ud af vinduet en dag i marts og igen i juli og opdager, at jordkloden nu er blevet betydelig varmere. Man ville nok opnå et bedre resultat, hvis man målte i marts og så ventede til næste marts med at måle igen. Men selv her får man jo en temperaturforskel mellem de to målinger, selv om man måler på samme tidspunkt på dagen begge dage, hvilket naturligvis hænger sammen med naturlige *fluktuationer* i temperaturen. Hvis man derimod målte mange år samme tidspunkt på året ville man efter et tilstrækkeligt antal år kunne sige om temperaturen på pågældende lokalitet har en tendens til at stige eller falde.
Hvis de middelændringer der sker, er så små i forhold til årets naturlige variationer, så skal man måle over langt længere tid for at få en sikkerhed for, hvad middelændringen er. Hvis man antog at temperaturen på jorden voksede med 5 grader om året, så behøvede man muligvis kun et år til at finde ud af, at temperaturen i det mindste voksede ud over de årlige variationer. Vokser den derimod kun 0.1 grad om året, så skal man måle mindst 15-25 år for at indse om der er noget om det.

Vender vi tilbage til kysten er problemet nøjagtigt det samme, jævnfør figur 1.4: der er ikke nogen kraftig tendens til at sandvolumenet stiger hele tiden, tværtimod går det op og ned hele tiden, og vinterværdierne ét år er ikke lig med vinterværdien næste år. At værdien hele tiden er positiv skyldes, at målingerne begyndte lige efter den store storm 8. og 9. januar 2005. Her må man formode at bølgerne har eroderet kysten kraftigt, og samlet et reservoir af sand udenfor kystlinien. Dette er så skyllet tilbage på stranden igen under mere roligt vejr.
Det eneste der kan konkluderes af figur 3 er, at rørene i hvert fald ikke sikrer at strandvolumenet vokser vinter efter vinter, så rørenes effekt må i bedste tilfælde være meget svag.

Det er derfor umuligt at sige noget som helst om en eventuel påvirkning i et forsøg, der kun kører 3 år.

Tidligere ændringer af kysten:



Figur1.5 Gennemsnitlig ændring af kysten fra 1987-2004.

Figur 1.5 viser hvorledes kysten i gennemsnit har opført sig de forrige 18 år (1987 -2004) langs det område, vi kigger på. I alle årene har man sandfodret syd for Hvide Sande, dog kun rigtigt meget siden 1993. Nogle steder lægger kysten til med nogle meter om året, andre steder eroderes der. I gennemsnit langs hele strækningen kan man se, at kysten er stabiliseret på grund af sandfodringen. Variationerne langs kysten er i øvrigt ikke helt usystematiske, men kører i et bugtet forløb. Dette tyder på at der er lange bugtninger, der bevæger sig langs kysten, hvilket også kan observeres på satellitfoto (og Google).
I virkeligheden er det disse tids-midlede værdier man skal sammenligne med, hvis man skal se, om rørene har nogen virkning. Således antyder Figur 1.5, at f.eks. reference område 3 bliver eroderet med ca. 1-2 meter om året. Tabel 1.1 viser, at dette område er vokset ganske betydeligt gennem hele forsøget, og sammenholder man det med at der her tidligere var erosion, ville man få en endnu større ændring af aflejringsforholdene. Så på trods af at der i reference 3 ikke er rør, er erosion åbenbart vendt til betydelig aflejring. Modsat er der i reference 2 tidligere aflejring, men her har man nu betydelig erosion, og det burde tale til rørenes gunst (da ref. 2 er uden rør). Men det gør det absolut ikke, da den store erosion i ref2 kan forklares af ganske naturlige årsager, nemlig et vindbrud – eller vindskår - i klitten. Vindskår i klitterne er et naturligt forekommende fænomen langs den jyske kyst, og ses f.eks. hyppigt ved Gl. Skagen.
I vort område er der f.eks. også tydelige vindskår i midten af rør 1 som vist på fotoet nedenfor.

Figur1.6. Vindskår i midten af rør område 1. Dette er af ældre data og bemærkes ikke synderligt i forsøgsdataene.

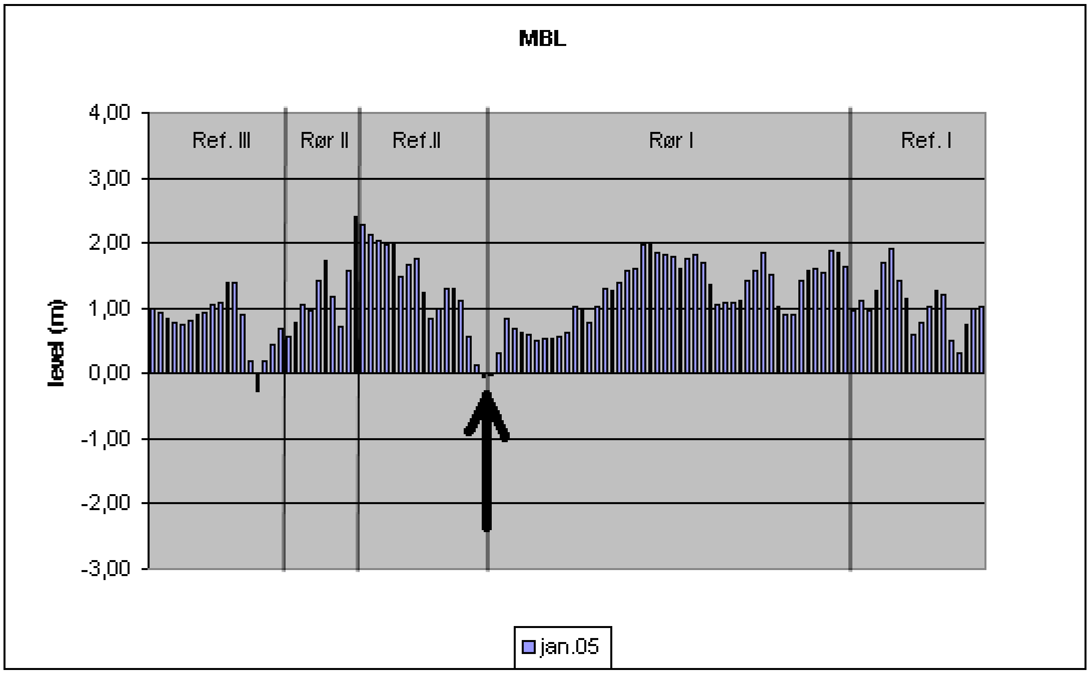
Under forsøget udvikledes et nyt vindskår i overgangen mellem rør område 1 og reference område 2 som vist i figur 1.7A og B. Det er klart, at kan man tillægge rørene ansvaret for at dette vindskår er opstået, så har rørene en særdeles kraftig virkning på kysten.(og denne ekspert ville nødig have et sommerhus ved kysten nedenfor det sted hvor rørene stopper).

Figur 1.7A: Vindskår i overgangsområdet mellem rørområde 1 og reference område 2. Foto fra 2006.

Figur 1.7B.Vindskåret i overgangsområdet mellem rørområde 1 og reference område 2 har udviklet sig kraftigt de sidste halvandet år. Foto fra 2007.

Hvordan opstår et vindskår?

Ved de høje klitter vi har her (nogle steder mere end 20 meter høje) er det ikke, som f.eks. ved Skallingen, havet der strømmer ind gennem klitten og laver et skår, det er derimod vinden. Vinden transporterer sandet på langs og på tværs af stranden, og vinden har lettest ved at transportere sandet, hvis stranden er tør og uden vegetation. Vegetationen i skræntfoden (hovedsagelig Hjælme) kan blive skadet af bølger under høj



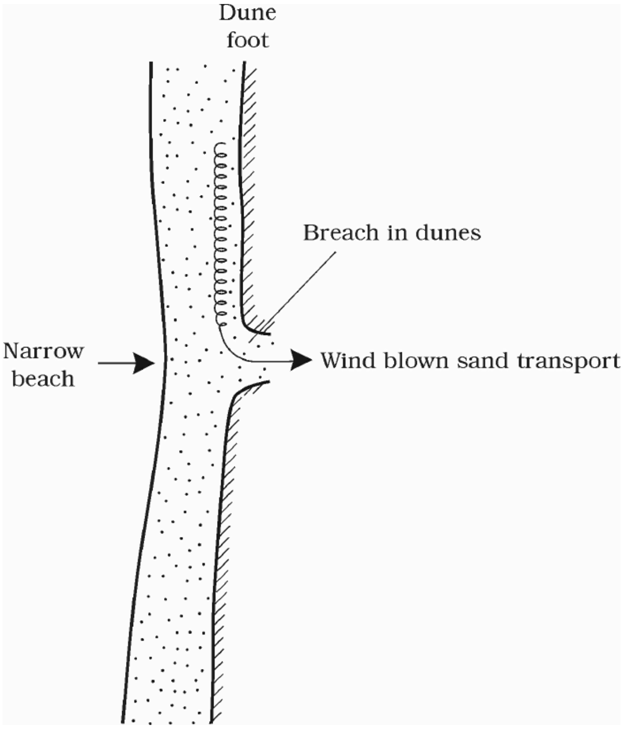
Figur1. 8: Styrke af stranden ved forsøgets begyndelse. Stranden er svagest hvor reference 2 begynder.

vandstand, specielt hvis stranden foran er svag, så bølgerne kan trænge længere ind. Ser vi på figur 1.8 ser vi, at netop overgangen mellem rør 1 og ref. 2 (sammen med eet sted i ref. 3, men her var stranden meget bredere og klitten højere) var det svageste sted på hele strækningen.

Samtidigt er klitten ved dette overgangsområde ikke særlig høj, ned til ca. 11 meter. Klittens højde har stor betydning for vindens evne til at passere over klitten. Er der en lavning i klitrækken koncentreres vinden her, hvis den har retning fra havet. Som skitseret i figur 1.9 har det store konsekvenser for sandtransporten langs stranden. Denne foregår for en stor del langs klitfoden indtil der kommer en åbning i klitten, hvorigennem sandet føres længere ind i landet.

Hele denne proces stabiliseres med tiden, dels når stranden foran igen får mere volumen og dels ved at nye klitter opstår inde i landet af det sand der fyger ind gennem skåret. Dette er grunden til at vindskåret i midten af rør 1 ikke har nogen synderlig effekt på volumenændringerne, da dette vindskår er ved at være fuldt udviklet og stranden foran er bred.

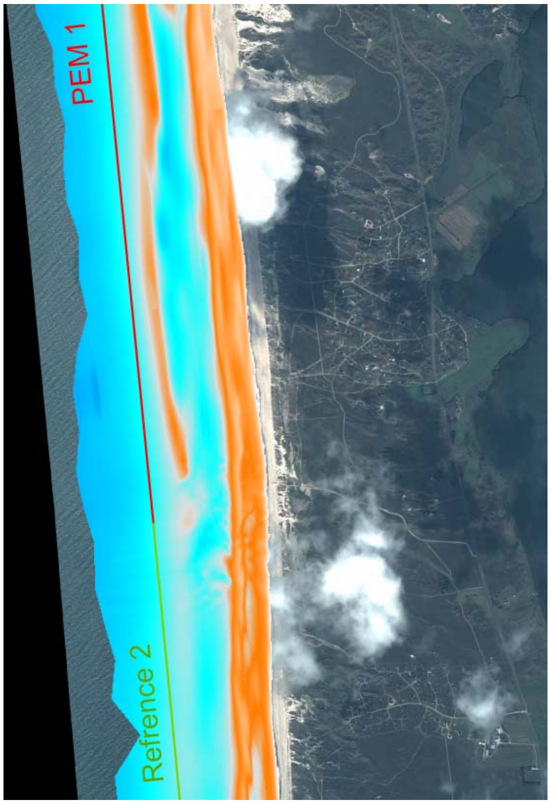
Kombinationen af lav klithøjde og svag og smal strand gjorde allerede inden testen overgangsområdet mellem rør1 og ref2 til et potentielt område for dannelse af vindskår.



Figur1. 9: Vinden transporterer sandet langs klitfoden og ind gennem eventuelle lavninger eller skår.

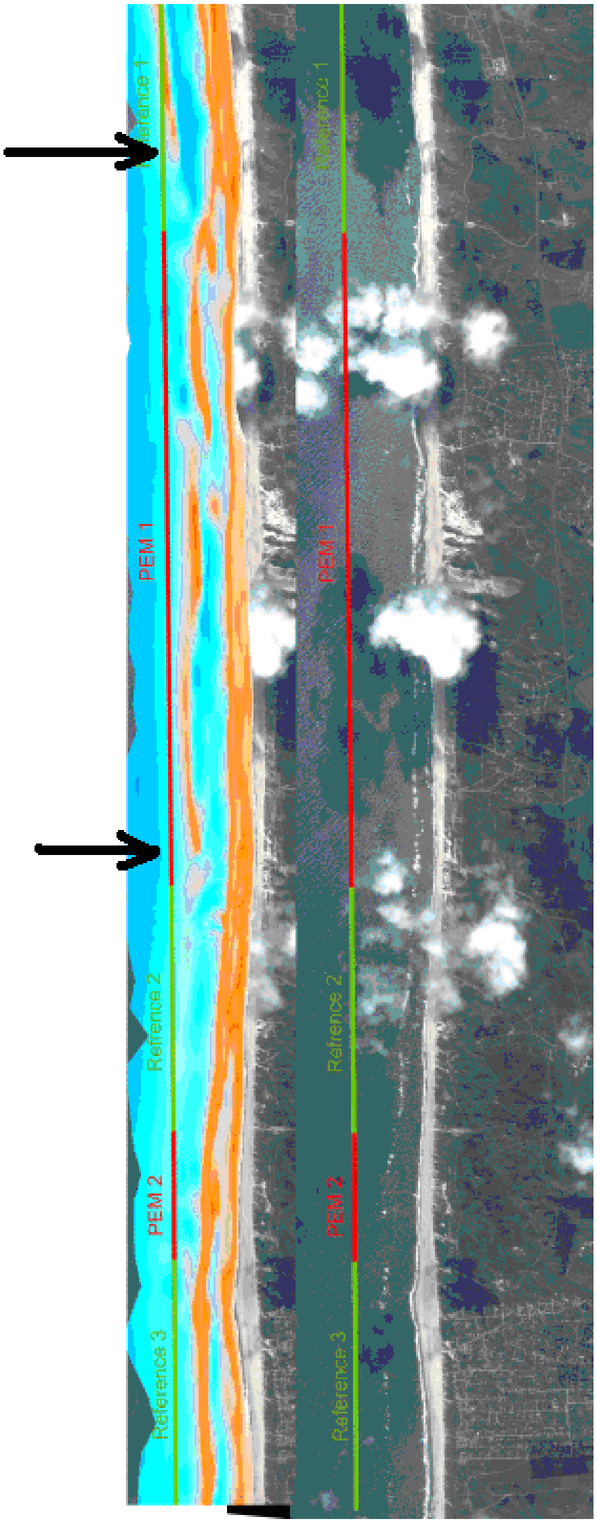
Hvorfor er stranden smal netop her?

I beskrivelsen om erosion og aflejring blev det nævnt, at revlerne har stor betydning for strandens udseende. Overgangsområdet mellem rør1 og ref2 er netop et sådant eksempel. Figur 1.10A viser revlesystemet ud for pågældende lokalitet. De orange områder er lavvande områder, der beskriver hvor revlen ligger. Den ydre revle standser netop kort før reference område 2 begynder. Bølger bryder når der bliver lavvandet, og det er der på toppen af revle. Derfor kan man normalt se, hvor revlerne ligger ved at kigge på, hvor bølgerne bryder. Dette kræver naturligvis, at de indkommende bølger har en vis højde, idet man normalt har at bølgerne bryder når deres højde er cirka 80 % af vanddybden. Fotoet figur 1.10B viser samme lokalitet som figur 1.10A, og man kan tydeligt se at bølgebrydningen standser mod syd på den ydre revle.
Hermed er der plads til de store bølger at vandre ind og angribe kysten som vist i figur 1.12.

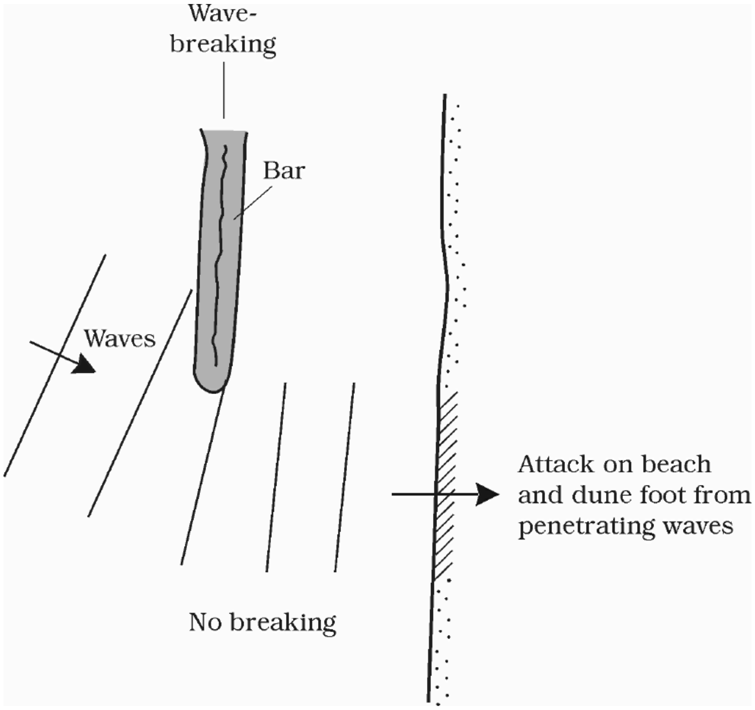


Figur 1.10A. Den ydre revle standser lige nord for overgangsområdet…

Figur 1.10B …som det kan ses på bølgebrydningsmønsteret på dette foto



Figur1.11… og den ydre revle stopper også lige før overgang mellem reference 1 og det store rørområde 1. Begge steder det giver det sig udslag i en svag strand på grund af bølgeerosion.



Figur 1.12: Bølgerne bryder på revlen som det ses i figur 1.10. Hvis revlen stopper, fortsætter de store bølger ubrudte længere ind og kan derved angribe tættere på stranden. Dette forårsager erosion og hermed en smal strand.

Yderst uheldigt er også det nordlige overgangsområde mellem reference 1 og rør 1 lagt lige nedenfor det sted, hvor den yderste revle stopper. Også her observerer man en svag strand.

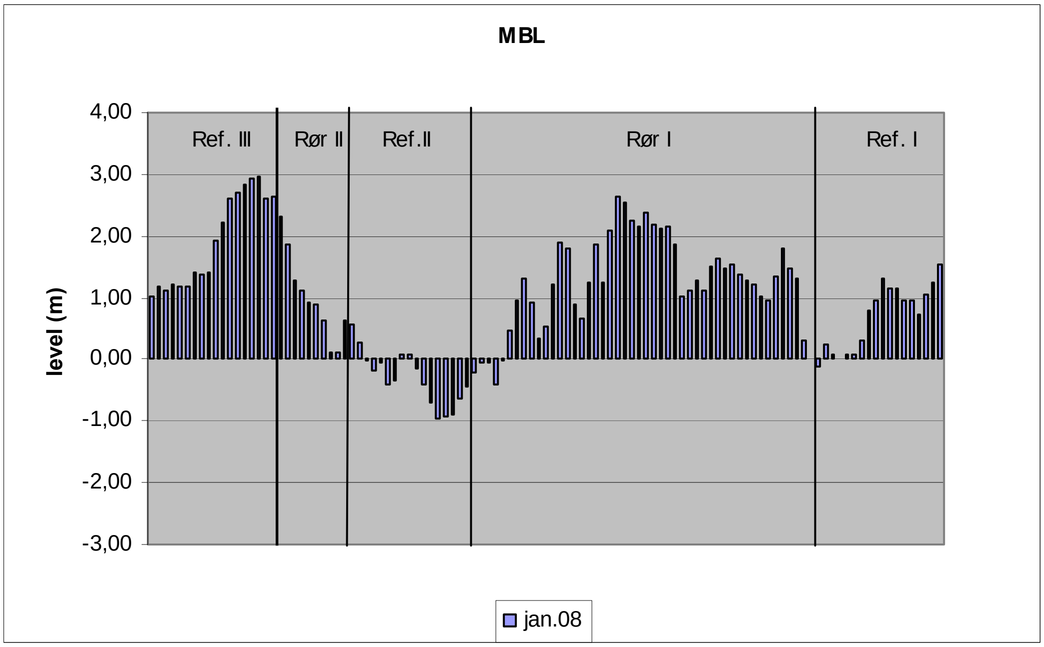
Set i bakspejlet burde man have lagt overgangsområderne et andet sted. Eksperten bliver her nødt til at sige at han ikke var medlem af gruppen i den særdeles vigtige indledende fase af forsøget i efteråret 2004, der burde inkludere en detailleret inspektion af stedet. Det var dog ikke sikkert dette havde forandret noget, da det først var med de mange detaillerede målinger af kysten under selve forsøget, at mange af kystens karakteristika blev klarlagt for denne ekspert.

Har rørenes afslutning noget med vindbruddet at gøre?

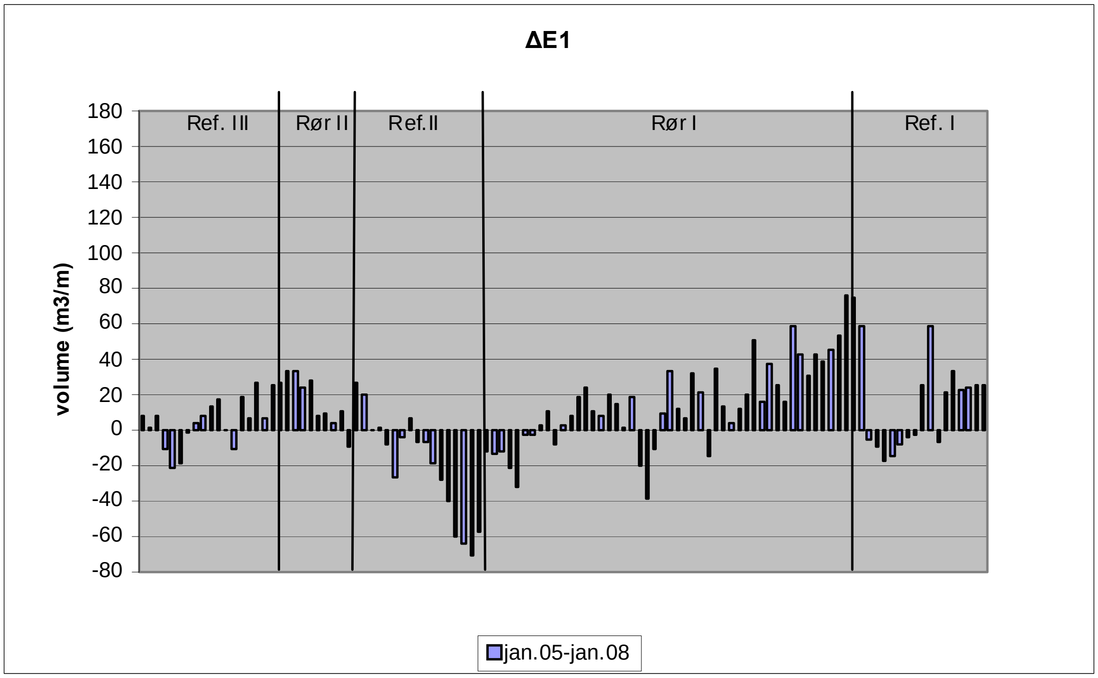
Som beskrevet ovenfor har vindbruddet i klitten meget at gøre med svag og smal forstrand og en eventuel lavning i klitprofilet. Alle forudsætninger var til stede helt fra forsøgets start som beskrevet ovenfor.

Derimod kan man diskutere hvor meget samspil der er mellem klitter og strand.

En høj strand er mere tør end en lav. På en tør strand vil der derfor blæse mere sand fra strandplanet op i klitterne. Gennem vores forsøg kan vi dog ikke se nogen sammenhæng mellem volumen i strand og tilvækst i klitvolumen. figur 1.13 og 1.14 viser dels volumen sand i stranden og dels mængden af aflejret sand i klitterne over de 3 år forsøget varede.

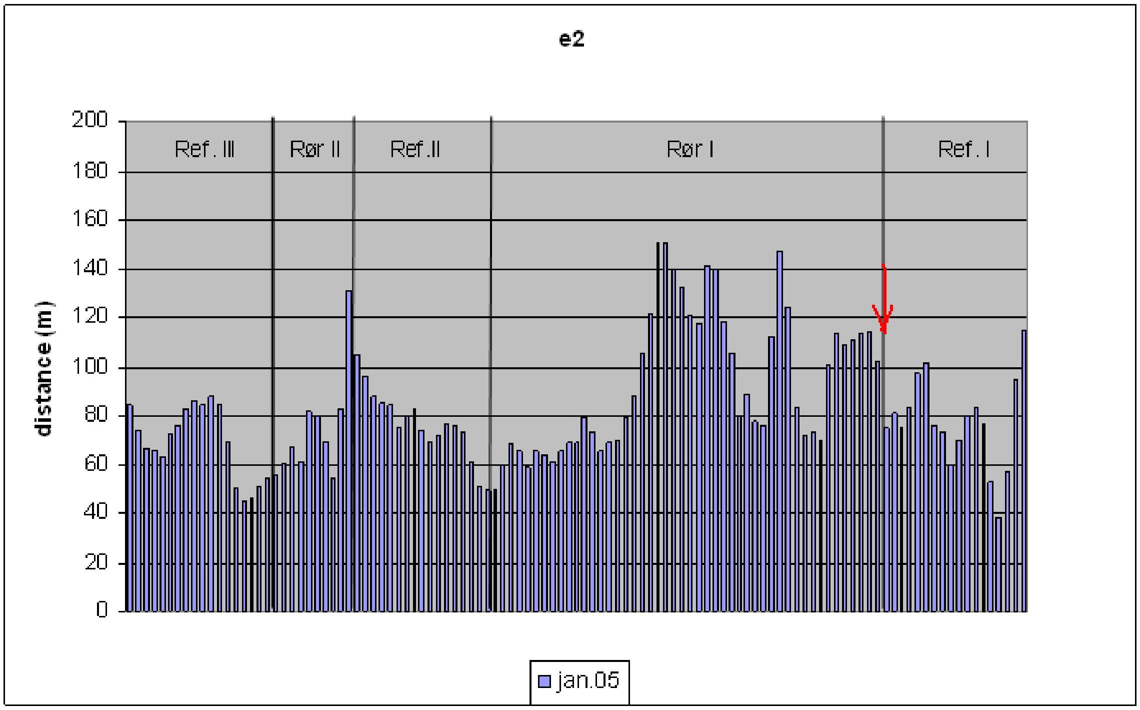


Figur 1.13 Strandvolumen langs strækningen til sidst i forsøget.



Figur 1.14: Aflejring af sand i klitten gennem de 3 år.

Bortset fra de tydelige negative effekter af vindskåret mellem rør område 1 og reference 2 er de langsgående variationer helt forskellige. Én årsag til dette er formodentligt, at der er en stor tidsforskel mellem opbygning af klitter og opbygning af strand: først ændres stranden, så klitten. En anden årsag er at vindtransporten af sand under stærk blæst ikke er særlig lokal bestemt, det fyger blot derhenad. Inde i rapporten er dette diskuteret detailleret, og man kan se at klitterne reagerer mere end halvandet år senere på ændringen i stranden.



Figur 1.15:Variation I strandbredde ved forsøgets start. Den røde pil viser at strandens bredde forøges ca 40% (fra knapt 80 m til ca 110 m) i overgangsområdet mellem det nordlige reference område og det store rørområde.

Figur 1.14 viser i øvrigt at der stadig fyger lidt sand ind gennem vindskåret i midten af rør1.

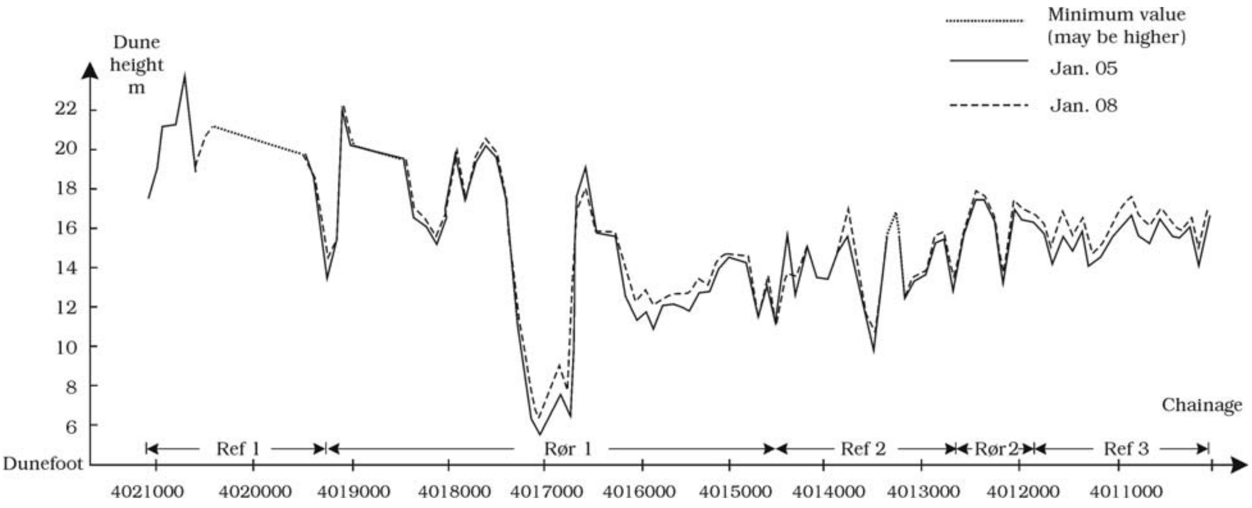
Ved sammenligning af figur 1.14 og 1.15 kan der observeres en lidt større sammenhæng mellem den lokale bredde af stranden og hvor meget der fyger op i klitten. Dette hænger sammen med, at hvis stranden er bred, så har vinden et større areal at virke på, hvorfra det kan blæse sand op.

Skal man prøve at argumentere for at der er en vekselvirkning mellem rør og klit må det så være følgende: Rørenes virkning er i første omgang at gøre stranden højere og mere tør for derved i næste omgang at øge vindfygningen til klitterne. Herudover vil en strand med meget volumen formindske angrebet på vegetationen ved klitfoden.

Effekterne er imidlertid meget små, og som beskrevet ovenfor er der ingen klar sammenhæng mellem strandvolumen og tilførsel af sand i klitten. Da der samtidigt er langt mere nærliggende naturlige forklaringer på vindbruddet må man konkludere at *det ikke umiddelbart ses, at vindskåret skyldes at rørene stopper lige før vindskåret.* I øvrigt kan man fra figur 1.13 se at stranderosionen siden har bredt sig cirka 500 meter mod nord ind i rørområdet. Da sandtransporten langs kysten overvejende er mod syd, indikerer dette stærkt, at strandens volumen afhænger af andre årsager end rørenes tilstedeværelse.

De stærke klitter i begyndelsen af rør 1.
Figur 1.14 viser at der er blæst megen sand op i klitterne i begyndelsen af rørområde 1. Klitterne er her meget høje, omkring 18-22 meter, se figur 1.17. Klitterne er ikke blevet højere her gennem de sidste tre år end de er andre steder, men de har fået mere volumen ved at der fra stranden er blæst en del sand op i klitten. Dette kunne forventes, da stranden i nøjagtigt samme sted pludselig vokser fra ca. 80 meters bredde til ca. 150 meter, se figur 1.15, og dette *før forsøget gik i gang.* Diskussionen er som før, at det er svært at se at ophobning af sand i klitten er relateret til at rørene begynder: den stærke vækst i klitten begynder 300 meter nord for overgangen. Var det rørskabt måtte man forvente at det begyndte syd for overgangen, baseret på at sandtransporten er sydlig, så rørenes effekt må være i sydlig retning. Derimod er geometrien af klitterne i dette område således, at der er en "hylde" bagved forklitten som er særdeles velegnet til at fange sand, se figur 1.16.

Figur 1.16: Geometrien af klitter i overgangsområdet mellem ref 1 og rør 1: området bag forklitten er velegnet til at fange sand. Det ses også, at stranden bliver bredere mod syd.



Figur 1.17: Klithøjdens variation langs strækningen

Afsluttende bemærkninger om strand og klitter: Der er i det ovenstående beskrevet en hel del om klittens dynamik. Dette skyldes, at der under hele projektet fra SICs side er fokuseret meget på klitten. Denne ekspert mener, at der i første omgang skal fokuseres på stranden. Rørene står nu engang nede i stranden, og her kan man end ikke se lokal ophobning omkring rørene. I stedet skal vi diskutere en hel masse om vindskår og sand blæst op i klitten, der jo befinder sig langt væk fra rørene. Eksperten mener, at dette er at flytte fokus fra det væsentlige: hvad der sker nede på stranden, og om rørene samler sand. Klitternes adfærd er jo først i anden omgang påvirket af stranden. Men stranden reagerer derimod omvendt lynhurtigt på et brud i klitten.
Men som vist i ovenstående kan man faktisk godt forstå, hvorfor klitten har reageret som den gør.

Det tredje overgangsområde og det nederste reference område.
Det er på sin plads at nævne at det sydligste overgangsområde mellem rør 2 og ref. 3 slet ikke bemærker at rørene stopper.
Og at langt den største tilvækst der sker i stranden sker i reference område 3, hvor der overhovedet ikke er rør.

Sammenfattende giver kontrolkasserne følgende resultat, samlet over hver strækning:

	Reference 1	*Rør 1*	*Reference 2*	*Rør 2*	*Reference 3*
Klit	-	+	+	+	0

	Reference 1	*Rør 1*	*Reference 2*	*Rør 2*	*Reference 3*
Strand	+	0	+	-	-

Tabel1.2: Samlet ændring i klit og strand over de tre år. + står for erosion i reference områderne eller aflejring i rørområderne, + er med andre ord til fordel for rørene.

Som nævnt ovenfor er analysen meningsløs, da den ville give et andet resultat hvis forsøget var kørt i enten længere eller kortere tid. Ikke desto mindre: fire plusser, 3 minusser og 2 nuller: der er ikke meget der taler for at disse rør på en overbevisende måde kan sikre de danske kyster.

Oversigten har ikke fokuseret meget på forholdene ude i havet, opmålingerne her er mest nyttige til at beskrive revlesystemet. SIC systemet har jo ingen direkte betydning for koterne i havet, højst indirekte som klitterne. Desuden indgår en del af havet nogle gange i stranden, da stranden er defineret som 100 meter bred, uanset hvor bred den i virkeligheden er. Men for at fuldstændiggøre de sammenfattende tal gengives i tabel 1.3 de tilsvarende tal som givet i tabel 1.2, men nu for de inderste 300 meter af havet (øverst i tabel 3) og de næste 300 meter (nederst i tabel 3).

	Reference 1	*Rør 1*	*Reference 2*	*Rør 2*	*Reference 3*
Indre Offshore	+	-	-	+	-

	Reference 1	*Rør 1*	*Reference 2*	*Rør 2*	*Reference 3*
Ydre Offshore	-	-	+	-	-

Tabel 1.3: Total ændring udenfor kysten i havet: indre: 300 meter ud. Ydre dækker området fra 300 meter til 600 meter. Plus og minus som i tabel 2.

Også her er det helt tilfældigt om det er plus eller minus, - som det skal være hvis det er naturen og ikke rørene, der bestemmer.

Konklusion:

1.: Alle målinger og beregninger indikerer at strømningen af vand gennem rørene er meget små, af størrelsen 20-30 cm per minut. Der hertil hørende dræningseffekt udgør højst ca. en halv promille af det vand, der skal tømmes fra en strand fra ferskvandsafstrømning, højvande og tidevand.

2. Man kan heller ikke i bølge-opskylszonen i overgang mellem den mættede og umættede zone se nogen som helst tegn på at der skulle være nogen sænkning af vandstanden omkring rørene, tværtimod forløber vandspejlet uforstyrret igennem rørrækkerne.

2. Den ringe dræningseffekt giver sig udslag i at der ikke samles sand omkring de enkelte rør, hvad man normalt ser når man pumper vand væk fra et dræn i stranden (det såkaldt aktive dræn modsat PEM-systemet, der er passivt).

3. Når man ikke ser en sådan lokal ophobning må man konkludere at PEM-systemet formodentligt ikke har nogen effekt overhovedet.

4. Strandens volumen vokser og aftager med årstiden. Ud fra de observerede data ses ingen klar tendens til forøgelse eller formindskelse af strandvolumen over de 3 år, da årets variationer totalt overskygger enhver langtids tendens. Dette indikerer, at rørene i bedste fald kun har en særdeles beskeden effekt.
Forsøgsdataene antyder at et sådant forsøg skal løbe mindst 15-25 år eller mere for at man kan få vished for om denne beskedne effekt overhovedet eksisterer.

5. Strækningen er delt op i områder med rør og områder uden rør. Det er fuldstændigt tilfældigt efter tre år om der tillæg eller erosion på de forskellige områder. Dette er igen en klar indikation af en særdeles beskeden rør-effekt.

6. Der er een spektakulær ting i dette forsøg: udviklingen af et vindskår mellem et rørområde og et referenceområde. SIC tillægger dette, at der ikke er rør i reference området. Men skåret er kommet hvor man mest ville forvente det, nemlig hvor stranden var svagest og klitterne ikke særligt høje, allerede *før forsøget.* Så man kan højst konkludere at placeringen af dette overgangsområde var uheldig. Vindskår er almindelige langs den jyske vestkyst, og dette adskiller sig ikke fra andre steder, men det ødelagde desværre hele ideen om et referenceområde i midten af rørområderne.

Overordnet må det derfor konkluderes, at rørenes virkning er overordentlig svag, så svag at man må køre et sådant forsøg mange flere år for overhovedet at vurdere om rørene har nogen virkning. De naturlige variationer i tid og sted er så dominerende, at de totalt overskygger nogen som helst rør-virkning.
Da denne virkning er så svag, kan det efter denne eksperts vurdering ikke afhjælpe en kyst mod erosion.

Chapter 2: Introduction

In accordance with the agreement of 18 August 2004 between Skagen Innovation Centre (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 should run in a three year period.

Composition of the group and selection of the site.

The composition of this group was so, that SIC was assigned to choose one expert, and they selected Professor H.F.Burcharth form AAU. KDI was similarly expected to choose the other expert, and suggested Professor Fredsoe, DTU to act as an expert. However SIC would initially not accept Professor Fredsoe, because they claimed, he was not impartial (Danish: ikke uvildig). (Later SIC also claimed their own expert to be non impartial, and would like to substitute him by another, but this was not accepted by the ministry).
To be not impartial means from a legal point of view to in one way or another have economic interest in the project.
The only impartial persons in the group from this point of view are the people representing SIC.

However, it was accepted by the ministry that Professor Fredsoe could not be the KDI-appointed expert. Next KDI first suggested another expert from DHI, and again SIC opposed this selection, and finally a third expert from DTU suggested by KDI was accepted by SIC. This expert only participated in one meeting before he left, due to the working environment in the group. At the end, Professor Fredsoe was then accepted by SIC in December 2004.
Hence Professor Fredsoe was not involved in the critically important initial design decisions, where the location of the site should be decided and inspected: the final site should be appointed at the meeting in December 2004, so the tubes could be installed in January 2005.
In addition to the two experts, the group consisted of Director Poul Jakobsen, SIC, Air Captain Claus Brögger, SIC, Project manager, Chr. Laustrup, KDI, followed after one year by Per Sørensen, KDI, and John Jensen, KDI (all three years).

Scope of the experiment

The scope of this large field test was to investigate whether a beach with a PEM-system installed will collect more sand than a similar one without tubes. The PEM system consist of vertical perforated tubes (for details see chapter 4), and is a so-called passive drain, i.e. a drain from which you do not pump (active drain), so nature must take care of the flow by itself.
The agreement of August 18th 2004 does not include any consideration of understanding *how* the drain works. Anyway, since we later have to evaluate the observed trends, and

some of these trends are explained by SIC through the functioning of the system (for instance “washed sand”), this expert has tried to discuss the impact of inserting vertical tubes in the beach. These considerations are supported by numerical modeling and presented in chapter 5. Also a field test on the water table fluctuations and a simple lab test have been performed.

However the main scope according to the agreement must therefore be to evaluate the fingerprint of the system on the coastal morphology.

The approach of a field study should be to examine both the local scale (i.e. surrounding an individual tube) and the array scale (i.e. rows within study area), and beach scale (i.e. the overall morphologic response of the beach) The tubes are installed in the beach in rows: each row consist of 6-10 tubes with a mutual distance of 10 meters (se chapter 4), and the distance between the rows is 100 meters. At the local scale, there was no evidence of sand deposition in the area immediately surrounding the tube. At the array scale, there was no evidence of the deposition any particular row being larger than the surrounding non-modified beach (or reference section). This observation will by itself be an extremely strong indication of no impact from the tubes at all. An investigation of the beach scale, requires that the array site (tube covered stretches), prior to the experiment, have a behavior that is fundamentally consistent with the surrounding beach without any arrays.

Natural fluctuations.

To get meaningful result of such a test, you must get the same outcome independent of whether you stop this test a little earlier or later (for example whether this test has run for 2 years or for 3 years).

Natural fluctuations occur with timescales of several years. So an increase in beach one year can be followed by a decrease other years. So if the fingerprint is not very distinct (i.e. very local accumulation around each tube (row)), an experiment like this actually requires many more years than the three available in this project. The average position of the coast line at the study site varies on average along the test site from + to – 3meters in average during the last 20 years. The annual fluctuations at particular locations are as large as 50 meters. So if the tubes generate a change in the coastal development which is significantly less than 50 meters, then simple statistics tell us that you need much more years to realize whether the tubes have any significance or not. The results of table 11.4 (lower line) show enormous fluctuations. An illustration follows: if you stopped the test September 2007 (i.e. you only had two and a half years test), then you would conclude a positive impact of the tubes on the beach of 35 cbm/m, see table 11.4. Because we stopped in January 2008 the impact from the tubes instead became zero! So what is the right answer? An experiment like this requires at least 15-25 year to be meaningful and a true indicator of the success of the tubes! This is a significant perspective that needs to be considered throughout our evaluation.

Reference sections

We have included reference sections with no tubes on the test site to be able to observe less erosion in the tube covered region than in the no-tube reference sections. This is being used extensively by this expert in the report, but from the very beginning it was clear that this could not be used as an argument in the discussions with SIC: if you had deposition in the reference sections, it was either caused by “washed sand” or “lee-side deposition”. On the other hand side if you had erosion, then it was because of no tubes in the reference sections. So the discussions became throughout the total project period meaningless.

The dunes

The dunes are an integrated part of the coastal profile. Sand is transported to the coast by waves, and regarding the beach, the deposition is in the swash zone. The further transport mechanism from beach to dunes is by wind. The effect of tubes on the windblown transport is not that obvious as discussed in chapter 11.

SIC anyway focused very much on the dune behavior. It is certainly to remove focus to discuss whether the dunes become higher in the tube covered regions (which they actually don’t) when the idea is, that the tubes shall collect sand in the swash zone.

On the other hand side SIC never wanted to discuss the effect of rips and similar features on beach morphology.

Reporting

By the experts.

The experts were asked to report 4 times: after 6 months and after 1, 2 and 3 years. (This report is the 3-year report). You can certainly say nothing about natural variations after only 6 months, so that first report can only be considered as a progress report on the how the system is implemented, and a presentation of the first surveys (described in chapter 6). In several meetings after the first 6 months, SIC and Professor Burcharth had long discussions on how to describe the profiles, and the firstly used profiles, called B-profiles, was replaced by D- and E- profiles. SIC next wanted these changes introduced in the already published 6-month report. These changes were never done, mainly because it was meaningless since nothing could be concluded anyway after only 6 months. The two year report contained in the draft version some calculation errors, corrected in the final 2-year report. Since then SIC has claimed that a lot of data in the final 2-year report are wrong, but this expert never received specific corrections from SIC regarding the final report.

By SIC.

SIC published their own reports based on the measurements, and convinced several politicians and journalists, that the system worked very well.
SIC published their results in “Geologisk Nyt”, which, even though it is published by a group attached to “Aarhus University” is not been scientifically reviewed before its

publication. The same is the case regarding several conferences, where SIC got their contributions accepted. This suggests a contribution is accepted if it looks interesting rather than whether it scientifically is correct.

SICs reports are to this experts opinion of no scientific substance, they contain a number of undocumented postulates, and it mixes absolute values with relative values, cf. the remarks on the dunes above. All this will be touched in the report, but a number of examples will be mentioned here, because this expert had to include replies on many of these statements in the report. The readers will get confused, if they are not aware, why this expert from time to time has to discuss some not-so-relevant point of views.

- SIC simply neglected that the sand nourishment already has stabilized the coast on the site. They claimed incorrectly, that the tubes stabilize the coast.
- If you have erosion further down a tube covered stretch, then SIC says: sure, here you have no tubes! But if you have deposition further down a tube covered stretch, then SIC says: sure, here we have washed sand.
- The concept of washed sand is introduced by SIC to explain, why you sometimes have erosion down drift of the tubes. The concept of washed sand is not a possible mechanism! Even with very much flow through the tubes, the flow will decrease very fast away from the tubes, and this effect can not exist! (Chapter 10).
- Sometimes explanation changes: if you have deposition further down drift of a tube covered stretch, it is also explained as lee-side deposition. This was first used to explain, why you didn’t observe accumulation around each array. But you need initially to have accumulation to get a later lee-side effect! - and this accumulation has not been observed. Later the large scale undulation in rør1 has been used to explain deposition far to the south, namely in ref3. But just south of rør1 you have erosion, so how can you have leeside deposition downstream the erosion? The explanations are so strange, so a discussion must be included in this report.
- SIC explains one of the main functions of the drain by the removal of freshwater supply to the beach from land. But the site is located on a narrow spit, so the fresh water supply is negligible (ch. 6)
- In their final report SIC not only discusses *changes* over the past few years, but also include the total strength of the beach. For instance in relation to the impact of wind erosion. But you have wind erosion also before the test, so the only relevant topic is how this is *changed* by the tubes.
- A field test where the water table variation near and away from the tubes showed a difference in the watertable of order 10-15 cm. This is in perfect agreement with this expert’s estimate and also with the numerical modeling, which both show only negligible impact from the tubes. Nevertheless SIC persistently used these data to explain the success of the system.

The working environment.

Usually you do not report about the working environment in the group, but this is an exception. SIC totally dominated all meetings, and did not accept any of the experts evaluations or explanations. If for instance the concept of “washed sand” was discussed, they would not listen at all, but defended their postulates without any explanations.
They persistently accused us for writing the reports in collaboration with KDI, which was never the case.
They went to the public with the draft of our reports, and told anyone who would like to listen how stupid we were.
At the last meetings, we needed a lawyer to chair the meeting.

Chapter 3 Selection and description of the site.

Why the North Sea Coast.

The first question you can ask yourself is why such an exposed coast like the coast of West Jutland has been selected for the test. SIC may argue, that they would like to demonstrate, that the tubes work on a very long, more or less uniform stretch, which is heavily exposed to the environment. But such a coast also will have very large spatial and temporal natural fluctuations in beach-width and beach-volume, so it will be more difficult and you will need more time to identify the impact from the tubes.
Instead you could argue that a more protected place better could show the ability of the system to function.

Why so long.

The next question to be put forward is why you want that long a test stretch to document the functioning. Is the system not able to protect shorter stretches? Is the fingerprint not strong enough? Smaller experiments have already been performed, for instance at Gl. Skagen, where the other expert attached to this project (and appointed by SIC) after five years could not identify any conclusive effect. SIC would like to document, that the system can protect longer exposed stretches, but as to this expert, it is certainly enough to convince him if the system also works on smaller length, say 1 km.

Where along the West coast.

Several locations had been discussed in the early stage between SIC and KDI. One possibility could be at Husby, but the beach there should contain clay, so SIC would like another location. It is not fully clear to this expert, why SIC do not like clay in the beach, especially when they claim, that inhomogeneous layers could be important with respect to the functioning of the system. Of course clay will prevent the water to flow to the tubes, but without clay, i.e. pure sand, the beach does not need tubes to be well drained.

Another location could be Skallingen, and KDI and Professor Fredsoe was in favour of this location, mainly because this part of the coastline is not exposed to sand nourishment. There are a number of groins in the up drift part of Skallingen, but still there is 5-6 km undisturbed coastline available. SIC stated, that they were promised a much longer stretch.

At the end the location at Skodbjerge was selected at the first meeting in the final group in December 2004. This location is not optimal: At the up drift end, a lot of sand nourishment takes place, and it was made clear to SIC by this expert and KDI that this could be a problem for the interpretation of the results. KDI has an agreement with the local authorities about the nourishment scheme (based on the location of the line of 5 meter water depth), and this agreement can not be lifted. At that time SIC said, that if

KDI only did bar nourishment, and stopped the beach nourishment, this would not disturb the experiment. This agreement was made.

Another shortcoming is that at this location there is only a small fresh water pressure from land, since the location is on a narrow spit, 1- 2 km wide, between the Sea and Ringkjøbing Fiord. The average water level in the fiord is almost the same (a few centimetres higher) than in the sea, and will create nearly no flow through the beach at the site. This is quite unfortunate, since SIC claims, that the fresh water flow is an important agent for coastal erosion.

3.1 The reference sections

All details of the test site were decided at the meeting in December 2004. because SIC would like the tubes to be installed immediately afterwards (in January).

As described in chapter 2, the purpose of the test is to consider large scale changes on the coastline, and a possible fingerprint from the PEM-system. By large scale we mean scales of 100 meters or more (see also chapter 10: The morphological fingerprint).

The ideal case would be to have two identical beaches with same environmental exposure (waves and current and wind) with and without tubes for comparison.

Unfortunately we do not have that, so we have to interpret what is happening on the site, and try to evaluate whether this is within the natural fluctuations of the coast, or there is a distinct fingerprint from the tubes. For this reason reference sections was introduced on the site to get a comparison of the stretches with and without tubes. This actually requires more or less uniform conditions along the whole test stretch, which certainly is not the case: as seen on figure 3.1: the long shore sediment transport rate along the coast is not uniform, and this picture is even more destroyed because of the blocking of sediment transport at Hvide Sandy and the compensating sand nourishment. If sand nourisment was not in function, the coastline would retreat over the major part of the stretch. How the nourished sand will distribute down drift the site of dumping is not known into details, but in average the coast line is stable during the last 20 years, see also figure 3.16.

Rips and other non-uniform features in the bars and breaches at some locations in the dunes makes the long shore variation in the beach and in the coastal profile even further complex. Therefore it is not straightforward to compare sections with tubes with those without, since conditions are not the same all over.

KDI advocates for quite long reference stretches, of equal size as the tube covered stretches. This make sense since the reference stretches are of equal importance as the tube covered regions for comparison [In a medical blind test you don’t have a large group getting the medicine and a small group having the fake pills]. SIC insisted on having a very long uninterrupted stretch with tubes, so they got it! There was a general agreement to have a reference stretch at the northern and southern end of the stretch.

Further KDI as well as this expert would like a couple of interruptions in the stretch with tubes to investigate the coastal response on such a configuration. SIC was actually against this, because they preferred a very long undisrupted test stretch with tubes. At the end, as a compromise, it was decided to include one more reference stretch without tubes. The location of this was selected by SIC, who would like a long undisrupted site, so the first tube stretch became 4700 m, followed by a 1800 m break, followed by 900 meter of tubes.

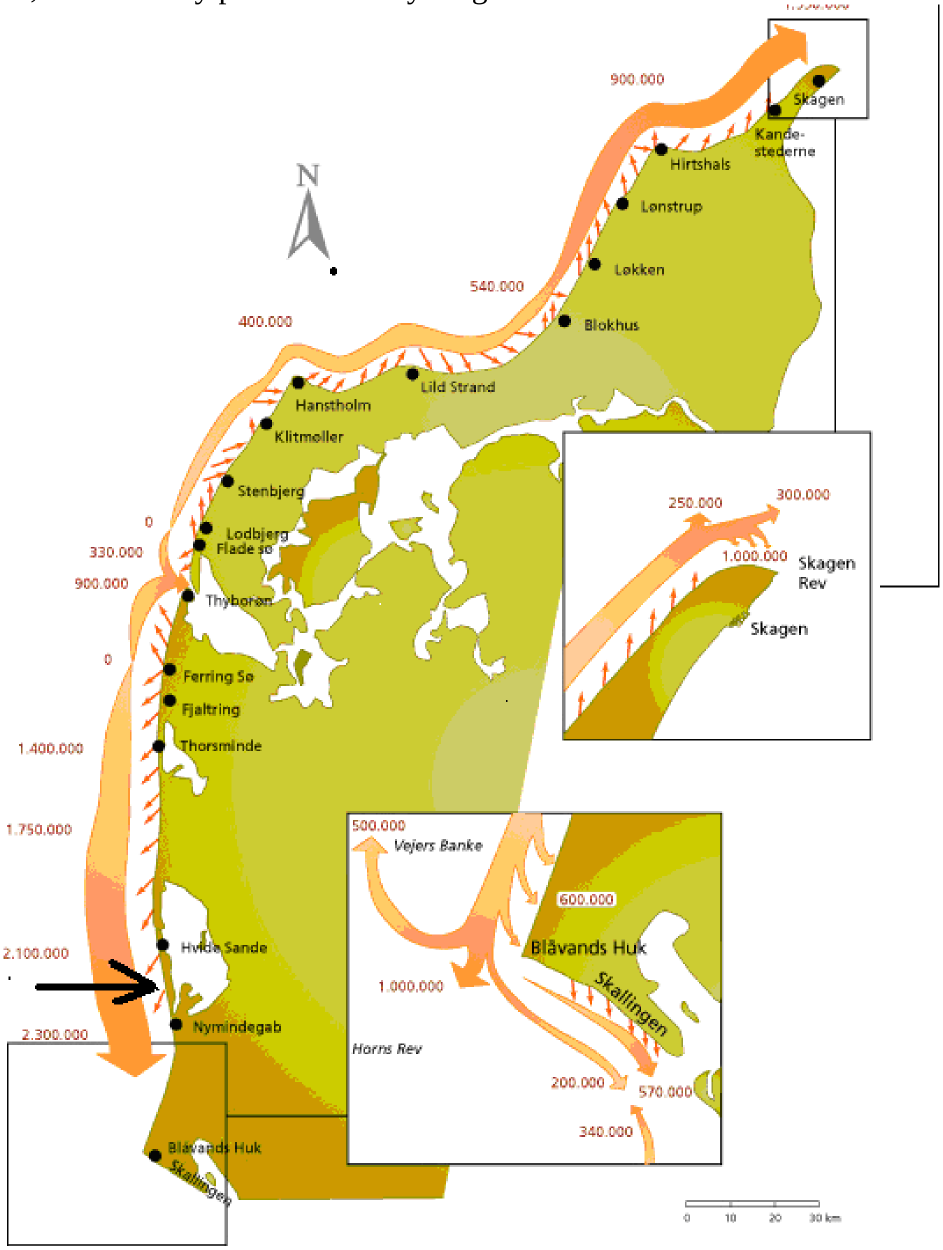


Figure 3.1: The net long shore sediment transport along the West coast of Jutland. The black arrow shows the location of the test site. (The map is taken from KDI's homepage).

The length of the reference stretches at the two ends (ref 1 and ref 3) were both 1800 meters long. So the rør2 is actually very short, only 900 m,   and the reference sections is only 40% of rør1 in length. The system is shown in figure 3.2.

But this expert would certainly also have preferred to have two stretches of tubes and three stretches without tubes, all being 2200 meters long. Then you could also avoid all the problems with where you exactly should locate the transition regions, which has created a lot of problems in this test:

The location of the break (called reference 2) was chosen quite unfortunate: just at the transition from the tube covered region to the reference region, the beach was the weakest at all, as can be seen from the mean beach level measurements, figure 3.3. Further the outer bar stopped just up drift this location, see figure 3.4.

Because a breach in the dune system at this location, this weak point expanded with time, and you have to judge, whether this is due to the tubes or due to natural processes.

The location of the transition from the northern reference region to rør 1 was also- quite unfortunately- placed just south of where the outer bar terminated, see fig 3.4.

Both things sounds a little bit strange, but as explained in the introduction and above, the time window for choosing the right locations for the reference regions was nearly nil.

Figure 3.2: The splitting up of the test site in regions with ("RØR") and without ("REF") the PEM-system installed.

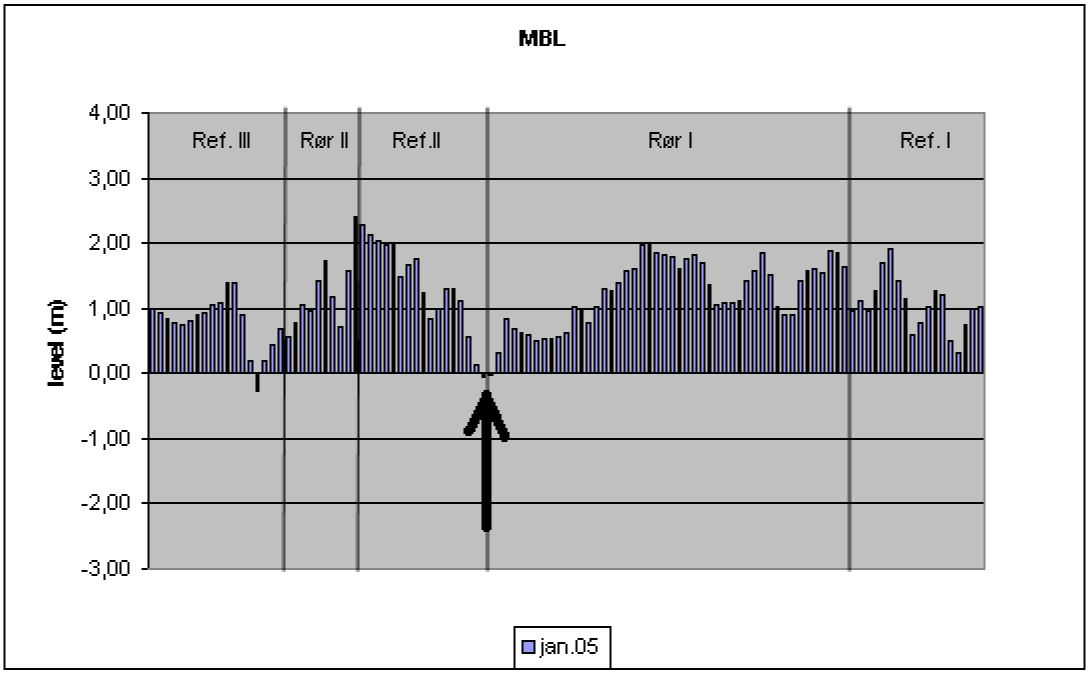


Figure 3.3: Variation in initial beach volume along the whole test site. The beach was weak at the transition between Rør1 and Ref2 already when the test started.

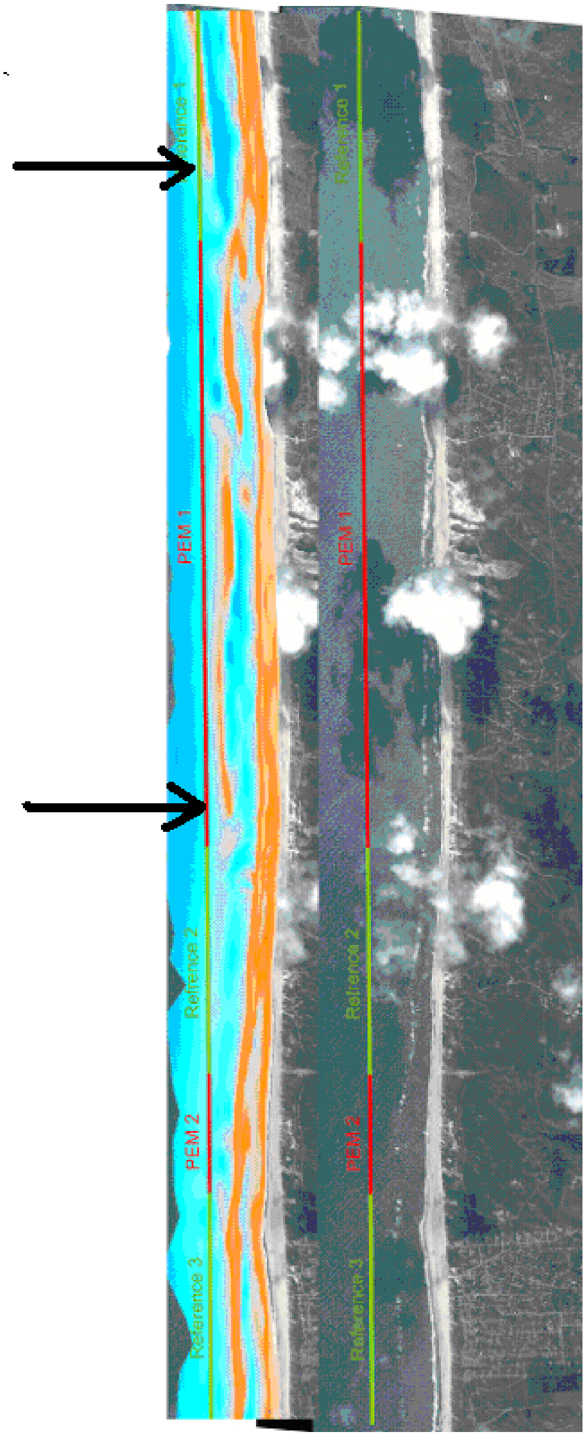


Figure 3.4: The black arrows indicate the locations, where the outer bars stop. Unfortunately both locations are close to the transition regions.

3.2 Description of the Coastal, beach and dune profiles

Location

The test site is on the southern part of a barrier spit separating the Ringkøbing Fjord lagoon from the sea and is shown with an arrow in figure 3.1. 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.

The coastal profile

The distance from the coastline at level 0.0 m (equal to Mean Sea 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 annual fluctuations with changes in position ranging from 50 m to 100 m.

The bars

Several shore parallel bars, typically three, are formed along the coast, see figure 3.4. More detailed plan view of the bars can be found in chapter 9.
The net sediment transport in front of the test site is southwards amounting to approximately 2.1 million m^3 per year in average, see fig. 3.1. Most of the long shore transport takes place in the bar zones.

The beach

Grain size analyses of the sand in the foreshore and in the beach top layers show medium to very coarse sand with grain diameter in the range 0.3-2.5 mm. Also shingles and stones can be found in the beach, see figure 3.6. 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.

Figure 3.5: Typical view of the beach. The dunes at the right are typical 6-12 meter high, measured from the dune foot, defined as +4.00 meter above MSL. The changes dune volume is according to SIC an important feature for the success of the tubes.

Figure 3.6: The beach is often covered by pebbles. Inhomogeneous layers play a role in SICs explanation of the systems functioning.

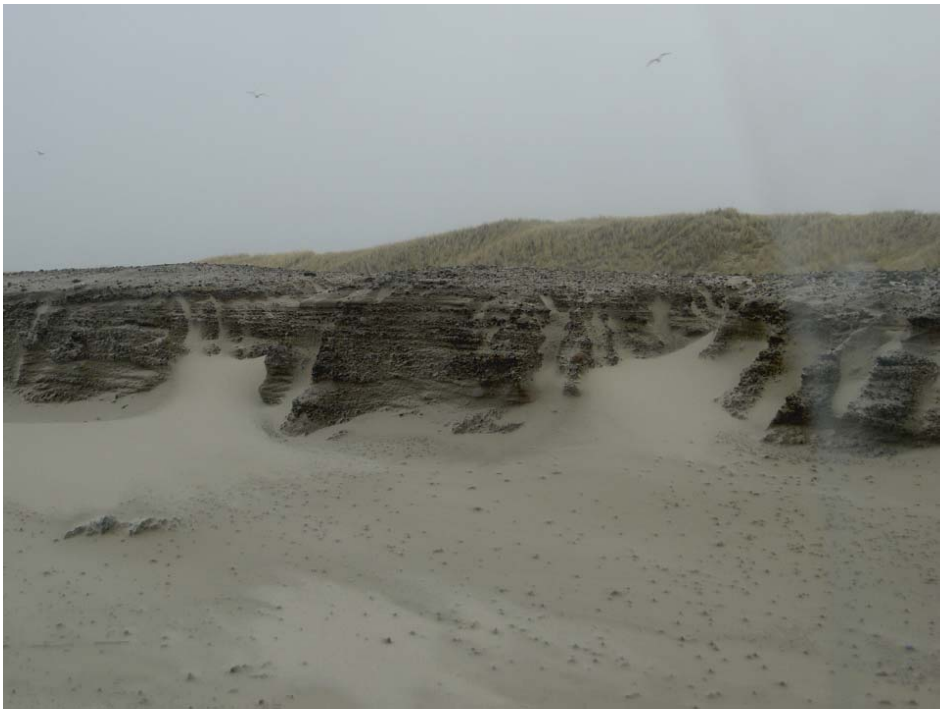
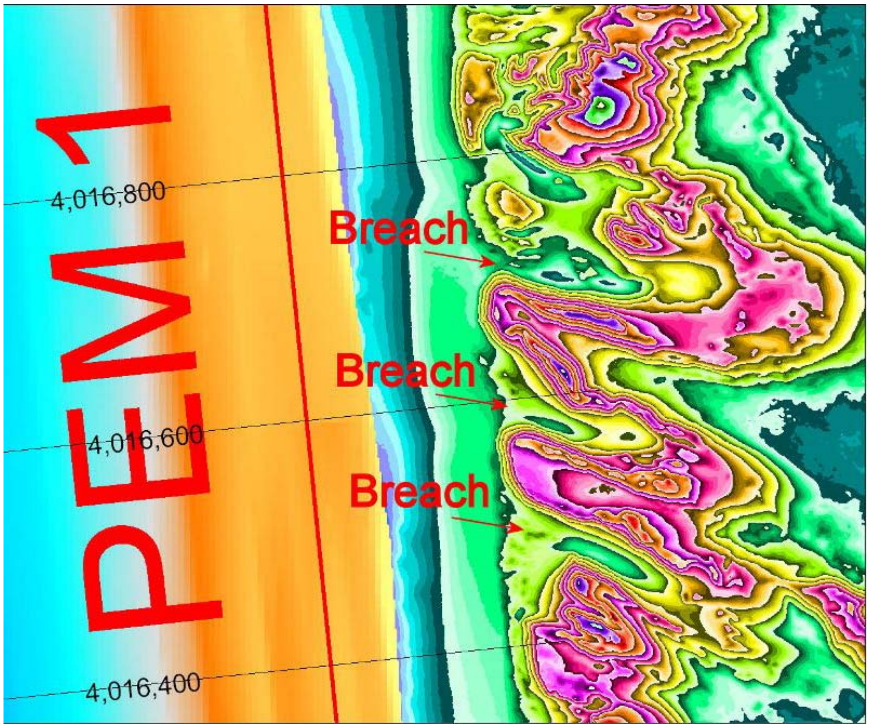


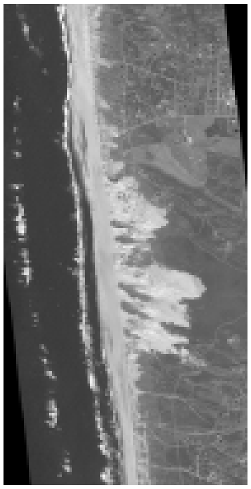
Figure 3.7: The structure of the dune foot varies. Her stratification is observed in the reminiscence of beach nourished sand. Beach nourishment was stopped during the test and only bar nourishment was maintained.

The dunes can also be seen on the pictures, figure 3.5-3.8. Figure 3.9 shows the spatial variation, the dunes are 6-20 meters high, measured from the foot of the dune, which we in this study define as +4.00 above MSL. On the main part of the stretch the dunes are partly stabilised by a man-made cover of different kind of grasses (“Marehalm” (English: Marram) or “Hjælme”). In a large region in rør1, no man-made invention has been made, and here the dunes are mainly uncovered of any vegetation, see figure 3.8 (satellite photo, July 2005). Here a larger landwards transport of sand has taken place through an earlier breach. The soundings of beach and coastal profiles during the test period show that nothing special (erosion) occurs at this site any more. This is because a new barrier has been build up further landwards, see the contour plots figure 3.8 B, where the purple colour shows higher levels, so the breach system is stabilized.

A.



B.



C. *Figure 3.8 About one kilometer of the dunes are free to develop without any vegetation to stabilize the dunes in "rør 1". From picture C the main incoming wind-direction is easily seen.*

3.3 Waves and water levels

Water levels

At the coast the difference between mean high water and mean low water is in average 0.7-0.8 m. The tide is bidiurnal. Storm surge caused by strong westerly storms and low pressures can give water levels of up to more than 3 m above mean water level. Low water levels down to -2.0 m can occur during easterly winds.
In the Ringjøbing Fjord the water level varies between -0.5 m and +0.5 m, dependent on the operation of the sluices at Hvide Sande and on the wind set-up. In average the water level in the lagoon is a few centimetres higher than MSL outside in the sea.

Waves

The prevailing westerly winds cause quite frequently storm waves with significant wave heights in the range H_s = 3-4 m offshore in 15 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 are 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. Figure 3.10 and 3.11 are time series recorded by a directional wave rider buoy in 15.5 m water depth offshore Nymindegab before and during the test.

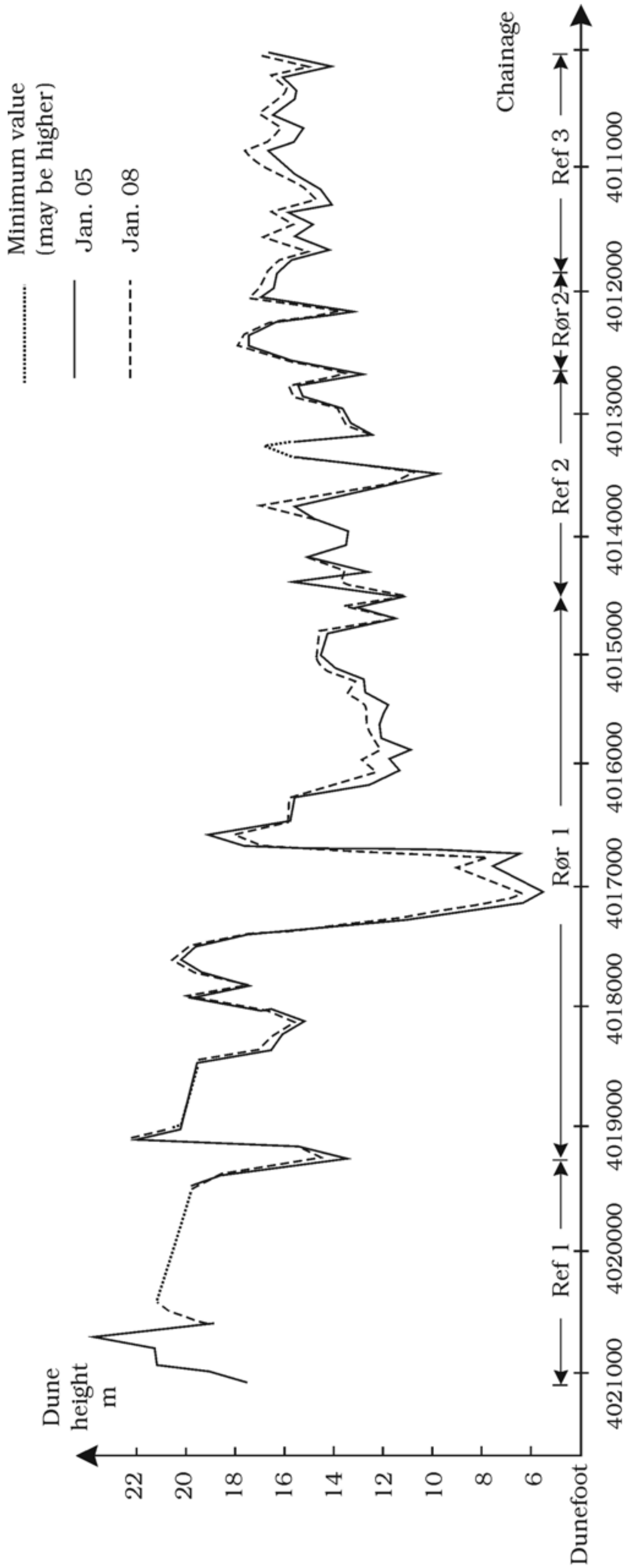


Figure3.9: Spatial variation in the dune height.

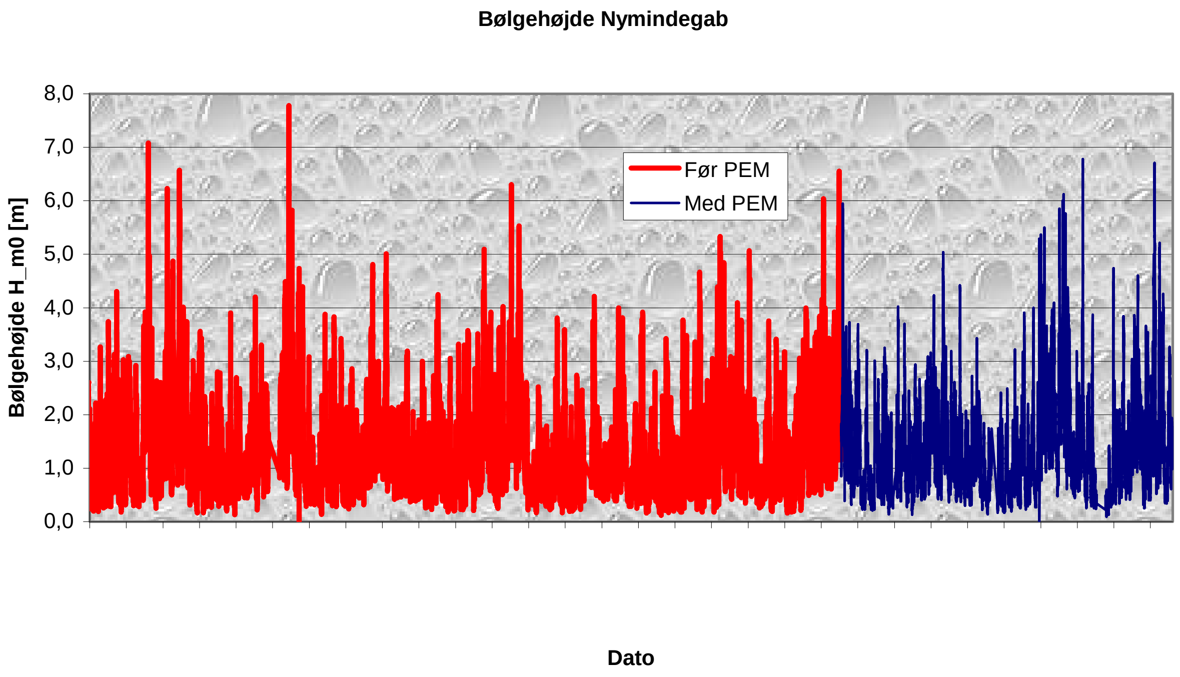


Figure 3.10A: Waves 1998 to now. The red color is before the test.

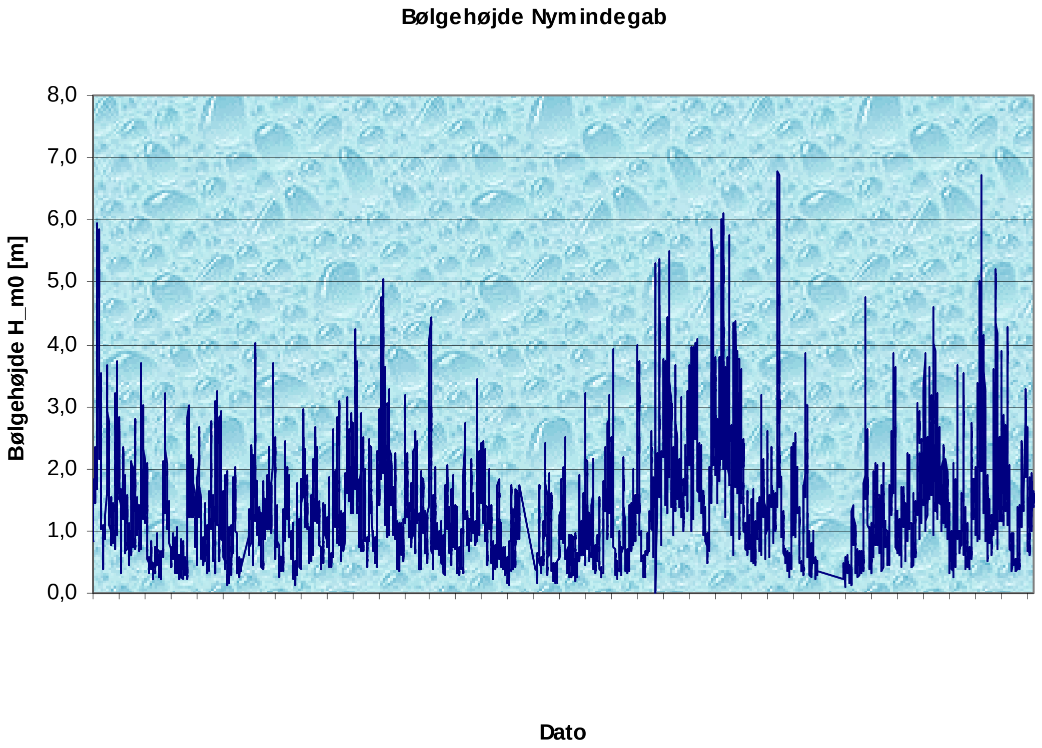
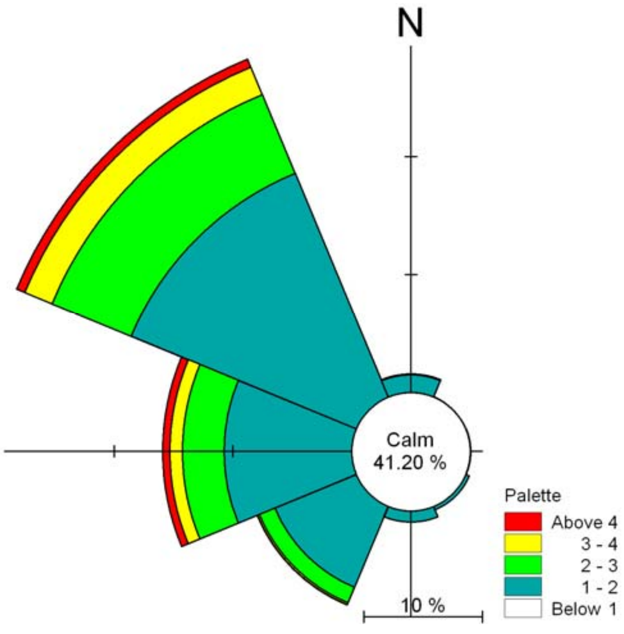


Figure 3.10B Waves during the test. (The blue part of figure A).

Fig. 3.11 and 3.12 show the one-year 2005 and 2006 statistics as wave roses.



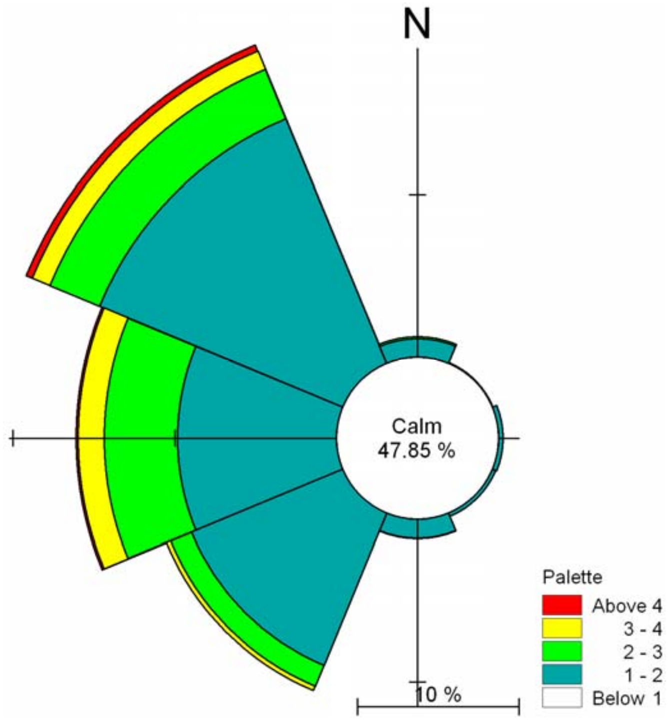


Figure 3.11 Wave roses year 2005 and 2006

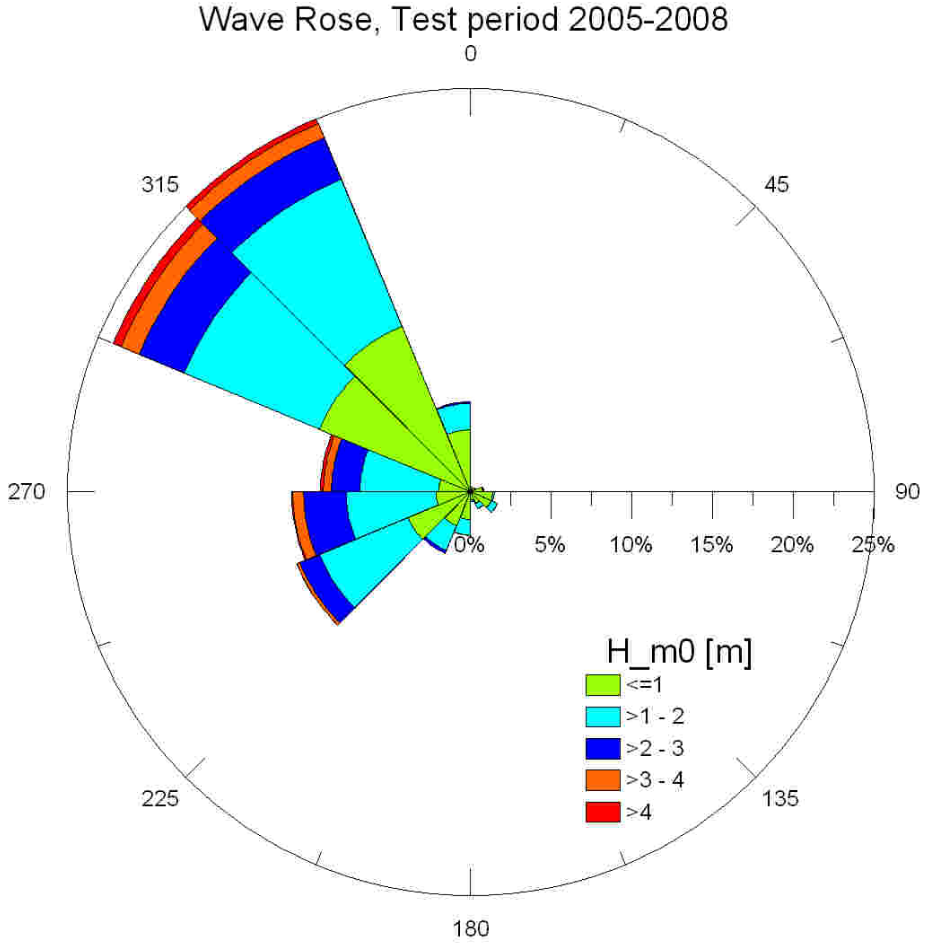


Figure 3.12 Wave rose year 2005-2008.

It is seen from Fig. 3.11 and 3.12 that the angle between the coastline and the dominating incoming waves is approximately 45^o, thus causing a net-sediment drift in southern direction.

Figure 3.13 shows the 15 most severe storms from December 2003 till January 2008, i.e. covering the whole test period, and one year before that as well. It is observed that after implementation of the tubes in January 2005, no severe storm occurred before October 2006.

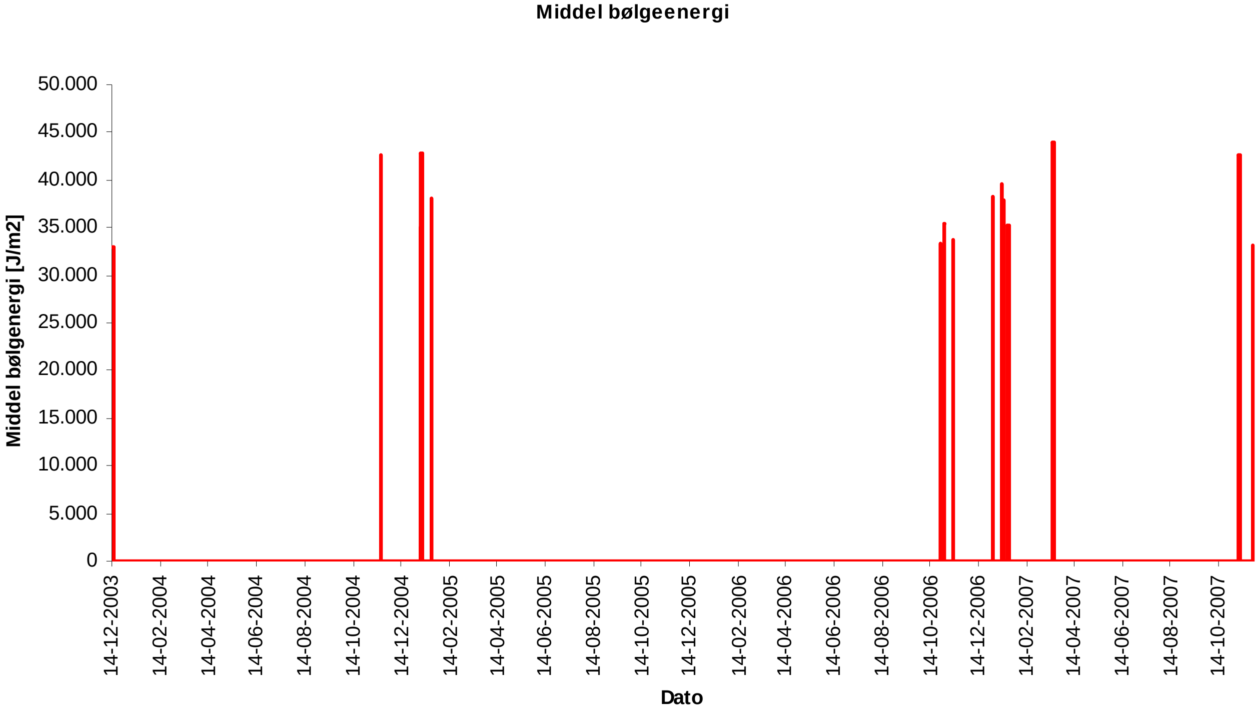


Figure 3.13: the 15 most severe storms from December 2003 till January 2008.

3.4 Former coastal changes and nourishment

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. This period is before the nourishment really increased to the present amount, cf table 3.1. The actual erosion is different due to nourishment. Actually the coastline has, apart from fluctuation, in average been stable over the last 5-10 years. Figure 3.14 shows the fluctuations along the test site, while figure 3.15 shows the average movement from 1987 to 2004.

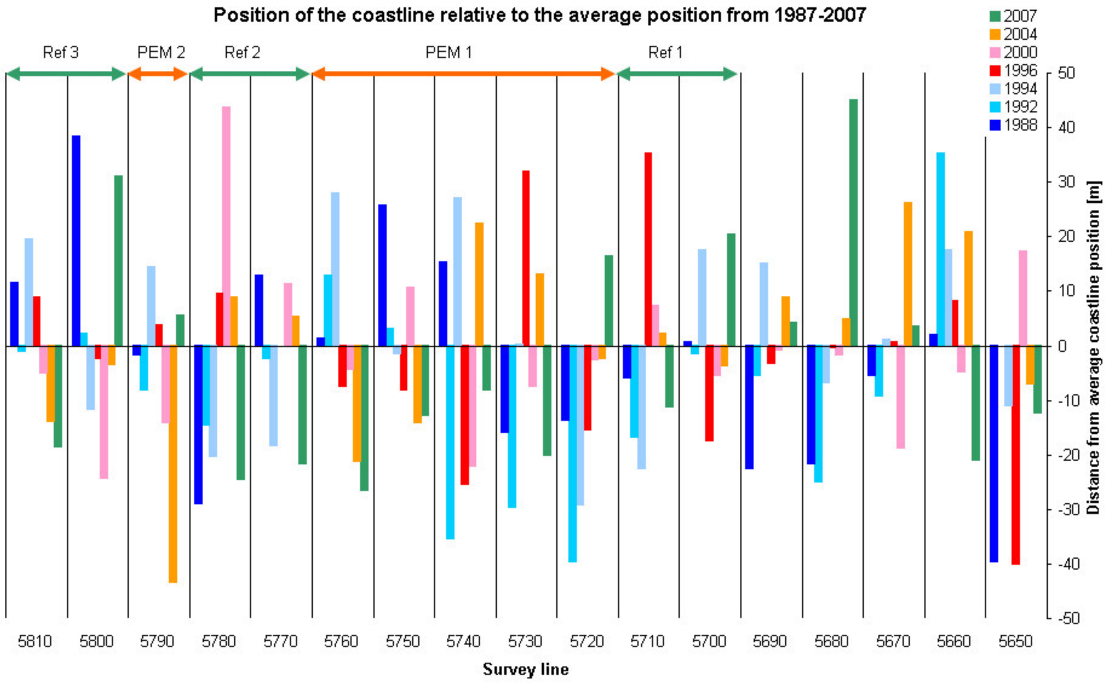


Fig 3.14 Natural fluctuations in the coastline position: The diagram shows the fluctuations around the average position, averaged over the years 1987-2007.

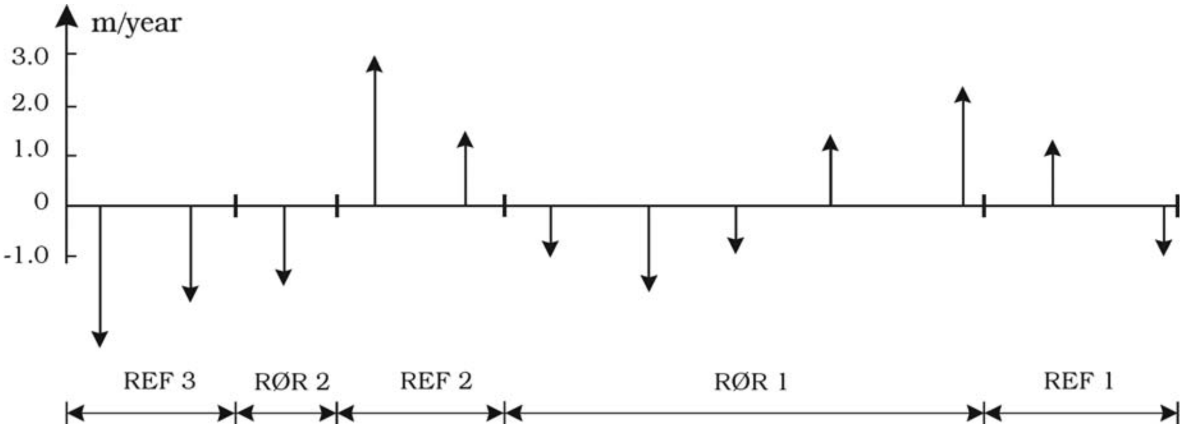


Figure 3.15 Annual Average changes in Coastline position in m/year from 1987-2004.

Figure 3.16: location of bar nourishment during the test.

Table 3.1. Man-made interventions, 1977-2007

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		94.800	11.443		600.041		3.951			15.061
2005		192.400			200.419					
2006		145.884			505.105					
2007		180.000			300.130					
Total	2.246.230	4.736.147	138.855	307.224	1.608.327	1.346.563	385.855	200.255	352.124	614.242

Table 3.1 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).

In average 5-600.000 cbm of sand are nourished annually just up drift the site. If this is evenly distributed over the test site, it corresponds to around 50 cbm/m/year.

3.5 Ground water levels across the barrier spit

According to SIC one main function of the drain relates to changes in the ground water flow caused by pressure equalisation in the surroundings of the drains.

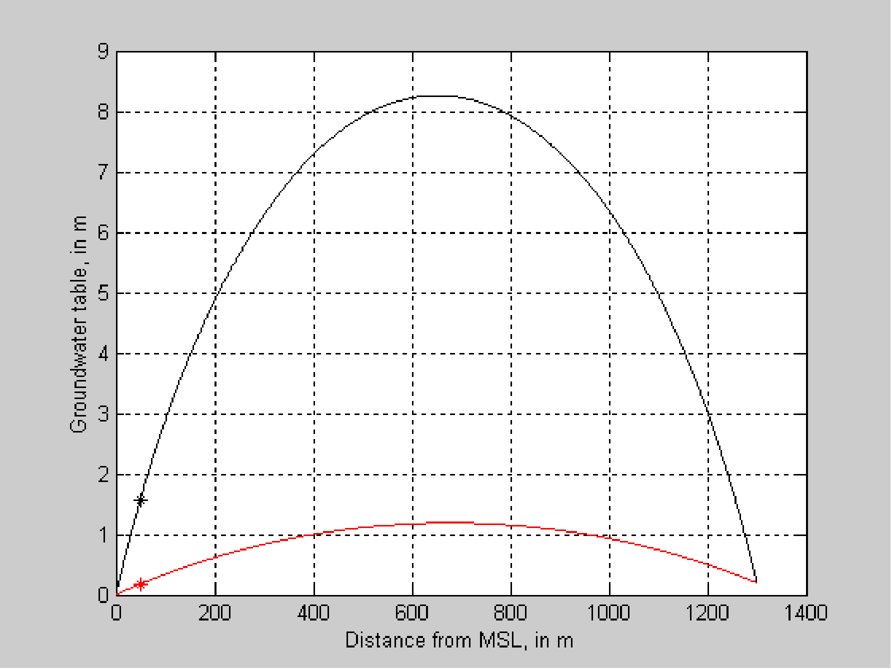


Figure 3.17: Predicted mean ground water table across the spit. The red line is based on a realistic K-value equal 25 m/day in permeability, the black is based on a 10 times lower value. Earlier studies suggest a value of 25 m/day for instance at Ho Bay south of the present location. The stars at the left correspond to the head at the dune foot above MSL.

Fresh water supply.

A pertinent argument by SIC is that the tubes will relief the fresh water pressure on the beach. This freshwater must stem from inland. Because SIC claims that the freshwater pressure is very important for the functioning of the tubes, it was decided in the July meeting 2005 to monitor in one line the ground water table across the narrow land spit between Ringjøbing Fjord and the test beach. Application for permission to establish wells was forwarded to the authorities. However, the campaign was stopped in 2006 as SIC found that the actual ground water table variation across the land spit had no influence on/or could not enlighten the function of the drains. For this reason we only have the calculations given below to our disposal to evaluate the fresh water pressure.

The spit which separates the North Sea from the Ringkjøbing Fiord is in average around 1.3km wide. The water level in the fiord is in average a few centimeters higher than that in the Sea. This *water level difference* itself will only create a flow from the Fiord towards the Sea about 1.5 Littre pr hour pr meter beach, assuming a coefficient of permeability equal K= 25 m/day, a water level difference of *20 centimeters* (conservative estimate) and a flow depth of 10 meters. This corresponds to less than one per thousand of the tidal induced flow.

Also *precipitation* on the spit will contribute to the freshwater discharge. If we assume an annual precipitation of 90 cm (SIC says 70 cm, in that case our estimate is conservative, so this estimate can accommodate the uneven distribution of precipitation over the year), and that half of this will be drained off as groundwater flow (the other half will evaporate or run off through ditches), and of this flow 60 % will flow to the Sea, and 40% to the Fiord (where the water level is slightly higher), this will cause a fresh water run off through the beach equal 0.04 cbm/hour or less than 1 % of that amount to be drained from the beach due to tidal flow. Figure 3.17 shows a computed distribution of the groundwater table across the spit. The level at the beach face is assumed to be zero, and in the Fiord it is assumed to be 20 cm.

The groundwater table in the spit depends strongly on the permeability. A realistic value in sandy soil is K= 25 m/day. The red line in figure 3.17 corresponds to this value, which suggests a water level around 1.2 m in the middle of the spit, and a head equal 17 cm in the beach at the dune foot. The dark line corresponds to much denser soil in the spit with K= 2.5 m/day: now the predicted ground water level in the middle becomes 8 meter, which probably is higher than the ground level of the spit in the middle. In this case the head at the dune foot is 1.5 meter. Figure 3.17 shows that half of the water will flow to the sea (to the left in the figure) and half to the fiord, independent of K.

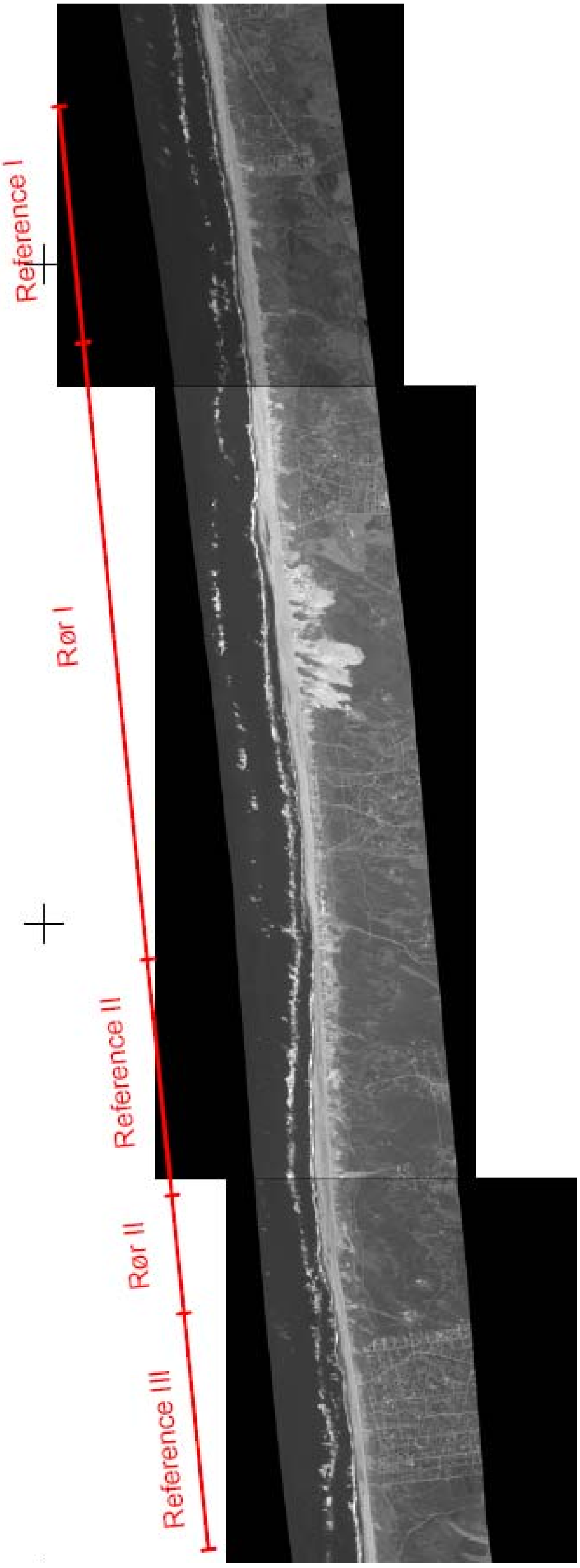
So this expert must conclude that at the specific site, the freshwater runoff through the beach is less than 1% of the total salt and freshwater runoff, so to speak about freshwater pressure has no meaning at this site.

3.6 Undulations along the coast.

It has been a heated issue in the group whether there are undulations along the coast or not. KDI has worked with these issues for several years (as this expert has done in University, independently of KDI). SIC claims that there are no undulations and actually, SIC accused him of scientific dishonesty for bringing undulations into the problem. This is a little hard to understand, since it simply is based on satellite pictures, so what is presented is measured data, no theory. From the upper satellite photo this expert can see that the beach is not a straight line, but has large scale undulations. This means that you have long shore variations in the beach width and thickness. By following a number of satellite pictures like those shown in figure 3.18 below you can follow how these undulations moves long shore. Figure 3.18 shows pictures from 2005 and 2006. Figure 3.19 shows earlier results, from 2000 to 2005. The figure contains the actual measured variation in beach width, and additional to that also a curve fit. The figure shows that you have very large variation in beach width (more than 100 meters) alongshore, and further that the undulations moves down drift (towards south) with a celerity of about 250 meter. Also it can be observed that a weak part of the beach is just entering ref 2 at the start of the test, as the beach also is weak a distance up drift the transition to rør 1.

Importance of undulations.

The transport of sand in the undulations is described in appendix 1, where also some additional remarks on the dynamics of the undulations are given. It is estimated that the long shore transport in such an undulation can be 20000 cbm/year. The length of the undulations varies, but a reasonable estimate is 3 kilometres. Using this information you can estimate that the annual fluctuations along the beach due to undulations lies in the range 10 to 100 cbm per meter long shore beach where you have the largest long shore changes in beach width, so the undulations can certainly not be ignored when considering beach dynamics.


Reference I
Rør I
Reference II
Rør II
Reference III

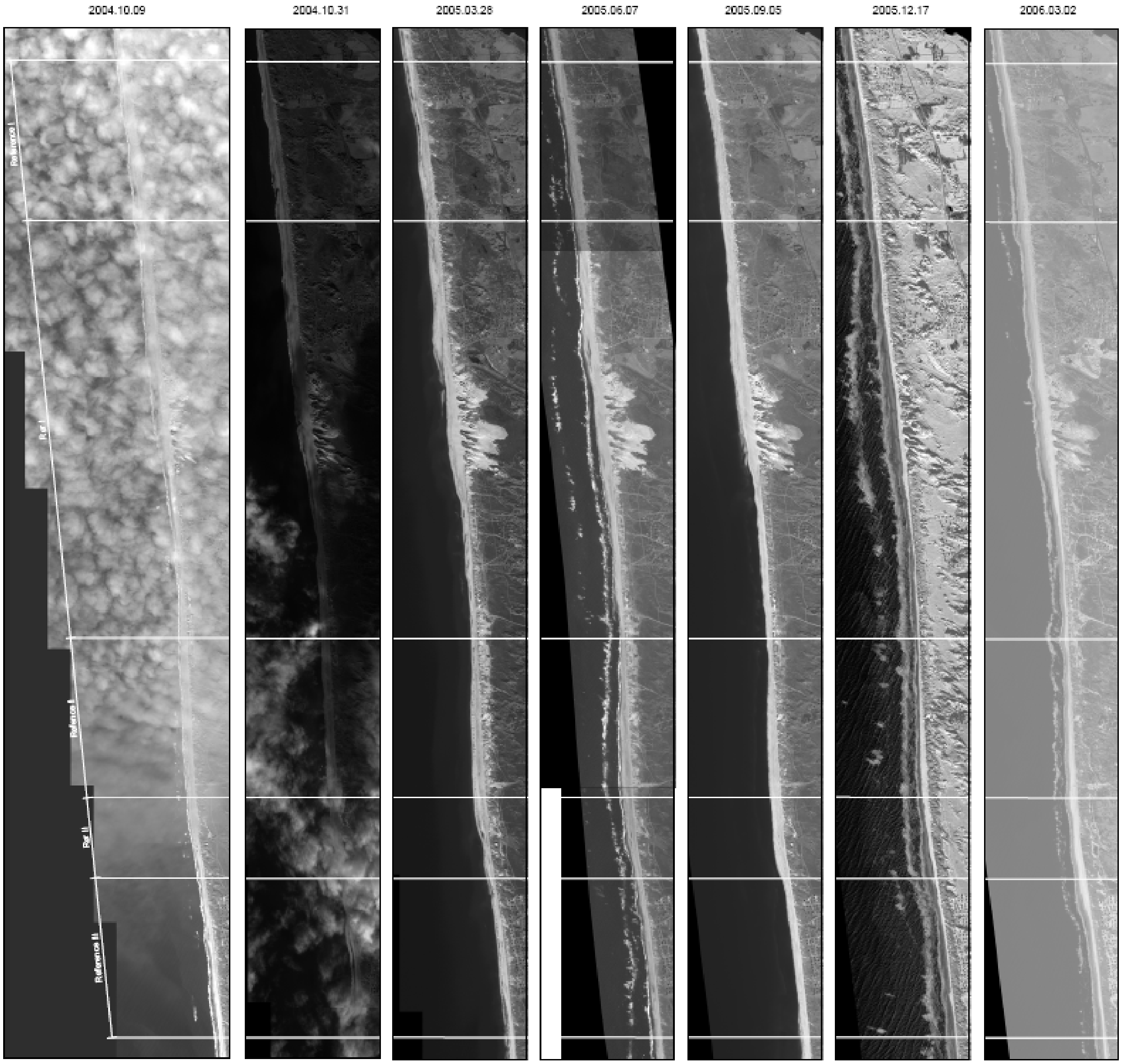
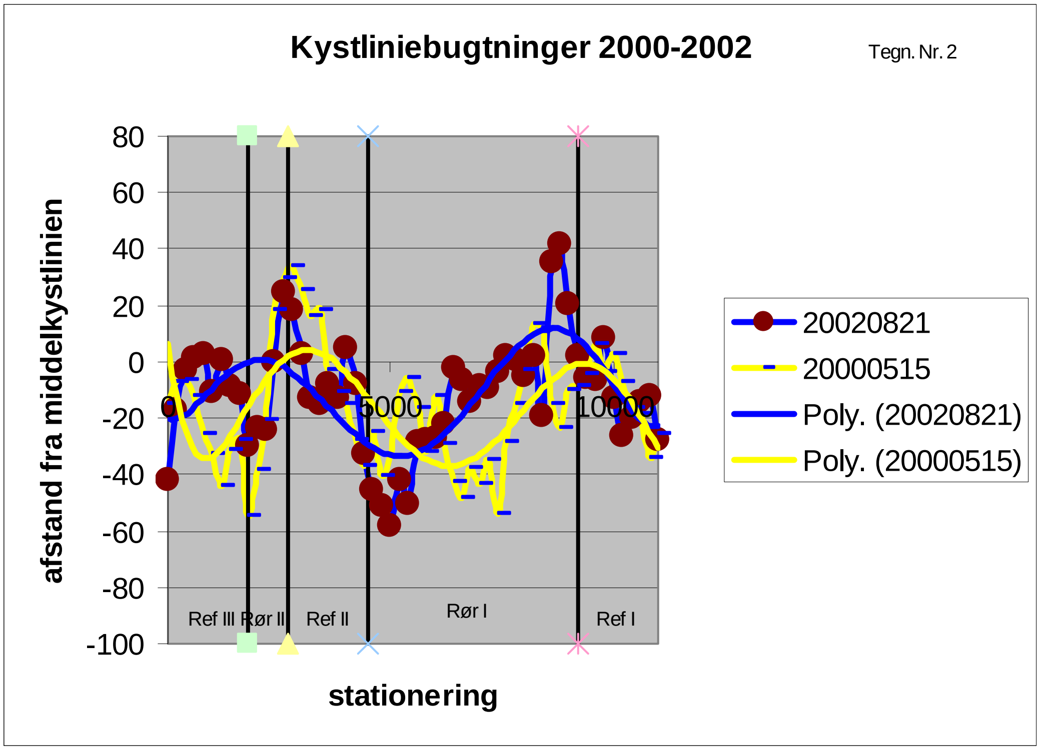
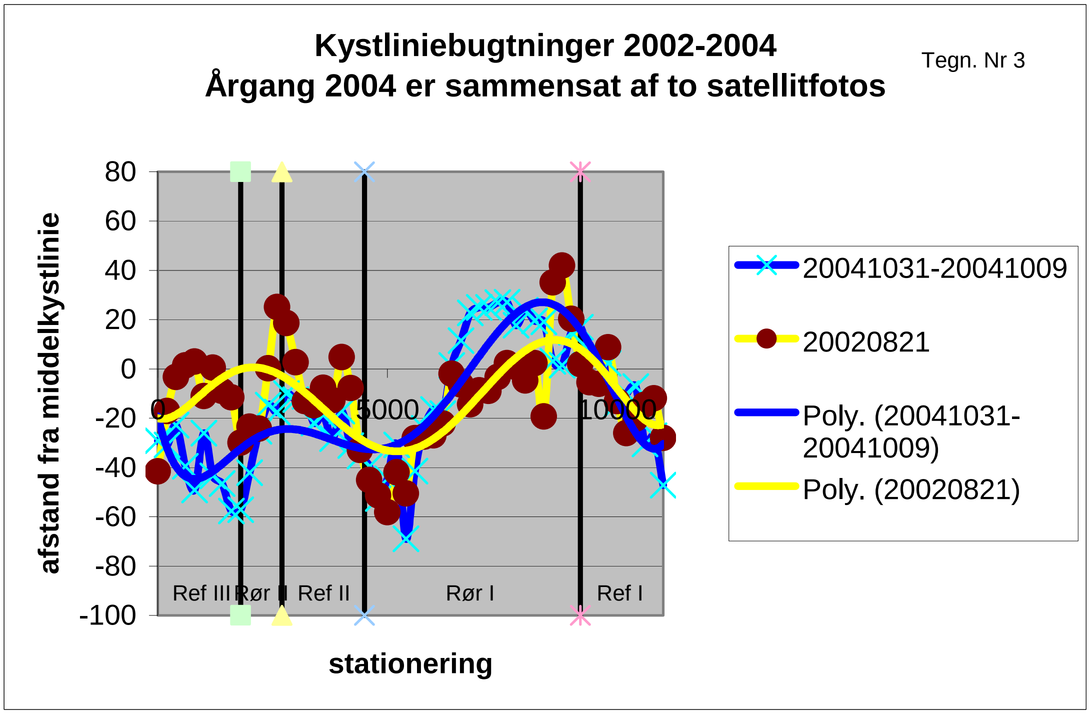


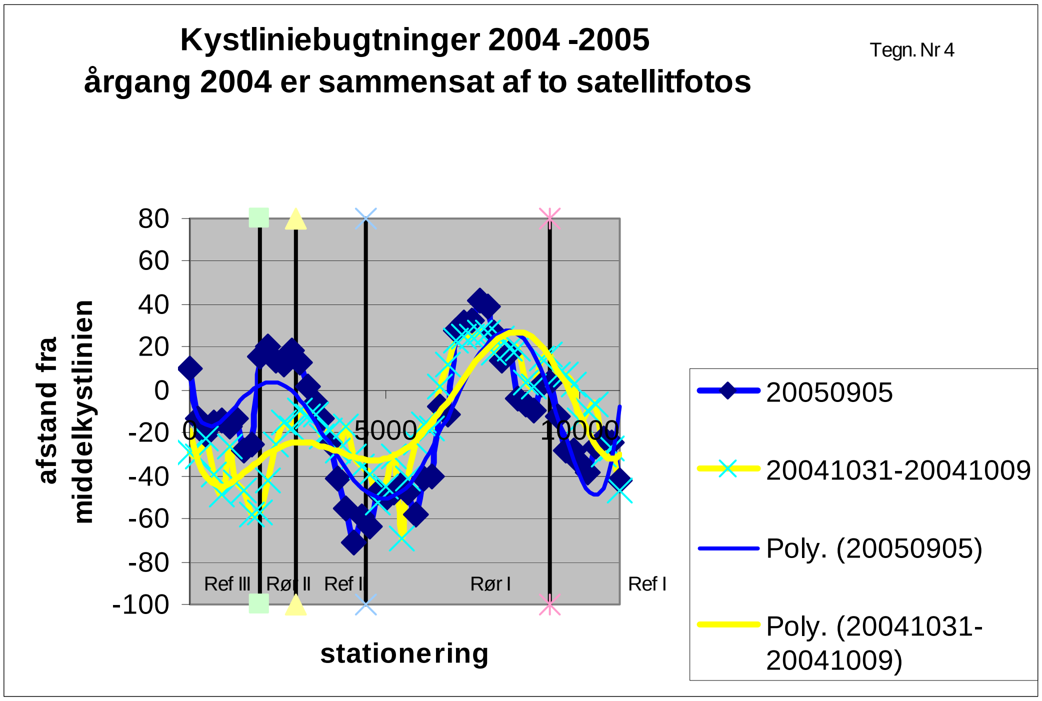
Fig 3.18. Satellite photos of the relevant part of the coast.

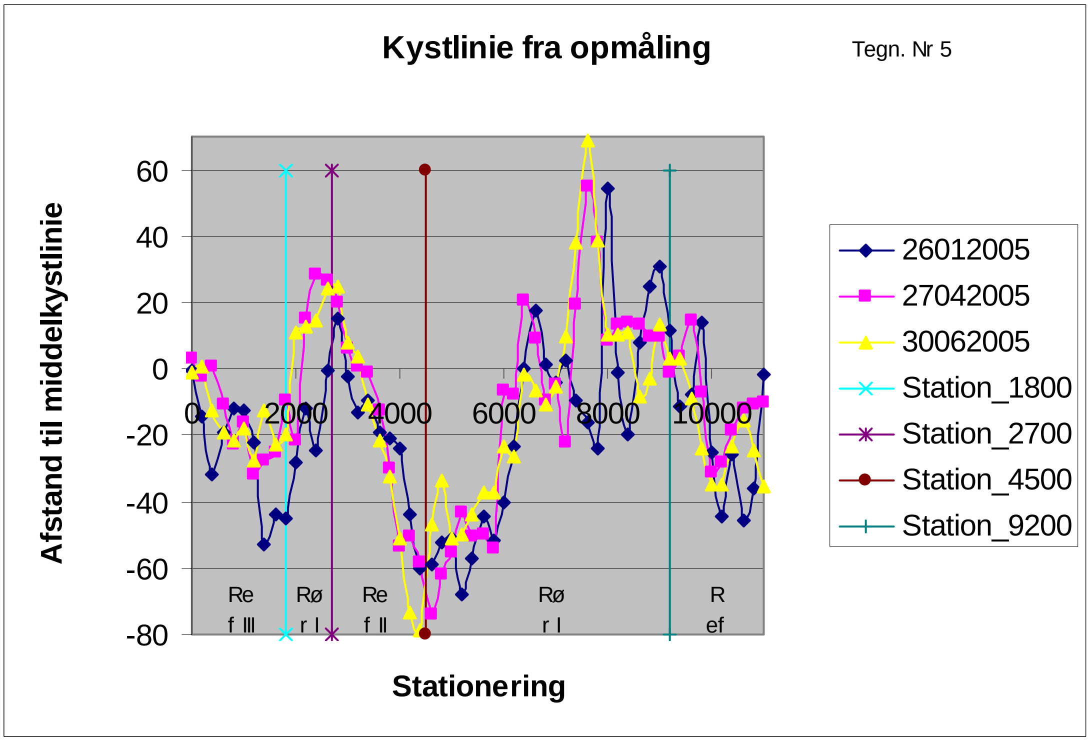

Kystliniebugtninger 2000-2002
Tegn. Nr. 2
afstand fra middelkystlinien
80
60
40
20
0
-20
-40
-60
-80
-100
0
5000
10000
stationering
Ref III
Rør II
Ref II
Rør I
Ref I
20020821
20000515
Poly. (20020821)
Poly. (20000515)

A

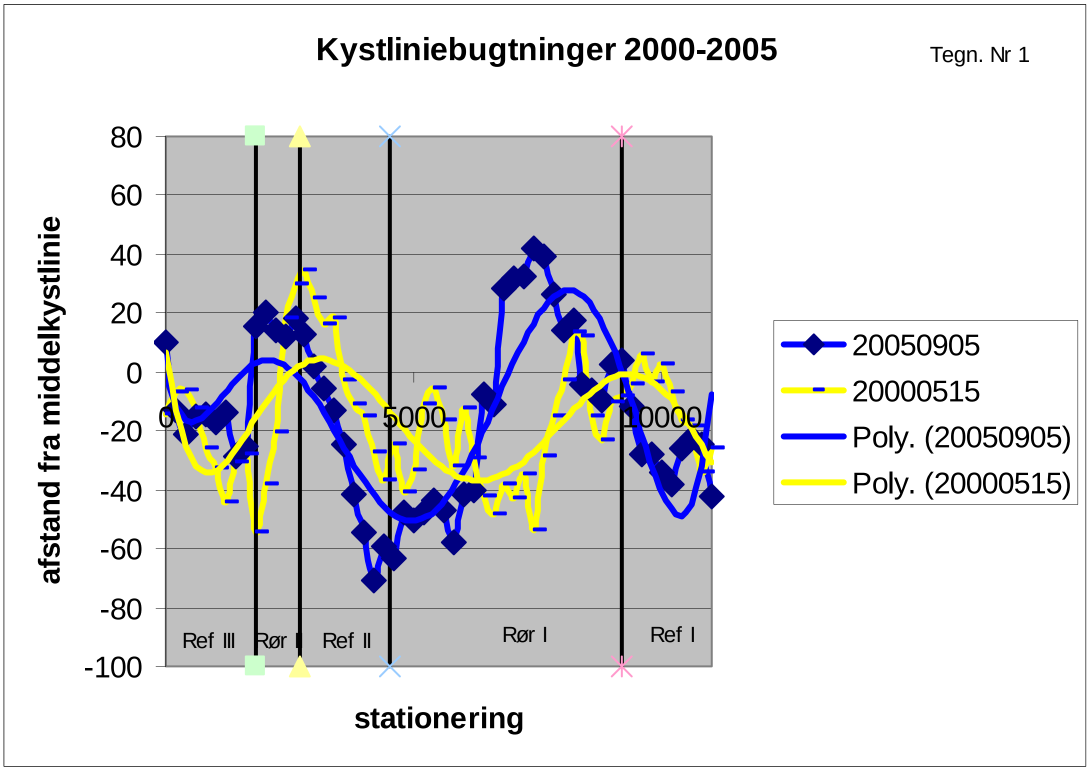

Kystliniebugtninger 2002-2004
Årgang 2004 er sammensat af to satellitfotos
Tegn. Nr 3
afstand fra middelkystlinie
80
60
40
20
0
-20
-40
-60
-80
-100
0
5000
10000
stationering
Ref III
Rør II
Ref II
Rør I
Ref I
20041031-20041009
20020821
Poly. (20041031-20041009)
Poly. (20020821)

B


Kystliniebugtninger 2004 -2005
årgang 2004 er sammensat af to satellitfotos
Tegn. Nr 4
afstand fra middelkystlinien
80
60
40
20
0
-20
-40
-60
-80
-100
0
5000
10000
Ref III
Rør II
Ref II
Rør I
Ref I
stationering
20050905
20041031-20041009
Poly. (20050905)
Poly. (20041031-20041009)


Kystlinie fra opmåling
Tegn. Nr 5
Afstand til middelkystlinie
60
40
20
0
-20
-40
-60
-80
0
2000
4000
6000
8000
10000
Re f III
Rø r I
Re f II
Rø r I
R ef
Stationering
26012005
27042005
30062005
Station_1800
Station_2700
Station_4500
Station_9200

D



E

Figure 3.19 A-E: plots from satellite photos on the long shore variation in beach width at different years before and during the test.

Chapter 4: Description of the PEM-system

The principle in the PEM-system is as follows: An array of vertical perforated tubes is drilled down in the beach sand.

Figure 4.1 shows a single tube handed over by SIC to this expert the total length is about 1.60 m with an inner diameter equal 6cm. There are different versions of the tubes, some are longer and with another diameter. Since these variations are not important for this report, this expert has kept the above mentioned properties in the reporting. Figure 3.2 shows the dimensions of the slots in the tubes. The slots are only 0.2 mm wide in order to avoid penetration of sediment into the tube. From Figure 4.2 it might be noted that slots only are present only in the lower 80 cm of the tube (that part to the right in the photo).

Where the slots are present, water is allowed to flow in and out of the tube, so this part is called the “active part” of the tube. In all following drawings and sketches, only this active part of the tube is shown. The expert doesn’t understand why SIC has decided to have slots only in the lower half of the tube. If the idea is to drain the beach you should have as long an “active part” as possible.

Figure 4.1: Photo of tube in full length, approximately 1.60 m. The tube is without slots in the upper half, but it is ventilated at the top, so air can go through.

Figure 4.2 Blow up of the tube: Slots of 0.2 mm width are cut in the lower half of the tubes, so water can flow in or out.

The distance between each row of the tubes is 10 meter, and the distance in between the rows is 100 meters. To this experts opinion this corresponds to one tube per 1000 square meter beach, but to SIC's opinion it corresponds to one per 10 square meter, see figure 4.3. You could ask, why SIC chooses 1 meter and not one feet in the long shore direction!

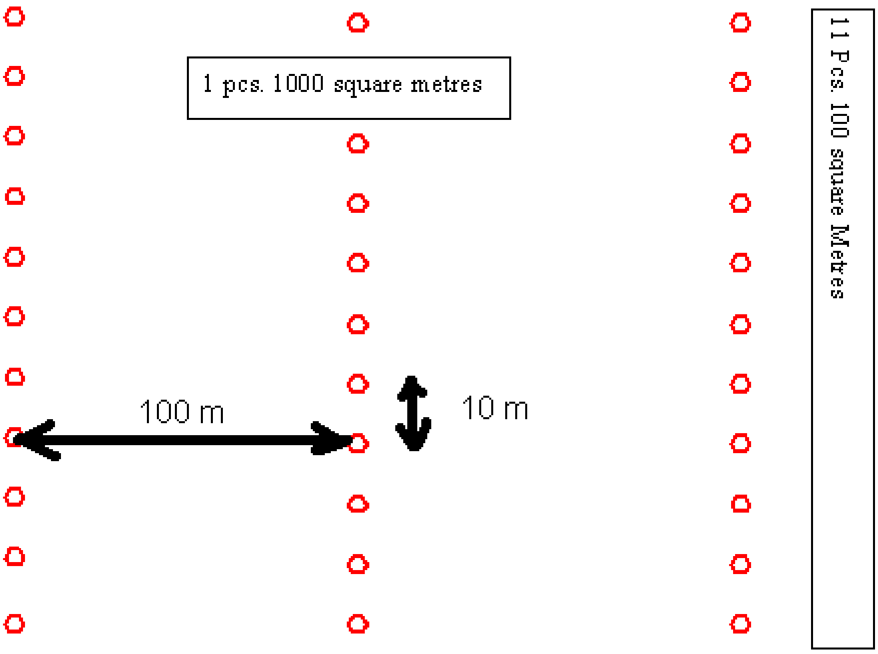


Fig 4.3: This is SIC's explanation on why there is a tube every 10 square meter. Because this expert claimed it was 1000 square meter, SIC accused him of scientific dishonesty.

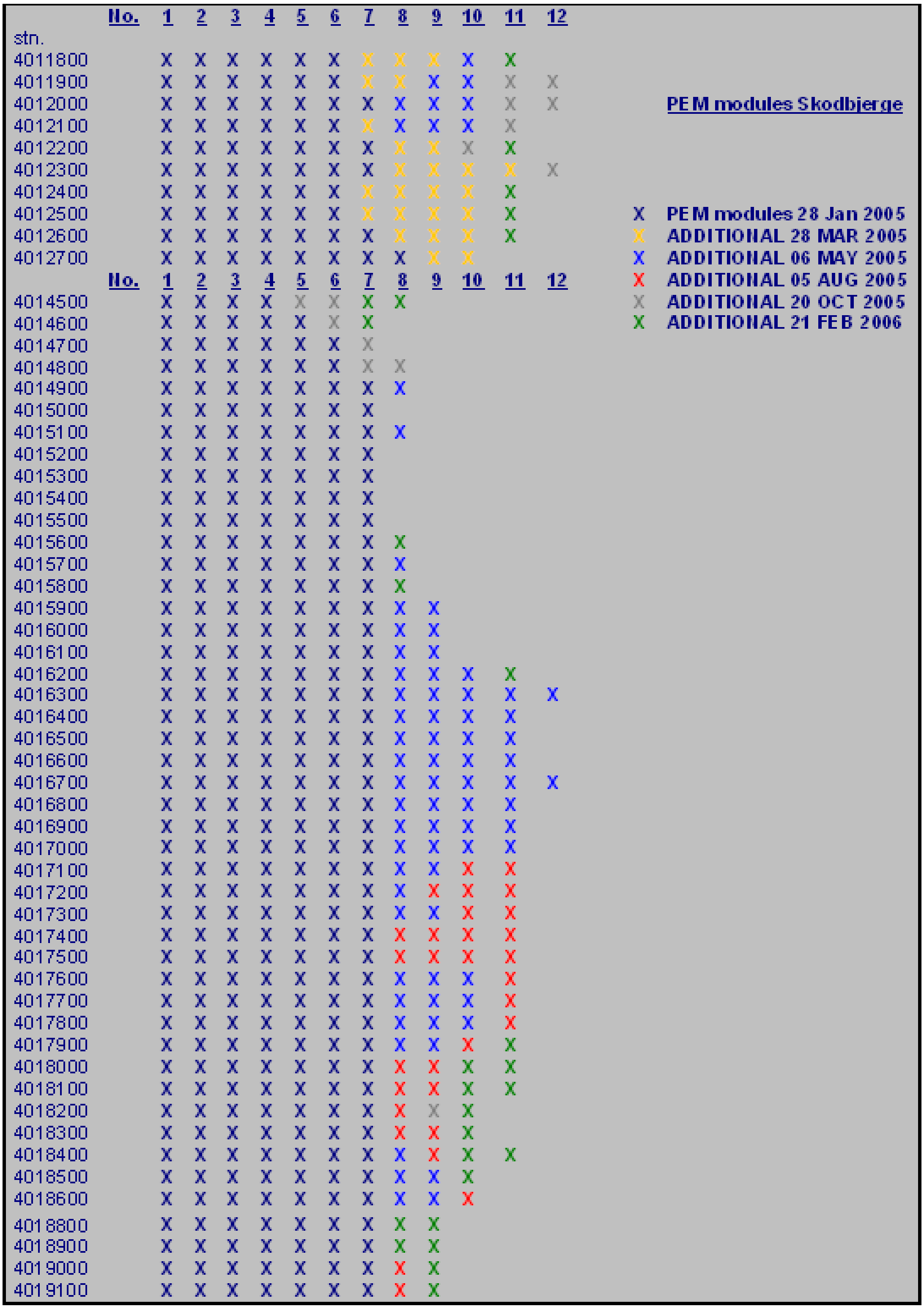
Most of the drains were installed in January 2005. These tubes were installed by drilling a hole in the beach. The tubes are placed so low in the beach, that they initially are covered by approximately 30 cm of sand, see figure 4.4B.

Later the beach was 'reinforced' by adding supplementary tubes. The positions and number of the drains and the time of installation during the first two years are shown in figure 4.6. As seen from the table, drains have been added all over, where increase in beach width made it possible. These were implemented by digging larger holes, see figure 4.4 and 4.5. Next to illustrate dimensions and installation of the additional tubes, figure 4.4 and 4.5 are included to illustrate how slow the flow from water filled sand to the dogged hole occurs: it takes at least 5-10 minutes, which suggests that the flow within the tube actually will occur extremely slowly, even if you uses a pump to remove the water from the tubes.

Figure 4.4A: Most of the tubes are installed by drilling, not to disturb the beach.

Figure 4.B: Left: The inventor of PEM Poul Jacobsen installs an additional tube in the beach (peaking). Right: The tubes are initially buried, so the top is around 30 cm below beach surface.

Figure 4.5: It takes 5-10 minutes before the groundwater shows up in the bottom of the hole. This gives an indication how fast you can drain the beach (at least by active pumping).



PEM modules Skodbjerge

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		
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			

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

Figure 4.6 Positions and number of drains placed.

Ch5 : The functioning of the tubes

5.1 Introduction

In this chapter the possible functioning of the tubes is investigated.
PEM stands for Pressure Equalization Modules, which indicates that a pressure difference must exist in the beach, which can be equalized by the tubes. It is not easy to localize this point.

If the tubes work, there must be a kind of transport of either fluid or gas through the tubes. If not – then the tubes can be replaced by solid material like a wooden pile, which have no effect at all.

Fluid.
The fluid must be either water from the Sea (usually salty) or from inland (usually fresh). The flow must be either up- or downwards directed. If you have a flow in the tube, and it is upward, then the water must enter the tube at the bottom (or lower half) and escape at the top (upper half). If on the other hand side, the flow is downwards inside the tube, the opposite must be the case. For this reason it is surprising that the tube only is permeable at the lower part as mentioned in chapter 4.

Gas.
The gas must be air from the atmosphere, assuming that biological production by bacteria not is a candidate in this context, since this production rate is very slow. For this reason the possible net air flow must be downwards directed, stemming from the air above the groundwater table. To get an air flow you need a pressure difference. In a homogeneous sandy beach no pressure difference can be build up in the air, because sand is able to breath.
Finally air in the tube can move up and down together with the instantaneous water level in the tube, since the tube is ventilated at the top. This requires a free water surface in the tube, which frequently exists.

The water level inside the tube varies with the groundwater level outside the tubes. This feature is discussed detailed below, but anyway: the amplitude of the water table inside the tubes varies with a slightly smaller amplitude than outside (water flows from a higher level to a lower!), and also with a small phase shift. The dampening increases with the frequency in the oscillation of the groundwater table.

The drainage

Due to the considerations above, in the following we restrict ourselves to consider the case, where the tubes may improve the drainage capacity of the beach. As shown in the next sections, it has not been possible for the expert to identify a drainage effect of the tubes of any significance.

In general a drain works as follows: The flow in the soil will always flow from a higher to a lower pressure. Such a difference in pressure can be created within a drain, if this is connected to a low-pressure outlet like a well or ditch or similar. The functioning of a drain in a beach is illustrated below by two examples in the section "Other drain systems".

Next it is explained and illustrated that the PEM-system cannot work in the same manner. For this reason it is not obvious why the system should have any kind of drainage effect.

The flow in the beach is usually quite complicated due to the composition of the beach (inhomogeneous layers) and salt-fresh water flow, which will create flow created by density differences. Some simple cases will be discussed below and in the appendix 3.

Water level variations in the beach.

If the water in the sea is calm, and there is no water supply to the beach from land, the water in the beach will have the same water level as that in the sea.

However, usually the Sea level changes with time due to

- Wind waves
- Tide
- Wind set-up and changes in atmospheric pressure (storm surge).

The variation in the sea level will create flow in the beach, where the water level will move up and down with the same frequency as that in the Sea, but with a phase shift in time and with amplitude, which is smaller than the water level amplitude of the sea level.

Figure 5.1A-C shows a number of sequences of the ground water level in the beach:

In figure 5.1A and 5.1B, the effect of the ground water table in the beach caused by wind waves with a period of 1-15 sec is sketched. In such cases, also the groundwater in the beach will oscillate, but this oscillation can only be felt a few meters away from the sea.

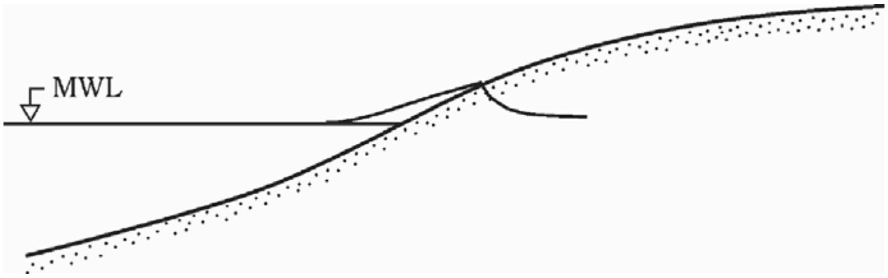


Figure 5.1A: Ground Water Level (GWL) during run-up of wind generated waves.

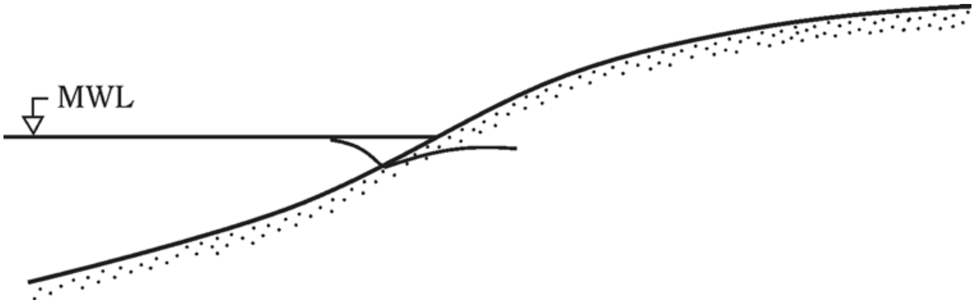


Figure 5.1B: Ground Water Level (GWL) during draw-down of wind generated waves.

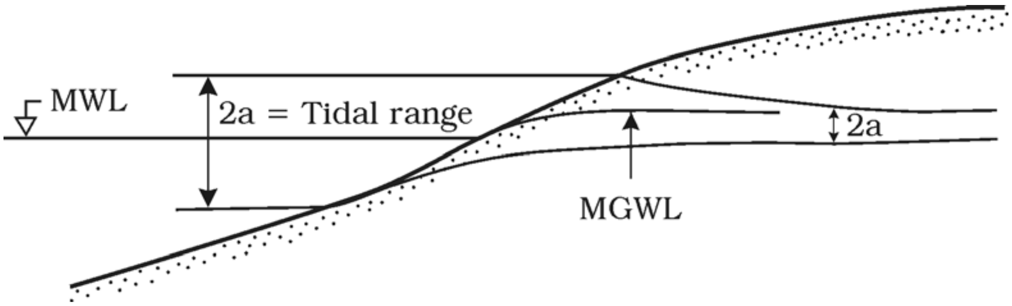


Figure 5.1C: Ground Water Level (GWL) due to long waves (tide) and storm surge. The dampening in the beach (the height of the tidal range 2a in the beach) is much weaker for these long period waves than in the shorter wind generated waves.

In figure 5.1C the tidal flow with a very long wave period (around 12 hours) is shown: from this long period motion, the variation in the sea level penetrates much further into the beach, so the dampening of the motion is much smaller than in the case of wind generated waves.

It is of some importance whether the beach is filled with water or not. If there is a lot of water (high GWL (Ground Water Level)), the individual swash will be of equal size in the run-up and in the draw down period, resulting in nearly equal deposition and erosion of sand in the swash zone, figure 5.2A.

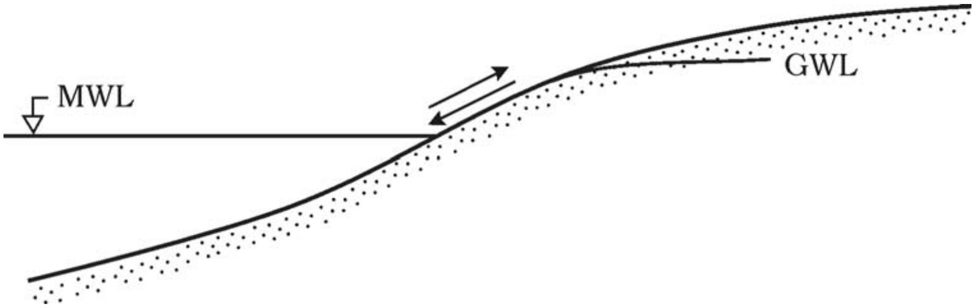


Figure 5.2a: The swash zone flow back and forth is more or less the same if the beach is saturated.

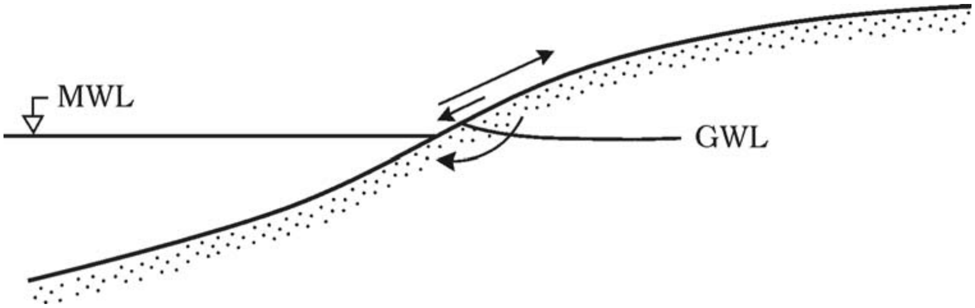


Figure 5.2b: The flow is stronger in the run-up phase than in the backwash-phase if the beach is drained, because some of the run-up water can filtrate into the beach.

If the beach is well drained, some of the water transported towards the beach in the run-up phase does not need to run down the slope through the draw down phase, but can instead be drained away through the beach as sketched in figure 5.2B. In this case some deposition of sand may occur leading to a stronger beach profile.
However, the importance of this effect is usually considered to be weak, see next section.

5.2 Other drain systems.

Active drains:

The concept of drainage of a beach is not new, and a few examples are given below: The idea of drainage has for instance been followed here in Denmark by Westerby, GEO, who developed the so-called Beach Management System (BMS), in which a tube is placed horizontally down in the beach as shown in figure 5.4.
The beach water is drained to the tube, and the water is transported further away by using pumps, thus creating a low pressure in the tube. Because you actually are pumping water away from the tubes, this is in the category “Active drains”. The BMS has demonstrated some success: a small berm of beach sand is accumulated in the neighbourhood of the tube. The size of the berm depends strongly on local conditions, but the magnitude of accumulated sediment is 1-10 cbm per meter beach. Bowman et al recently (2007) published in Coastal Engineering 54, pp 791-800 a paper entitled “Efficacy of beach dewatering-Alassio, Italy”. Here they used BMS on a not very exposed beach West of Genoa a locally increase of 30 cm in one year on the drained beach as compared to the control section. However the advance of the drained beach as compared to the control section was only 2 meters, so the authors concluded the local dewatering to be inefficient to trigger significant beach accumulation.
The created berm is good for recreational purposes, but is unlikely to provide a real measure of coastal protection, because it will be eroded away in a very short time during

a real storm. A negative part of the BMS system is that it requires electricity and maintenance of pumps.

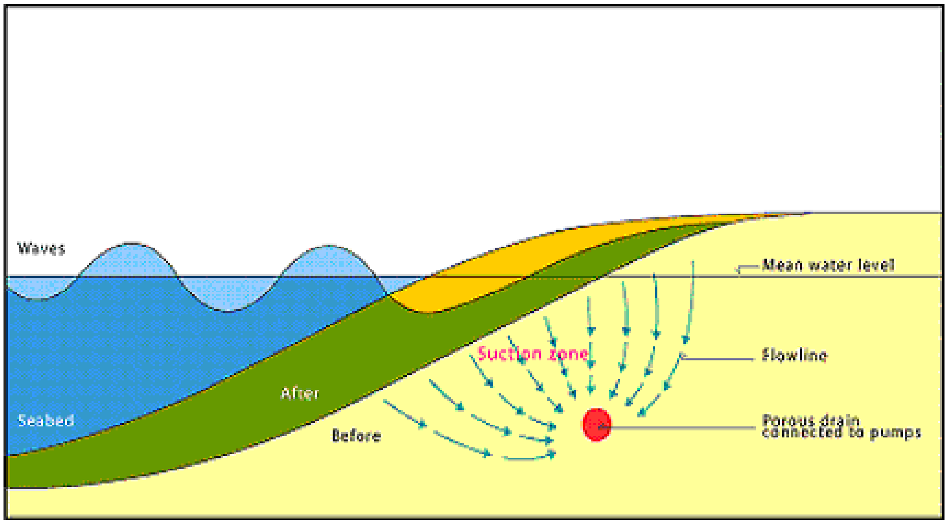


Figure 5.4. The Danish "Beach Management System" drains the beach by pumping through nearly horizontal tubes located parallel to the shore close to the swash zone.

Gravity drains:

Another drain approach is Japanese, and is shown in figure 5.5. In this concept, a permeable layer is placed in the beach reaching from a high level in the upper part of the beach to a level below the lower part of the beach with connection to the sea. In this way the system utilizes the slope of the beach to create a pressure gradient (from high to low pressure) within the permeable layers. Please note that the system in this case is connected to the seabed in order to ensure drainage.

Development of Gravity Drainage System for Beach Protection

Shin-ichi Yanagishima*, Kazumasa Katoh, Naoto Iwasa and Yoshiaki Kuriyama

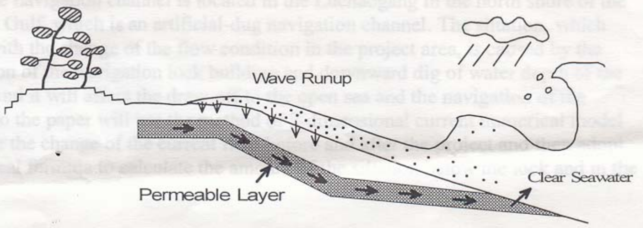


Figure 1 Beach protection system with gravity drainage.

Figure 5.5. A Japanese system to drain beaches: here the tubes are replaced by a highly permeable layer, which is emptied by gravity. Please note the sea-connection of the permeable layer.

In the gravity system shown in figure 5.5 accumulation of sand has also been observed, the magnitude being slightly smaller than that obtained by the BMS system.

5.3. The PEM-system

The homogeneous beach.

It has been discussed very much – and the discussion is still going on – how is the functioning of the tubes in the PEM-system.
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 beaches, which consist of permeable, sand all over, i.e. no impermeable layers are present. Usually the sand is characterized by an average size d and a geometric standard deviation σ. Very graded sand has a large content of sediment, which is much finer than the average size d. This sand is called *natural sand.* If you remove a lot of the fines, this will hardly change d, but will decreases σ. This is what SIC calls *washed sand.*

Because the different flow-resistance in the sand and in the tube, the water level will be different outside and inside the tube if a vertical pressure is present. This might be the case, if the ground water motion in the beach is introduced by an oscillatory motion in the Sea. This motion can be caused by wind waves, for which the experts and SIC – as this expert understand it – agree, that the PEM-system does not have any impact. The oscillations caused by the tide and storm surge water will infiltrate the beach much more because of the slow changes in water level, cf figure 5.1. This is therefore considered in the following.

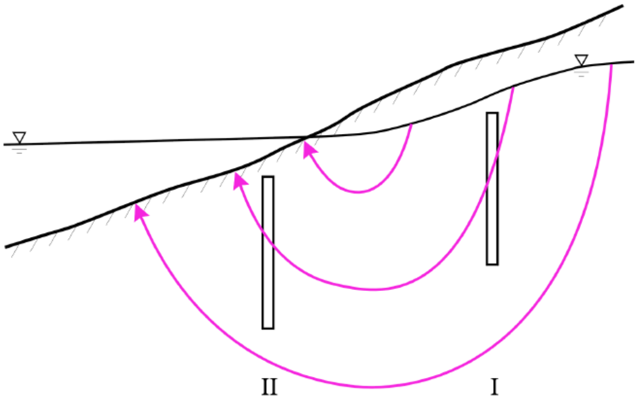


Figure 5.6: The flow introduced in the beach caused by tidal motion in the sea. The figure shows the ground water flow pattern in the beach during falling sea level.

The analysis given below considers the tidal situation, where a vertical pressure gradient leads to a ground water motion not very different from standing waves in front of a vertical wall, see figure 5.6.
If there is no freshwater supply from land, the flow pattern in the sand is like that sketched in the figure 5.6 during falling water level of the sea.
Let’s consider the pressure conditions at tube I and II:

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 5.7. 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 5.7a). 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.

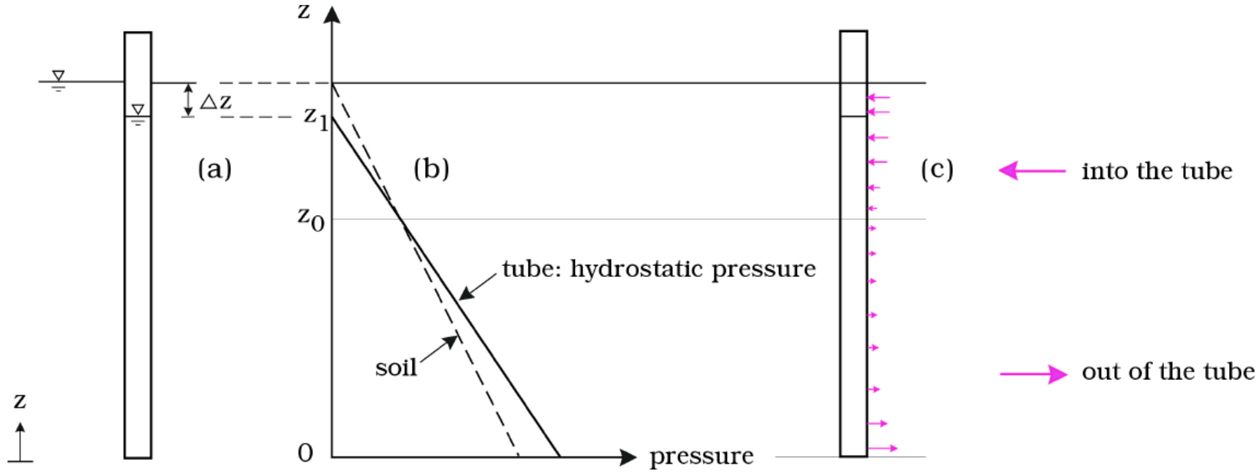


Figure 5.7: Pressure distribution along a tube, and the resulting flow pattern to and from the tube located at position I (figure 5.6) during falling sea level.

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 due to tide (a drop of 1 m in 6 hours) will be

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

Or

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

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

i=V/k = 0.05 mm/sec/ 0.005 m/sec=0.01

Over 2m (the length of the tubes – this is actually exaggerated since there are only slots in the tubes in the lower 1 meter of the tubes) this corresponds to a loss in energy head Δz equal 2 m multiplied by *i*, or a loss in energy head =Δz= 2 cm

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

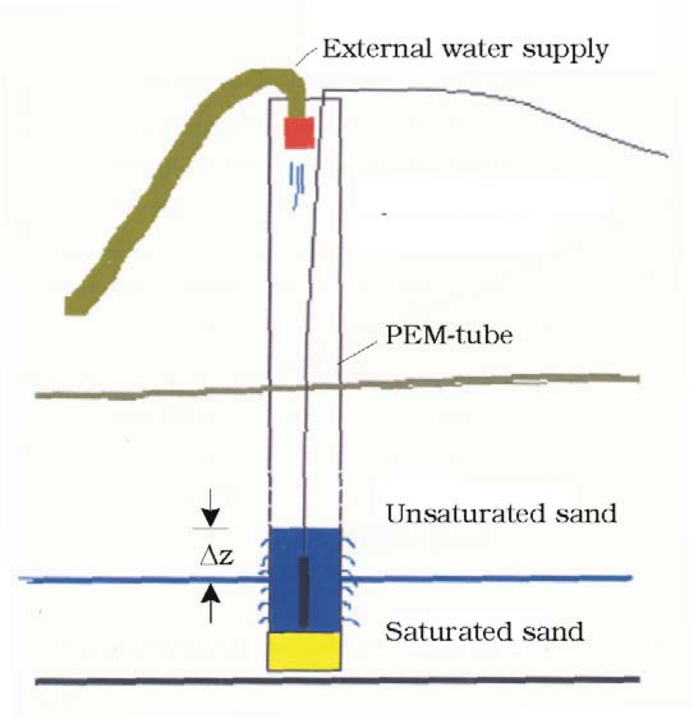
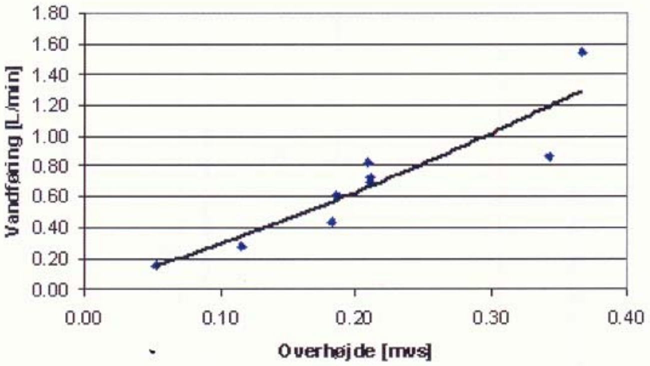


Figure 5.8: Set-up to determine the flow through the tube. The sand size in the experiment is about 0.4 mm.

For this we did a simple experiment in DTU, where we put the tube into sand as shown in figure 5.8, and looked at the flow through the tube. With a head Δz= 20 cm, the flow is around 0.6 l/minute (see figure 5.8), and for smaller heads like Δz= 2 cm, the flow rate is around q= 0.06 l/minute. This corresponds to a flow velocity of

V (tube) = q/area=0.00006cbm/minute/(π *0.03*0.03)=0.35 mm/sec.

The area is πr^2 = 28 square centimeters for r=3 cm. The flow velocity within the tube is with other words around 7 times higher than outside the tube for this specific case.



Figur 5.4: Grafen angiver sammenhængen mellem vandføringen gennem trykudligningsmodulets filter og overhøjden i filteret.

Figure 5.9 Relation in between Δz in meters (horizontal axis) and flow discharge l/minute (vertical axis)through the tube (diameter 6 cm).

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 m^2

The area of the tube is

A (tube)=0.0028 m^2 = 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 the table 5.1 below, the impact of different sand sizes in the beach for the drainage capacity of a tube is given. Lundgren and Brinch Hansen (Geoteknik, Teknisk Forlag, Copenhagen 1965) suggests k to depend on d (10) (10% of the sediment is finer than this size, d given in mm) in the following way:

$k=0.0125\ d_{10}^2$

and this expression has been used in the table, all other parameters being the same as used above. For the flow through the tube, figure 5.9 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 from the table 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).

d_{10} in mm	k in (m/s)	Hydraulic gradient *i*	Δz in m	V (tube) in mm/s	Improved drainage in 1 per thousand
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

Table 5.1 Improved drainage capacity of tidal flow in 10 m width along the beach due to the tubes placed in homogenous soil.

Let us finally return to figure 5.6 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 lesser 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)

This will cause a negative vertical pressure gradient at tube I shown in figure 5.6, and a positive vertical pressure gradient at tube II. It has been measured (see appendix 1 and 2) that the water outside the tube has an amplitude in the order of 1 meter, and this result has been used in the analysis to estimate the vertical pressure gradient needed to create this strength of the groundwater flow. The analysis suggests that during *falling* groundwater level the water level outside the tubes must be higher than inside the tubes, leading to flow directed towards the tubes at the top, and away from the tubes at the bottom of the tubes. During *rising* water levels the opposite will be the case, see figure 5.10 A and B.

The analysis described above is in agreement with the field test described below (and in details in appendix 1 and 2), and more advanced modelling done using a numerical model, see later in this chapter and appendix 3.

Field tests.

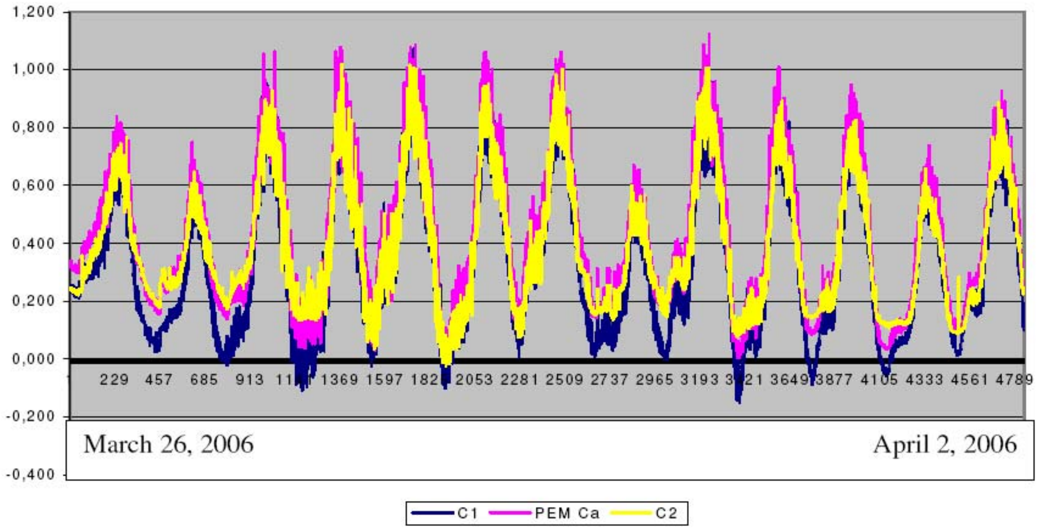


Figure 5.10: Example of Recording from the field test.

A field study just north of the test site was performed as part of this investigation to look at the pressure conditions in- and outside the tubes. The details and an analysis of these tests are given in appendix 1 and 2.

The idea behind the test was to measure the groundwater level variation in two lines perpendicular to the coastline in two different environments: in one week without the PEM-system installed and in the following week with the PEM-system installed. Figure 5.10 shows an example of the pressure variation inside the tubes (pink, PEM) and outside the tubes (black: in between 2 PEM-tubes, C1 is 5 m nearer the Sea than the PEM-tube, the yellow tube C2 is located 5m further landward of the PEM-tube)..

First of all it is seen, that the water level fluctuate slightly due to the wind waves (high frequency fluctuations, cf figure 5.1 A and B) but more clearly the level is seen to follow the tide (low frequency figure 5.1 C). In the present case the tidal range is around 1m, and it is seen that the water table variation is more or less the same at all three locations, so the flow does not seem to change radically near the tubes. Taking a closer look on figure 5.10 it is further observed that at high groundwater levels, the level is higher in- than outside the PEM-tube (up to 8-12 cm). This means that at high water levels, there is a flow into the tubes in the lower part of the tubes, and a corresponding outflow at the upper part of the tubes. This is in agreement with the considerations in the section above. In the real situation the flow is much more complex, and for that case you need a numerical model like that applied in appendix 3.

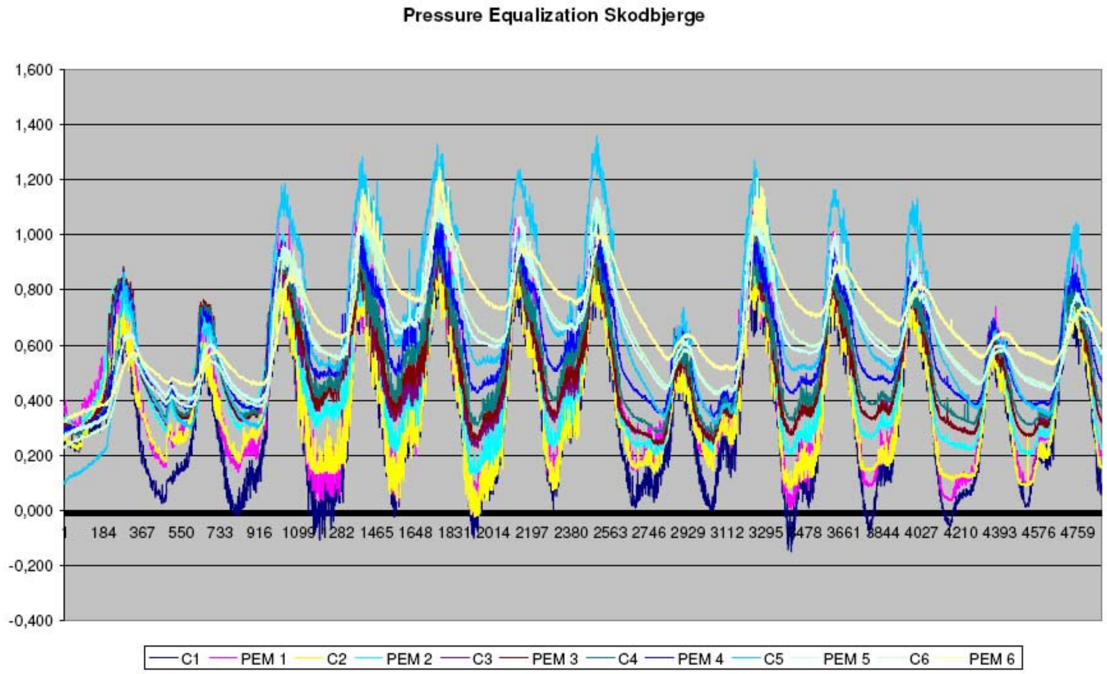


fig. 5

Based on the physical effects of the PEM tubes on the beach described above a separate test was made with water level sensors (Diver), to determine the effect of PEM on the water table in the beach. The test was carried out in the northern part of the Skodbjerge test area in control area 1.

Figure 5.11: Time variation in the whole row of tubes and outside the tubes

Appendix 2 presents the gross-behaviour of the beach, i.e. the dampening of the tidal wave as function of the distance from the coastline as sketched in figure 5.1C.
There was a change in the Mean Water Sea Level of 35 cm from the first week to the second, due to changes in the weather conditions. That means that the groundwater flow in the second week incorporated an additional 35 cm thick layer of the beach in its flow domain.
The analysis of the dampening shows, that the dampening characteristics of the beach was the same before and after the implementation of the PEM-tubes, which demonstrates that the PEM-system has no significant drainage effect. The inclusion of the 35 cm layer of beach has not changed the characteristics as well, which demonstrates how uniform the composition of the beach actually is.

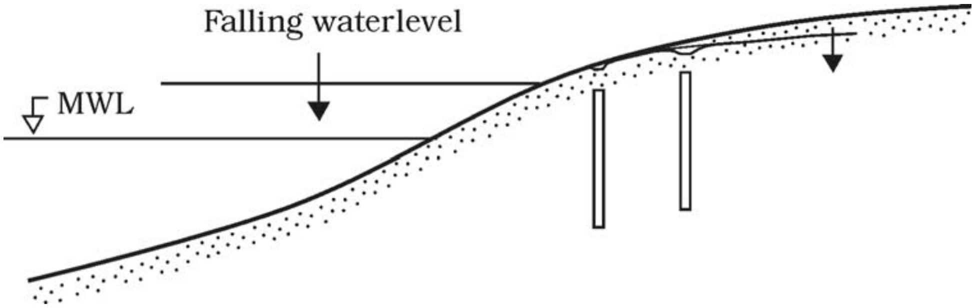


Fig 5.12a: During falling water level (ebb flow or after a storm), the tubes will improve the drainage; the impact is however estimated to be insignificant, actually less than one per thousand.

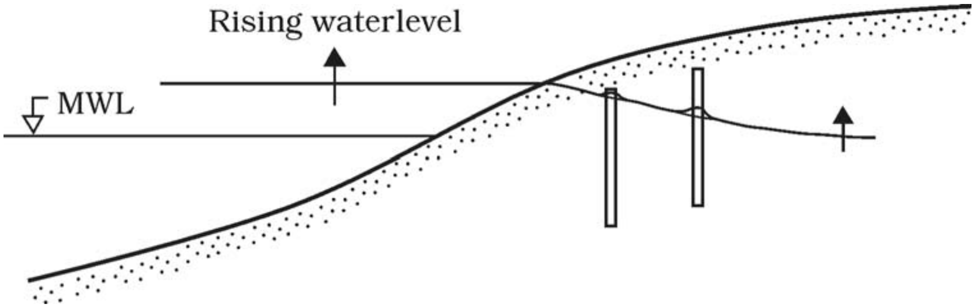


Figure 5.12b: During rising water levels (flood or storm surge), the beach is filled slightly faster with water, because the vertical tubes can lead the water easier to the beach. Like in the falling stage, the impact is insignificant; less than one per thousand.

Summary:

Nearly no driving forces exist to activate the flow near the tubes. A simple estimate of the impact of the tubes is given above, in which it is demonstrated that there certainly is being created a flow through the tubes because of the less flow resistance within the tubes than in the soil outside, but this flow is very small, less than 1 mm per second. The effect is sketched in figure 5.12. Even though this is 5-10 times larger than the flow velocity in the surrounding soil if this soil is very fine, it will have no drainage effect because the tubes occupy a very small fraction of the area under consideration.

The in-homogeneous beach: presence of permeable layers.

A number of sketches are presented in the following, where the expected impact from the PEM-tubes is discussed regarding different combinations of soil properties. For simplicity only one tube is shown in the beach, and we are considering the case of a falling water table in the beach.

Figure 5.13 shows the basic case: the water will locally easier flow through the pipe, so you get a faster speed from A to B, but the water still needs to flow from B to C, and there is no trigger for this, so not much has been gained by installing the tube, it is nearly just as easy to flow from A to C as from B to C.

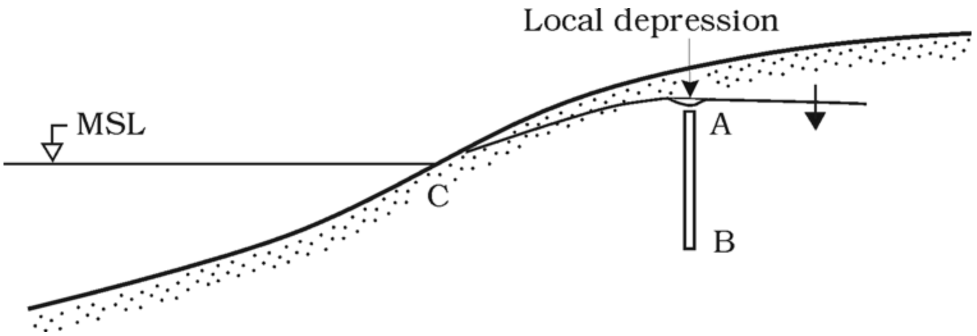
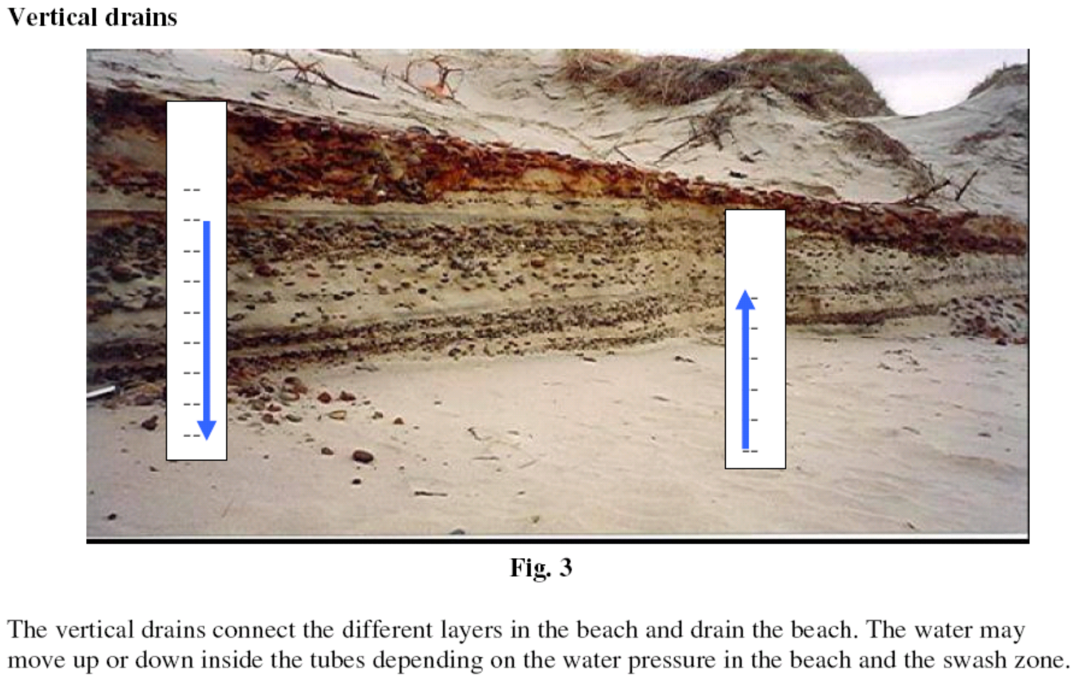


Figure 5.13: The drain will locally make a depression cone around the tube. However, the size of the cone is extremely small, and most of the beach water will flow directly rather through the tube towards the sea.

Figure 5.15 suggests that a trigger for the flow from B to C can be established by the presence of a permeable layer, see also the photo figure 5.14 from a SIC report.



Vertical drains

Fig. 3

The vertical drains connect the different layers in the beach and drain the beach. The water may move up or down inside the tubes depending on the water pressure in the beach and the swash zone.

Figure 5.14 SIC's explanation of trigger.

Figure 5.14 illustrates one explanation given by SIC of the functioning of the drains in the presence of permeable layers.
As shown in figure 5.15, the presence of a horizontal-like permeable layer will in all cases improve the drainage of a beach, even without tubes installed. The *requirement* will be, that the permeable layer must be sea-connected, so a low pressure can be established in the permeable layer. The layout in figure 5.15 is slightly different from the Japanese system shown in figure 5.5, because a sloping drain actually is not needed, just a pressure drop, which also can be created in a fully horizontal, but permeable layer.

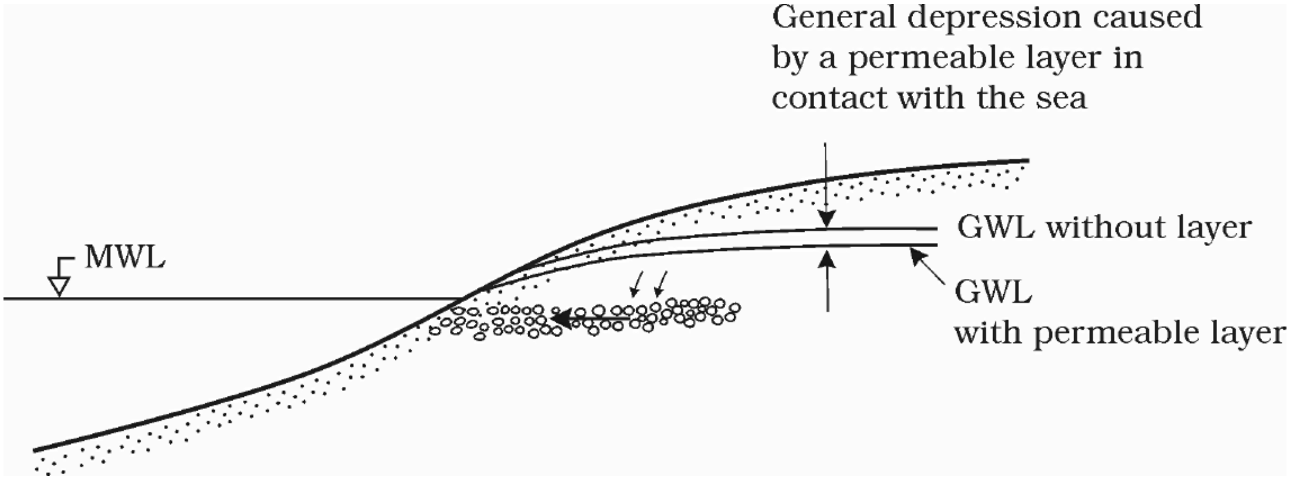


Figure 5.15: The presence of a sea-connected permeable layer will anyway improve the drainage of the beach.

Figure 5.16 shows the same situation as that in figure 5.15, but with a tube installed. Now

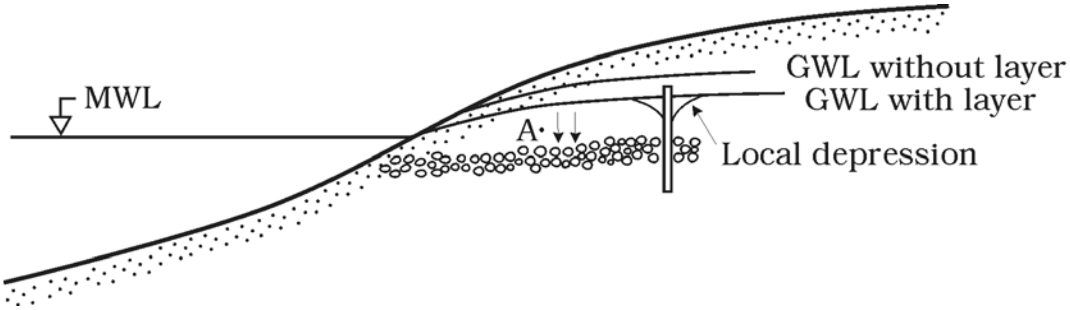


Figure 5.16: Tubes installed in a beach with sea-connected permeable layers will only have a local effect, because most of the water will go directly to the permeable layers.

next to the general lowering of GWL also a small local depression close to the tube is established. This depression can actually be expected to be larger in case of a permeable bed compared to the case of a homogeneous bed as explained in the following.
The presence of the permeable layer will anyway cause a general lowering of the water table, with or without tubes. Or, put in other words: it is easier for a water particle located far away from the tube (like in location A, figure 5.16) to move directly through the sand to the permeable layer, than to move from A to the tube (also through sand), and next further through the tube and the permeable layer to the sea.
Figure 5.17A-C illustrates this a little bit further: In figure a, we have a very permeable layer (like a PEM-tube) connected to the sea, and the drainage capacity is simply determined by the pressure drop ΔH equal to the difference in height between the actually GWL and the Sea Water Level.

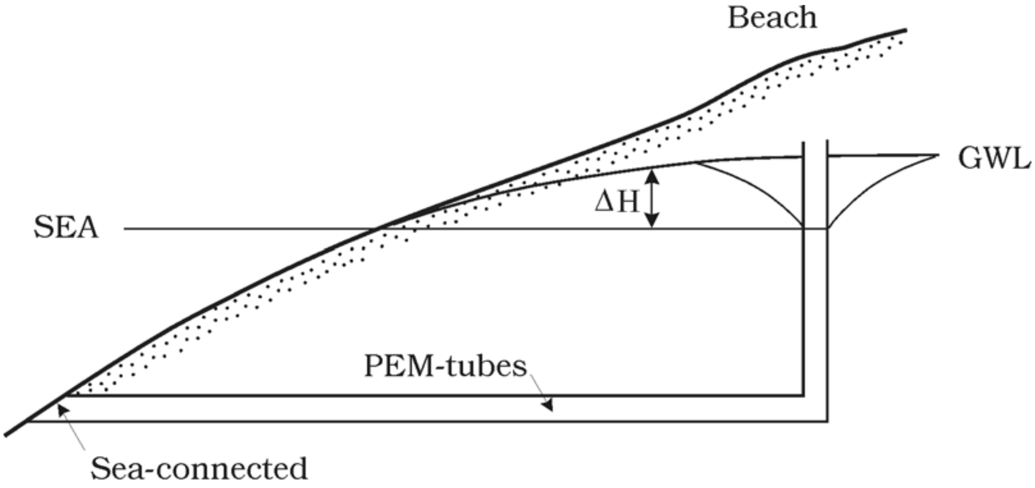


Figure 5.17A: An effective solution to drain the beach, if GWL is higher than Sea Water Level.

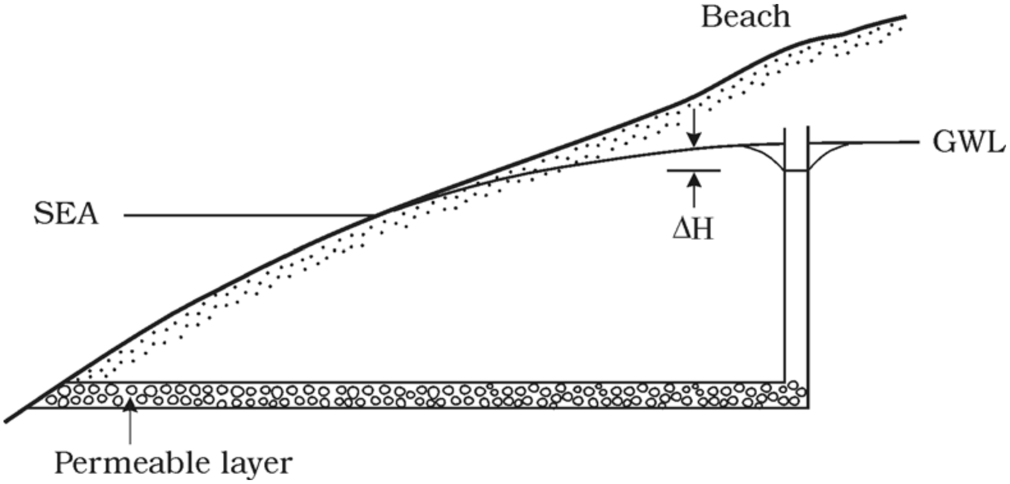


Figure 5.17B: the drainage capacity decreases if the sea –connection get a smaller permeability.

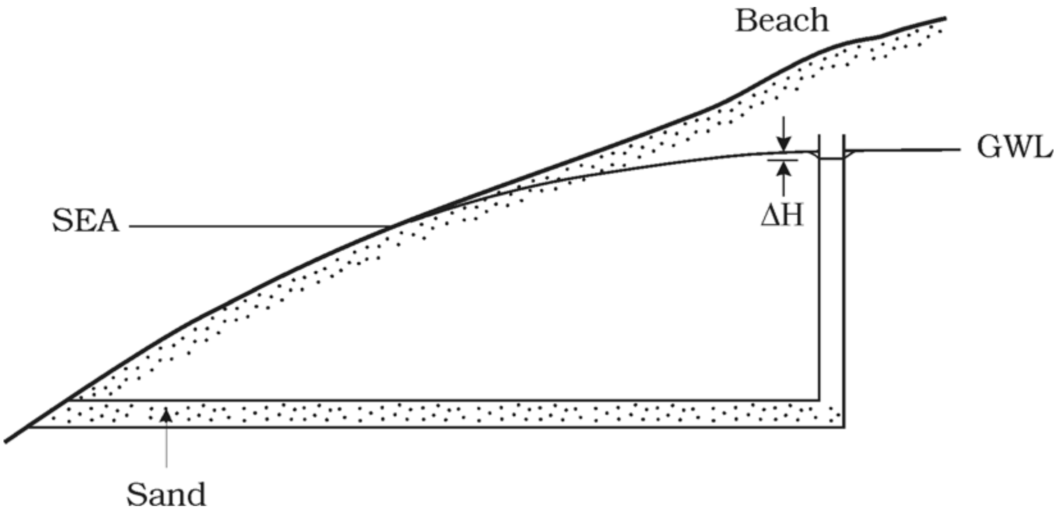


Figure 5.17C: in the case where the horizontal part of the drain simply consists of the same material as the original beach, the drainage effect disappears to be negligible.

In figure 5.17 B the highly permeable layer is replaced by a less permeable layer, but still more permeable than the surrounding sand. In this case there will be a certain energy loss through this layer, so ΔH becomes smaller because the water level in the tube must be higher in order to force the water through the permeable layer. In figure 5.17C the horizontal tube is filled with sand, and we are back to the situation shown in figure 5.13 with a very small local depression. From the sketches in figure 5.17 it is realized, that the drainage capacity strongly depends on the structure and permeability of the permeable layer.
If a permeable layer exists, it will be easier for the water limited within a circular cone around the tube as sketched in figure 5.18 to flow to the tube: The water confined within the dashed line will flow through the tube rather than directly to the permeable layer. This will certainly increase the impact radius, depending on the ratio k / k_p , where k is the permeability of sand, and k_p the permeability of the permeable layer.

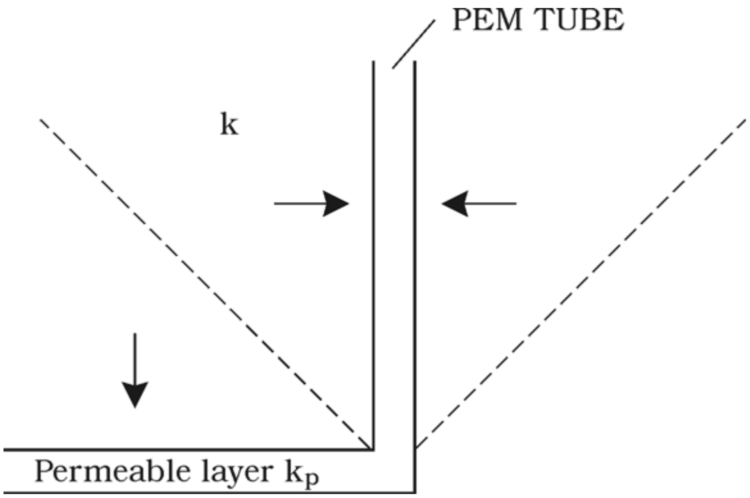


Figure 5.18: The water confined within the 45-degree cone will prefer to flow through the vertical tube if a sea-connected permeable layer exists.

Do permeable layers exist?

Permeable layers might be present in the beach, due to grain sorting by waves and wind. Figure 5.19 is a photo from the site, where layers of pebbles are present in isolated spots on the beach surface. One may ask what happens, when these layers are covered by finer material. It is most likely, that the voids in between the pebbles are filled with this sand from above; consequently the permeability of those layers will not be higher than that of the surrounding sand.

Figure 5.19: Layers of pebbles on the beach. ***But*** *if the change in grain size between sand and permeable layer is large, the voids in the course material will be filled with sand, and the permeable layer is no longer permeable.*

"Activation of Permeable layers".

As seen from figure 5.19, the distribution of pebbles on the beach is quiet "patchy" or 3-dimensional in its nature. So the situation as shown in figure 5.20 is a possibility: isolated layers of high-permeable layers (AB) may exist, which through the tubes can be connected to the sea through another high-permeable layer (CD).

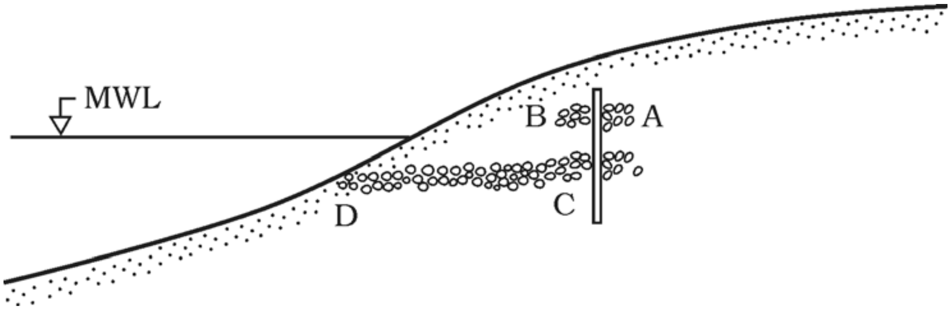


Figure 5.20: The upper layer A-B will be drained better to the sea-connected layer CD by a vertical drain

As sketched in the figure, the tubes can act as a vertical link in between the different permeable layers. At least it will mitigate the flow from A to C sketched in the figure, so there will be an improvement if this interconnection continues right to the sea, i.e. DC exists. If the interconnection does not exist, the flow through the tubes will still be very slow.

The array effect:
It could be asked whether an interconnection between a numbers of tubes might improve the drainage as shown on the photo figure 5.14 and in figure 5.21A and B, where it is sketched how more permeable layers are activated. This is possible, but requires the high-permeable layers to be connected to the tubes, and further a connection from one of the tubes to the sea.

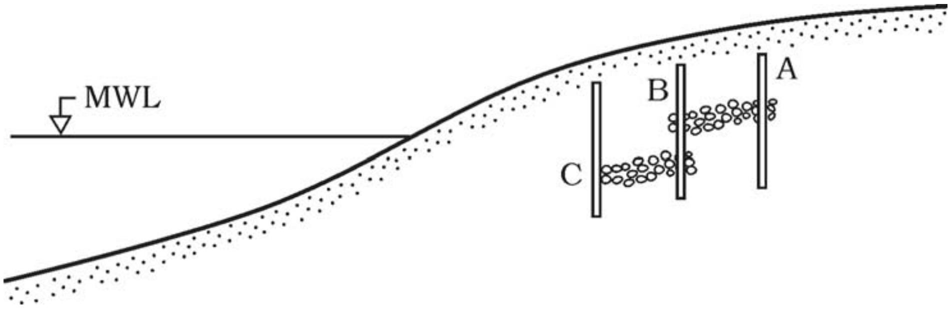


Fig 5.21A: A row of tubes can connect different permeable layers.

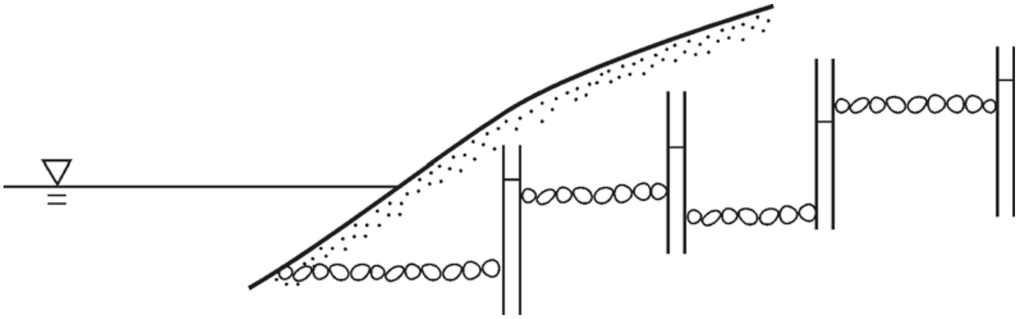


Figure 5.21B: To activate the different layers you need Sea-connection.

Will there be Sea-connection??
The situation with sea connection as sketched in figure 5.20 at point D may be possible. So the system may work, leading to deposition of sand. After this the Sea-connection has gone, the connection is blocked with the deposited sand, and the tube system stops functioning.

The in-homogeneous beach: Presence of impermeable layers.

Next we consider the presence of impermeable layers, formed be nearly horizontal layers of clay or other fines mixed with the sand.
Now the beach can't be drained as suggested in figure 5.22, because the impermeable layer with a nearly horizontal stratification prevents vertical motion. Instead the water entering the beach during high tide must be drained nearly horizontally to the sea. This will cause a higher average level of the groundwater in the beach as shown in figure 5.22.

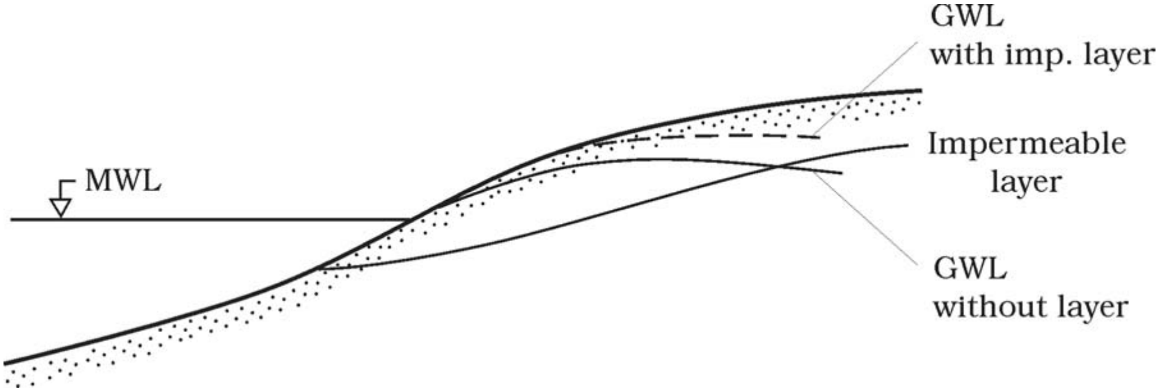


Fig 5.22: Impermeable layers will increase the ground water level in the beach during ebb flow because the flow will be more horizontally.

If a tube is installed, which penetrate the impermeable layer as shown in figure 5.23A, then the water can flow down through the tube if the pressure is lower below the impermeable layer than above.

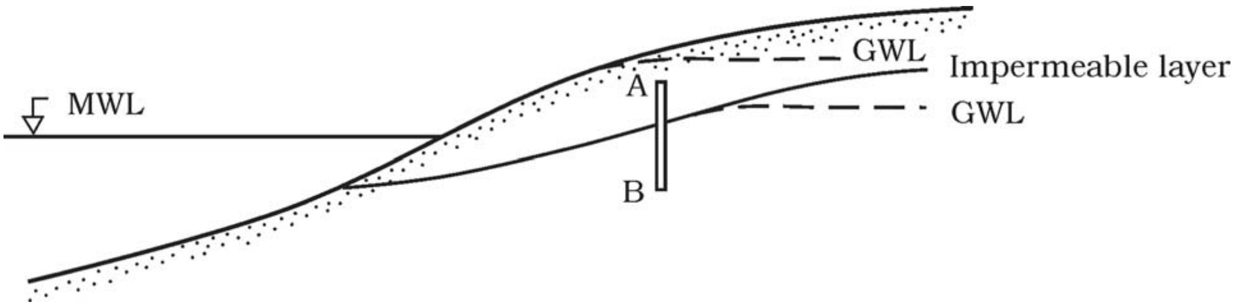


Figure5.23A: The ground water level can be lowered if a tube penetrates the impermeable layer, and the pressure below this layer is lower than above the layer.

This will require the extend of the impermeable layer along the coast to be large; otherwise there will be a pressure-equalization through the sand outside the impermeable layer.

As sketched in figure 5.23A, the pressure below the impermeable layer is most likely to be lower than above. However, since the water flowing through the pipe still need to flow further from the end of the tube (B) to the Sea; it would be quite helpful for the drainage capacity if the flow below the impermeable layer enter a high-permeable layer as sketched in figure 5.23B. If not the drainage improvement will be insignificant.

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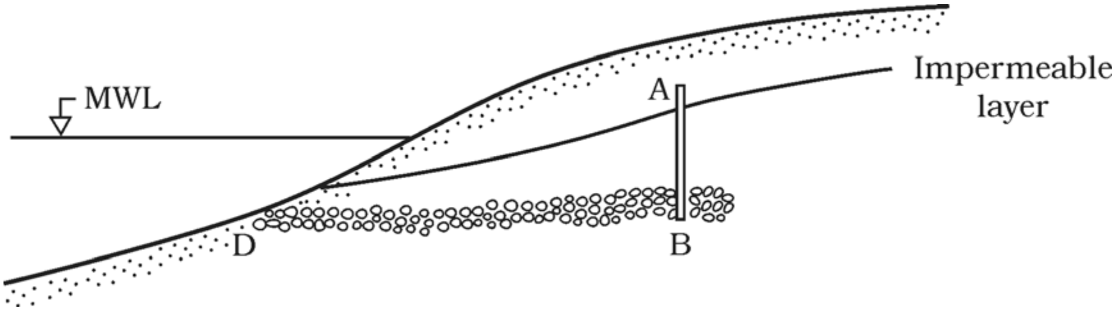


Figure5.23B: a drain located in a Sea-connected high-permeable layer, and penetrating an impermeable layer above the permeable layer will improve the drainage above the impermeable layer. This will require a very special configuration in the beach.

Finally figure 5.23C shows an example where the PEM-system certainly might work: if the impermeable layer has a convex shape like a bowl, water will be trapped during falling water level if the layer is placed sufficiently high. In this case, PEM may puncture this layer and allow the trapped layer to escape. This requires a very special configuration of the inhomogeneous layers and the effect will anyway only be very local around the tubes.

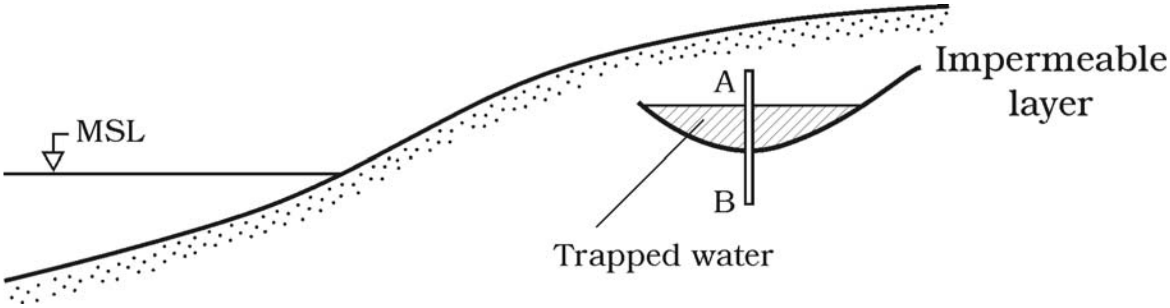


Figure 5.23C; water trapped in a bowl formed by the inhomogeneous layers may escape Through the tubes.

***Water supply from land*.**

One of SIC’s major arguments for the functioning of the PEM-system is that it drains away the water running from land to the sea through the beach.

The arguments put forward above do not change significantly if the water inflow to the beach does not only originate from tide/storm surge, but also stems from out-flowing water from land. The major difference occurs in the case of the presence of impermeable layers, which in the case of a special configuration as sketched in figure 5.24 can lead to a higher pressure from below than above the impermeable layer. In this case the water will flow *up* through the tube, leading to more water in the beach (artetic pressure) So the most important thing which can be said about the inland water supply will be, that in this case you don't need tidal flow or storm surge to demonstrate any need for draining the beach.

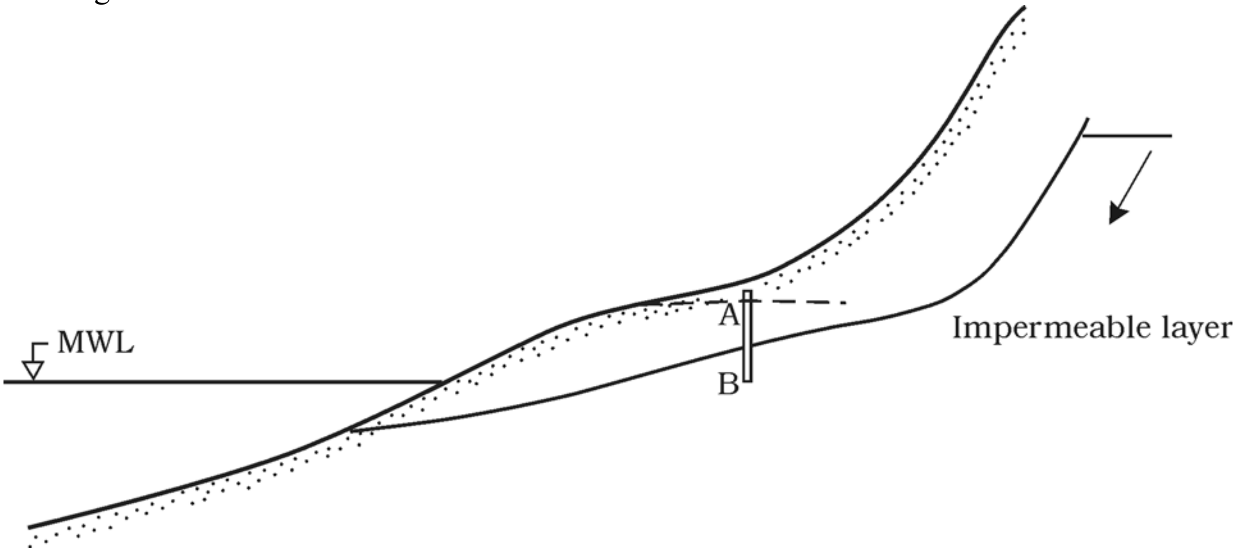


Figure 5.24: Supply of water from land will most probably flow up through the tubes (artesic pressure), and thereby make the beach more unstable.

5.4 Modelling of fresh-salty water in a tidal environment.

The arguments above are descriptive in their nature, and further do not include the combination of salt and fresh water. This latter is difficult to describe without any numerical model. According to SIC, fresh and salty water together is dangerous, because the fresh water will be restricted to a quite narrow outflow area. In their PR-material, they usually refer to the picture reproduced in figure 5.25. The picture actually does not explain much. Due to hydrostatic conditions, the surface elevations of the fresh water will be slightly higher than the salty water to get the same pressure along a horizontal line in the salty water below the fresh water. This is more clearly illustrated in figure 5.25 taken from a book by Davies, applied in SICs PR-material. In order to get a sloping water table permanently you need freshwater supply. The higher level at the right part of figure 5.25 will not by itself create any flow from right to left, since the pressure is in equilibrium with gravity all along the sketched pipe. However, due to the surface slope, secondary currents will be introduced, which in the long term will level the lighter freshwater to a thin horizontal layer, if you don't have steady supply of additional freshwater.

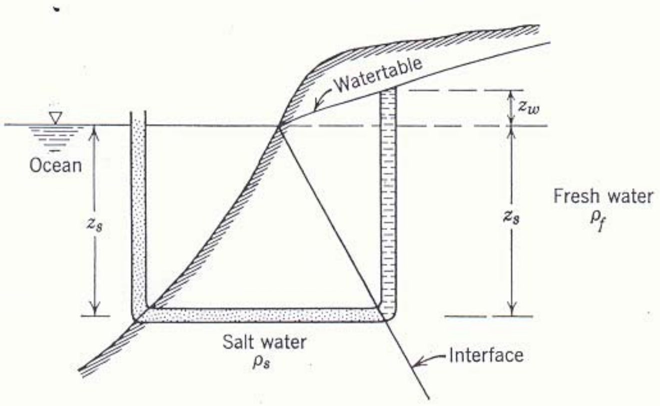


Figure 7.22 Salt water intrusion according to the Ghyben-Herzberg theory.

Figure 5.25: The concept of hydrostatic conditions. (Used by SIC to document the functioning, but it simply shows hydrostatic pressure).

Figure 5.26 illustrates the flow pattern when you have a steady sea state and a steady supply of fresh water (from the left). Figure 5.27 is a similar illustration given by SIC.

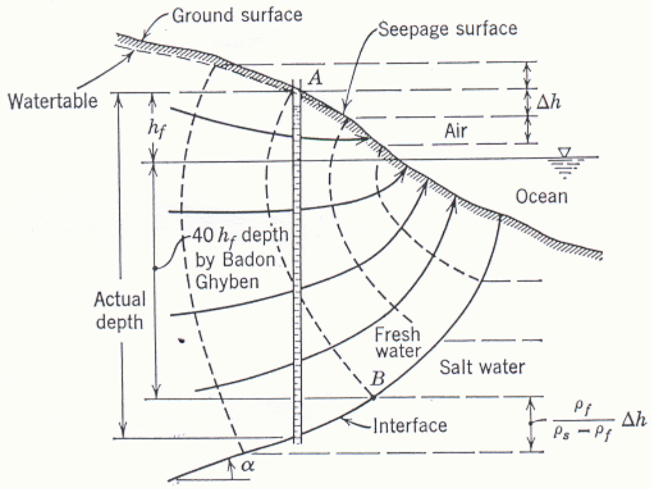
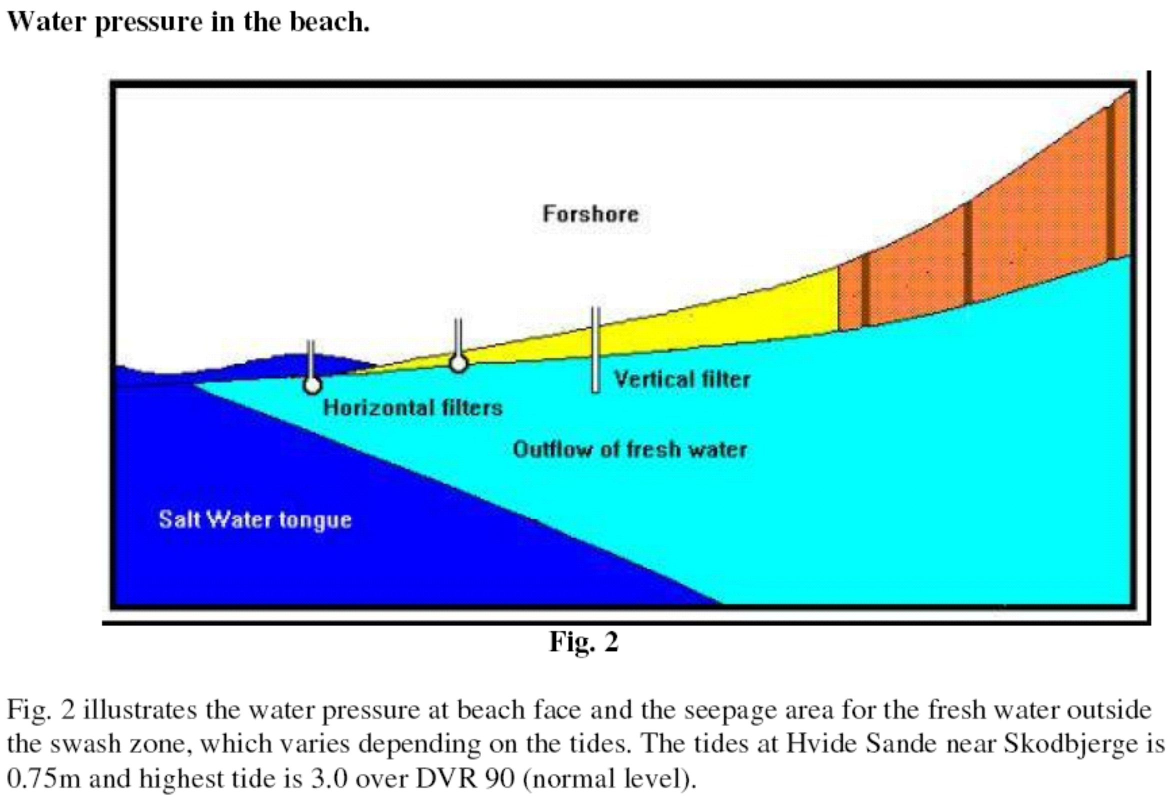


Figure 7.23 Discrepancy between actual depth to salt water and depth calculated by Ghyben-Herzberg relation. (After Hubbert.)

Figure 5.26 Seepage flow introduced by supply of fresh water over salt water.



Water pressure in the beach.

Fig. 2

Fig. 2 illustrates the water pressure at beach face and the seepage area for the fresh water outside the swash zone, which varies depending on the tides. The tides at Hvide Sande near Skodbjerge is 0.75m and highest tide is 3.0 over DVR 90 (normal level).

Figure 5.27: SICs illustration of the water pressure.

The figure 5.26 shows that there exists a pressure from the outflow fresh water in the seepage zone. Figure 5.27 suggests this pressure to be relieved by vertical filters.
You can evaluate the pressure as follows: the width X of the seepage zone is according to SIC given as (modified slightly by this expert to be correct in dimensions)

$$X = q\rho_f / \left[2K(\rho_s - \rho_f) \right]$$

q is freshwater flow (estimated to be around 1 cbm/day/meter), and ρ is fluid density (of salt and fresh water, 1.025 ton/cbm and 1.0 ton/cbm). K is hydraulic conductivity (around 25 m /day). This gives X=0.8 m. If this is correct, it will result in an upwards directed pressure gradient q/K equal 0.05. To approach fluidization, the vertical gradient shall be around unity, so the freshwater is far from fluidizing the seabed. Actually, the refined modelling, appendix 4 gives a value of X not far away from the above suggested, namely X being in order of 1-2 meters. When adding the tubes, you also sometimes get a slightly larger X, in the order of 2-3 meters, so the vertical seepage will be partly reduced due to the redistribution of the seepage flow. This is in accordance with what SIC is after: to reduce the pressure in the seepage zone.

The value of seepage velocity v=q/n =3 meter/day=4E(-5) meter/second can be compared with the fall velocity w of the sand: for fine sand, w is in the range 0.5-5 cm/sec or 1000-10000 times larger than the seepage velocity, so the fresh water will not destabilize the individual grains at all. The risk of fluidization is investigated in the next section.
The remarks above only relate to flow without tubes, and conclude, that even if the fresh water flows in a narrow zone of less than one meter, the upward directed pressure gradient due to this contribution is far away from mobilising the sand in the bed. The changes due to tubes is investigated by a numerical model (see below), and here it is demonstrated that the additional effect from the tubes are so small that you hardly can detect them.

Numerical modelling.

To support the arguments outlined above, Peter Engesgaard from University of Copenhagen was asked to do numerical simulations of the complex flow discussed above. For reasons of simplicity, he mainly focussed the 2D flow problem, which actually over-predicts the impact from the tubes, see below. In his work, the tubes are replaced by an 8 cm wide slot parallel to the beach, so while the flow velocities within the tube are reasonable well predicted, the discharge is over-predicted by a factor around 20-30 due to the larger area of the slot per meter alongshore (800 square centimetres) compared to the individual tubes (28 square centimetres per meter – if you contain a tube in the area under consideration, cf. figure 4.3). Moreover, the tubes are spaced with a distance of 100 meter along the beach, so in average along the beach, the drainage is in total over predicted by a factor of 2000-3000. Therefore the calculations given in the appendix 3 must be considered as a near-tube study, say in circle of 50 cm around each tube. However the study can anyway be used for our purpose, if we as output apply the predicted *velocities* inside the tubes. These are driven by the forced convection from hydraulic gradients and free convection caused by vertical density differences, and does only slightly decrease in the 3D-simulations. Using a squared tube in a one meter wide domain, some preliminary 3D model predictions suggest a reduction of the flow velocity inside the tube of about 30-40 % of that predicted by the 2D flow. In an even wider than one meter environment, the reduction becomes even larger, so 40% is a conservative estimate (over-predicts the flow rate in the tube).

Figure 5.28 shows the simulated water table variation in the beach during a tidal period. Supply of fresh water from hinterland is included, and has been put equal 0.9 cbm/day as explained in chapter 3. The flow pattern, strength and direction are shown in figure 5.29, which also includes salinity variation.

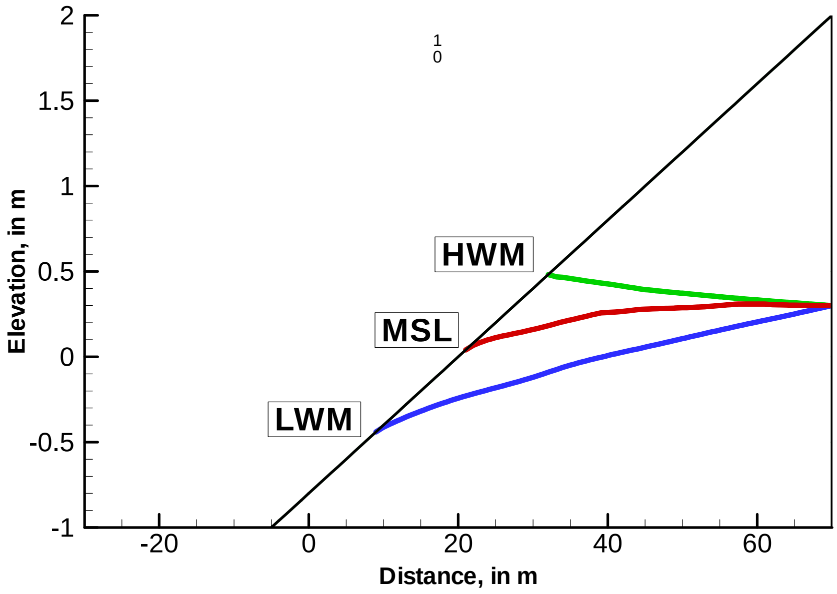


Figure 5.28: Simulated water table at different stages of the tide in a homogeneous beach with a fresh water supply of 0.9 cbm/m.

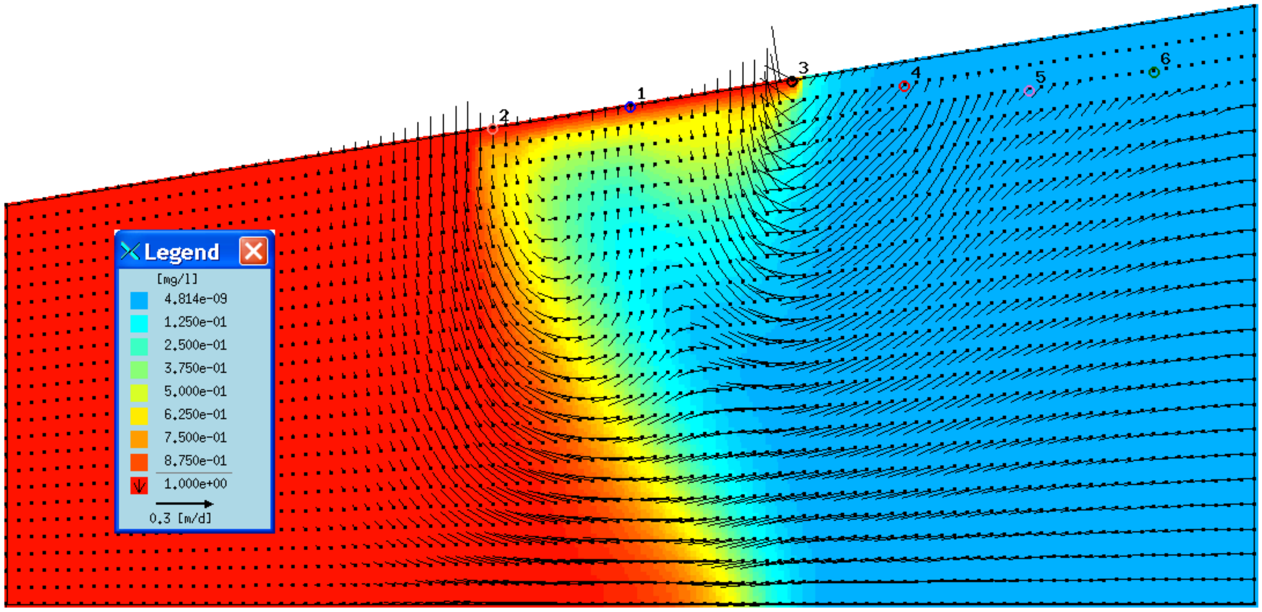


Figure 5.29a: Modelled flow pattern and salinity distribution at high water. (Blue= 100% fresh water, red= 100% salt water).

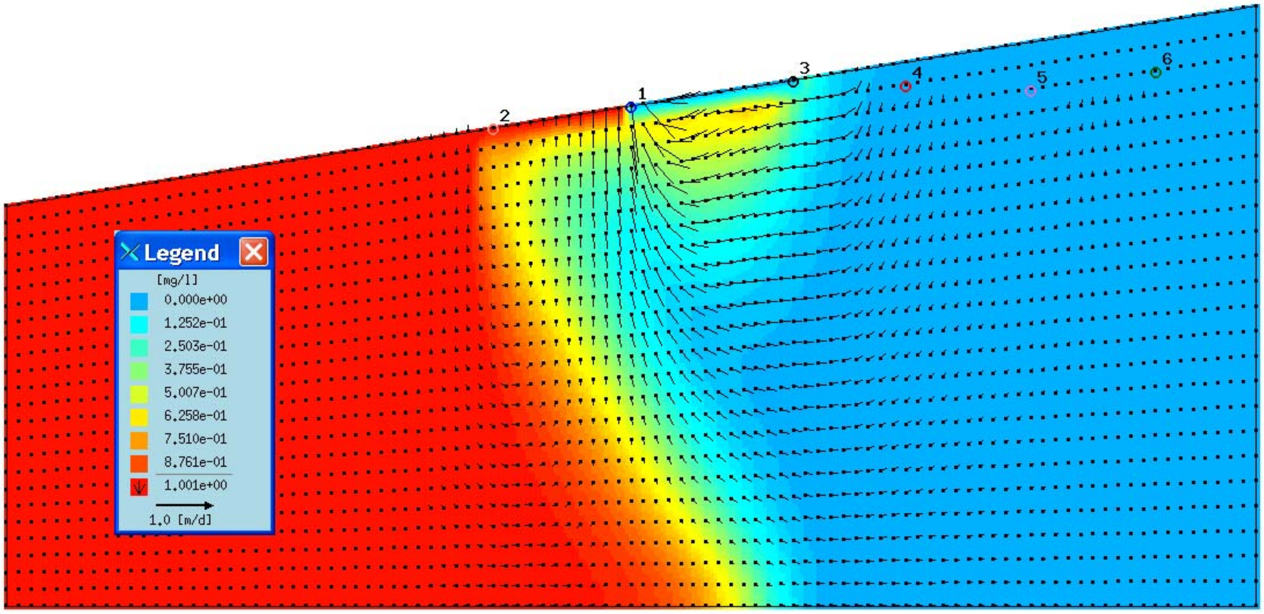


Figure 5.29b: Like fig a, but now at MSL.

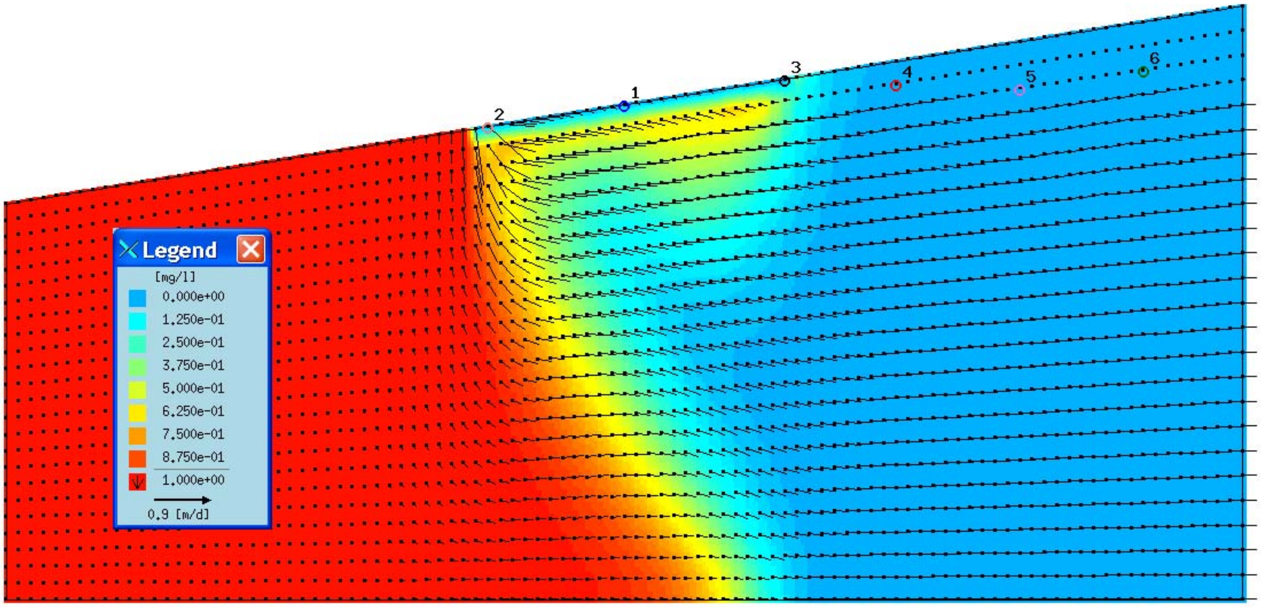


Figure 5.29c: Like fig a, but now at Low tide.

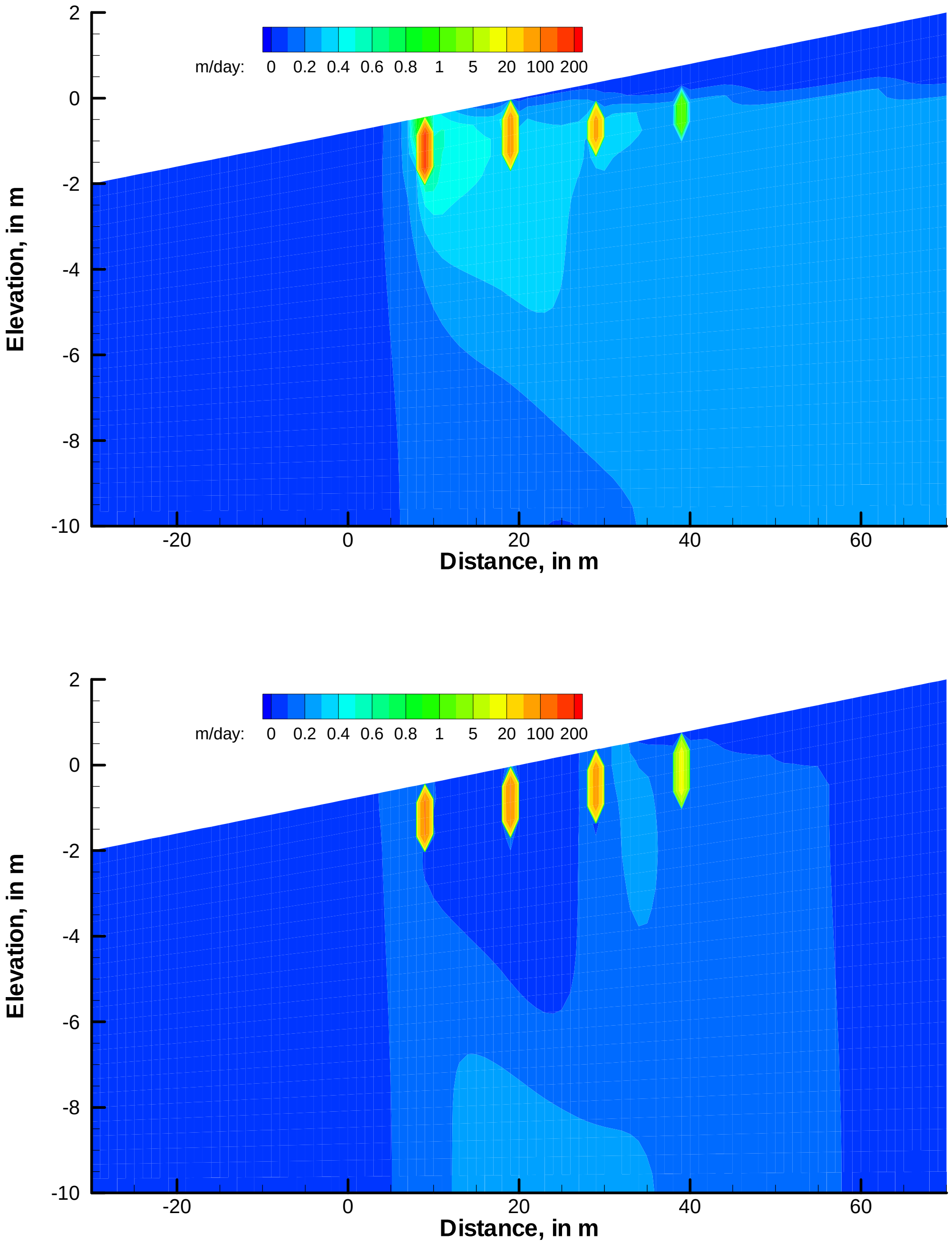


Figure 5.30 Different tubes are active at different times during a tidal cycle. Upper figure: low tide. Lower figure: high tide.

Figure 5.30 shows how the different tubes come into function as the Sea water level changes. Most flow occurs close to the instantaneous water line, where you have the largest pressure gradients. Of particular interest is the modelled drainage effect of the tubes.

At high water, the flow inside the tubes reaches its maximum between around 1 hour before low tide, and the velocity is here maximum 3 mm/sec. at the tube located nearest the Sea, see figure 5.31. In average, the drainage capacity is somewhat lower, about 2mm/sec for the outer tube, falling to less than 1 mm for the inner tube. The value corresponds quite well with the estimates given in table 5.1, but the hydraulic conductivity is certainly an important parameter.

For the 3D- real case we must reduce to less than 40% as explained above, so maximum flow becomes around 1 mm/sec. So the estimated drainage capacity from one array with two active tubes (cf. figure 5.30) will be 0.15 l/minute per tube or 0.3 l/minute for two active tubes. If you look at figure 5.9, this corresponds to a change in hydraulic head inside and outside the tube about 5-6 cm (for that particular grain size).

The numerical model confirms the earlier estimates that the drainage capacity in a homogeneous beach is only a fraction of one per thousand.

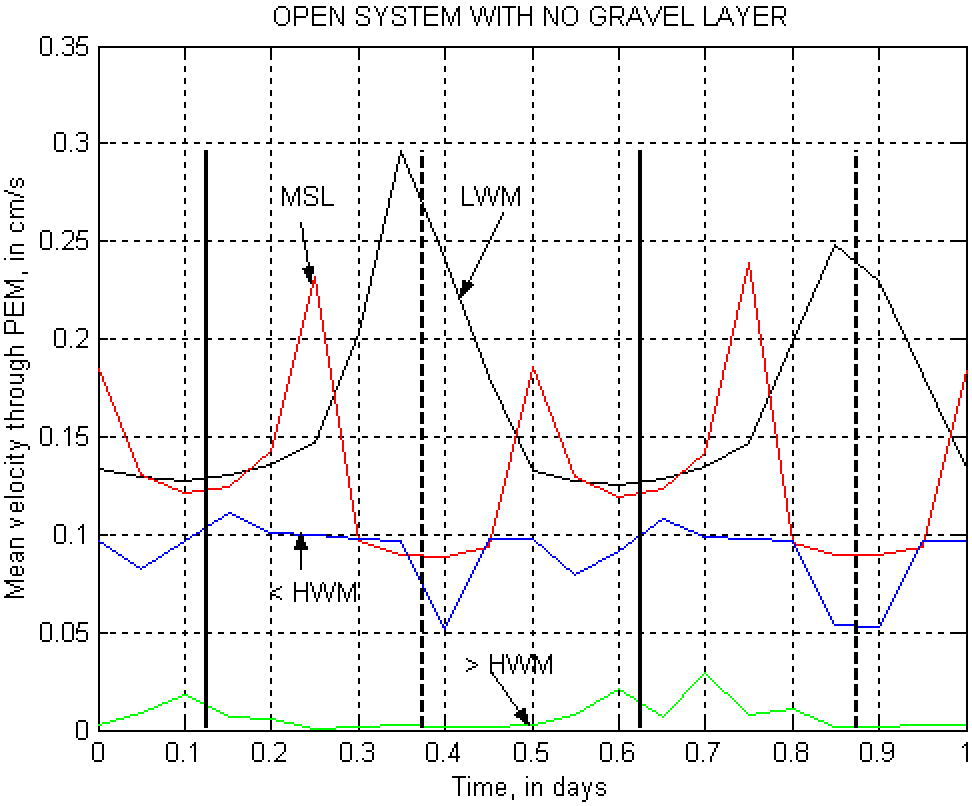


Figure 5.31 Simulated velocities at the mid-point of the four PEM over a tidal cycle. Black line (x=9 m, LWM), red line (x=19 m, MSL), blue line (x=29 m, <HWM), and green line (x=39 m, >HWM). High and low tides are indicated with vertical solid and dashed lines, respectively.

Pressure relief in the outflow zone.

The appendix 3 illustrates the changes in flow pattern with and without PEM. The changes are difficult to observe, but nevertheless there might be some impact on the pressure at the beach surface, where you have outgoing seepage.

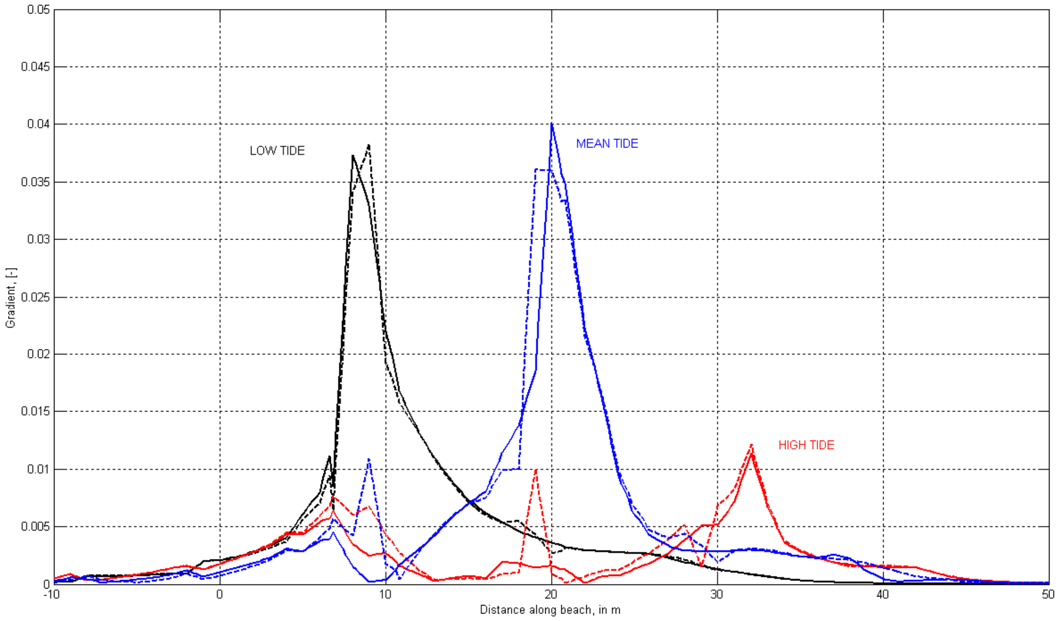


Figure 5.32: Simulated absolute hydraulic gradient along the beach at low, mean, and high tide. Solid and dashed lines are without and with PEM.

The figure shows simulated absolute hydraulic gradient along the beach at low, mean, and high tide. Two sets of simulations are shown; solid and dashed lines are without and with PEM, respectively. Recall that direction is not indicated, thus this figure can only be understood by also referring to the figure 5.29 above. In the cases of low and mean tide, the flow is always out, however at high tide the flow is in and out. Referring to the high tide case, the two peaks at 8 m (LWM) and 33 m (HWM) correspond to the inflow shown in the figure above, and the peak in-between at around 20 m (MSL) is outflow. The gradients are highest in the cases of low and mean tide, around 0.035-0.04. The area of outflow tracks the receding water table very closely. However, notice that in the cases with PEM (dashed lines) the two peaks are off-set by about 1-2 m. This is because the PEM are located at 9 and 19 m, 1 m off the point where the low and mean water table cuts the beach. The PEM therefore mainly redirects the point of maximum outflow during a receding tide. It is also seen that the PEM near the low tide line actually generates a higher gradient (and outflow) than in the case without a PEM. Otherwise, the simulated results are very alike. In the high tide case the two simulations are almost identical except that again the two PEM located away from the high tide line generates a stronger gradient (and outflow).

Finally here it must be mentioned that in the present test, the tubes only have slots in the lower half part of the tubes, while the upper part of the tube is impermeable.

Is the change in hydraulic pressure gradient significant?

If you have a strong outwards directed pressure gradient, the bed will softens and sediment is easier eroded. This is called *fluidization*. To get real fluidization, you need the hydraulic gradient i to be

$$i \geq 0.7(s-1)(1-n)$$

where s=relative density of sand (2.65) and n porosity (0.3-0.4). Therefore the critical value of i is around 0.75.

The tidal induced gradient is only 0.04, which corresponds to only 5% of the critical value 0.75, and can not be recognized in the field to be important for values lower than 0.1. (Foster et al: Field evidence of pressure gradient induced incipient motion: J. Geophys.Res., Oceans Volume: 111 Issue: C5 Article Number: C05004 2006). So the tide and freshwater outflow at this location is not important by itself for sediment mobility along the coast. In combination with wind waves and current it certainly can enhance the sediment mobility slightly during falling tide, while the sediment mobility similarly will decrease slightly during rising tide. The effect is still very moderate at this location, but with a higher tidal range, say 3-4 meters, it can have some impact.

Above, the impact on outgoing flow on sediment mobility from tide /freshwater outflow is discussed. But the importance with respect to the impact from the PEM tubes is not the total pressure gradient, but its relative change as compared to no tubes.

The discussion becomes similarly to the one regarding the improved drainage by the tubes: from each tube you get a small impact: you get a cross shore change over a 2 meter distance, where the redistribution in the flow due to the tube changes the gradient by up to 6-7 % in either negative or positive direction, cf figure 5.32. 3D effects will half this change. So on the conservative side, you get a reduction of around 3% in less than 1% of the beach face area or a reduction equal with a fraction of one per thousand on a pressure

gradient, which already is so small, that it by itself has negligible impact as outlined below.
The impact is so low, that even the change in the tidal range from North to South along the 11 kilometer long test site (which is about 5 cm) is of larger importance than the local impact from the tubes.

Other special features obtained from the model.

You get a lot of interesting things out of the model, all described in appendix 3. One feature is that the presence of the tubes actually for some cases allows the beach to be less well drained with tubes than without. This is because the tubes not only allow the water to escape easier, but also allows the seawater to flow into the beach faster. It is a well known non-linear mechanism, that the average water table level in the beach is higher than MSL in a tidal environment. This is due to the slope of the beach, so the water has to flow longer out into the sea than from the sea into the beach.
Appendix 3 also contains runs with permeable and impermeable layers, which all confirm the simple considerations given earlier in this chapter.

Conclusion:

It has not been possible to detect any significant impact from the tubes on flow or pressure gradient in the beach. In all homogeneous cases, the changes are only a fraction of one per thousand. In special cases an effect can be identified: for instance activation of permeable layers, where you make a shortcut between isolated pockets of permeable layers, and you further have sea connection either through the tubes or via a permeable layer. Or the puncture of a bowl-like inhomogeneous layer. These very special configurations are not likely to occur frequently in a beach.

Chapter 6 Description of the tests.

Because the impact from the tubes is such, that you can not observe accumulation locally around the tubes, the test is more a kind of a “box-study”, where changes in beach and dune levels were measured over longer distances along the beach. We are after an impact which can not be identified around each array, but on the other hand side it is expected to be so distinct, that the tube impact do not spread too much into the reference sections with no tubes. We have no idea what the scale is, but SIC introduced during the test the concept “transition zones”, so that the erosion occurring for instance in the southern part of rør1 was due to this effect. If so the transition zone here should be probably 3-500 meters alongshore.

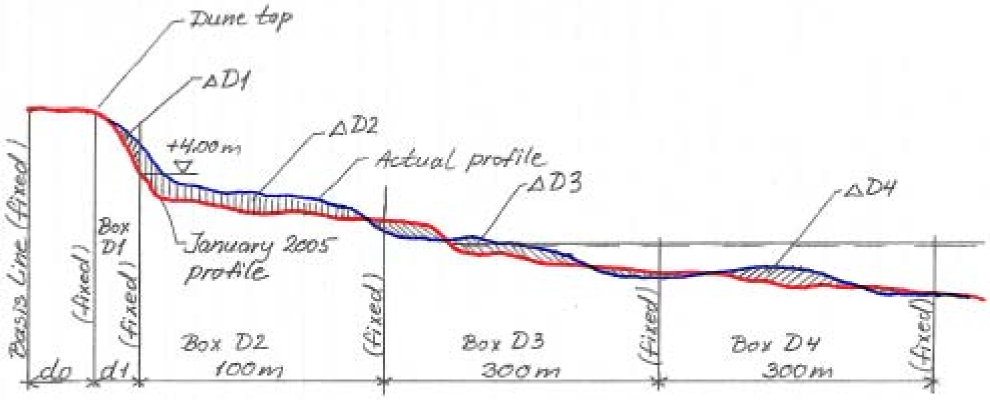
The **“**tests” are in other words mainly to measure the dunes, the beach and the coastal profile along the whole 10900 meter long site, and to interpret the results.

As described in the introduction, chapter 2, this is a difficult task, because you measure in only three years, and the impact from the tubes is not dominating as compared to the signal from natural fluctuations.

6.1 Parameter description of the profile.

After many discussions in the group, it was finally agreed to separate the measured profile in four fixed boxes (Eulerian approach) and study the volume changes in these boxes. The reason for this was to “measure the erosion-deposition where the tubes were”.
Moreover, it was decided to use parameters, which makes it possible to follow the changes in position of the dune foot and the coastline, and study the volume changes in dune and beach (Lagrangian approach, following the actual beach).

For convenience the parameters used for the fixed box study are denoted D-parameters, while the parameters used for the study of changes in the dune foot and coastline positions as well as dune and beach volume are denoted E-parameters. Positions of the four fixed boxes of specific widths and fixed positions are related to the positions of the level +4.00m intersection with the first surveyed profile of January 2005, figure 6.1. The changes in sand volumes in each box $\Delta D1$, $\Delta D2$, $\Delta D3$ and $\Delta D4$, are calculated. Besides this is calculated the mean surface level denoted MBL in the 100m wide box as well as the changes in this level, Δ MBL. All measurements on land were performed with alongshore intervals equal 100 meters.



Volume changes ΔD within each box are calculated positive in case of accretion and negative in case of erosion.

The mean surface level in Box D2 is denoted MBL. The changes in MBL from January 2005 is denoted ΔMBL

Fig 6.1: Definition of D-parameters. The "dune box"D1 measures changes in the dune volume between two fixed lines. The "beach-box" D2 is a measure of the volume from the initial dune foot (+4 m) and 100 meter in the offshore direction(so sometime the outer part of this is in the water, and in the worst case scenario the inner bar can be a part of the "Beach box"). The two offshore-boxes D3 and D4 are each 300 meter wide and also fixed in their position.

Figure 6.2 defines the E-parameters, while figure 6.3 shows a typical measured profile.
Soundings offshore have been performed along the whole test site along lines perpendicular to the coast with an interval of 200 meters.
Carl Bro A/S performs the landward surveying and KDI the depth sounding.

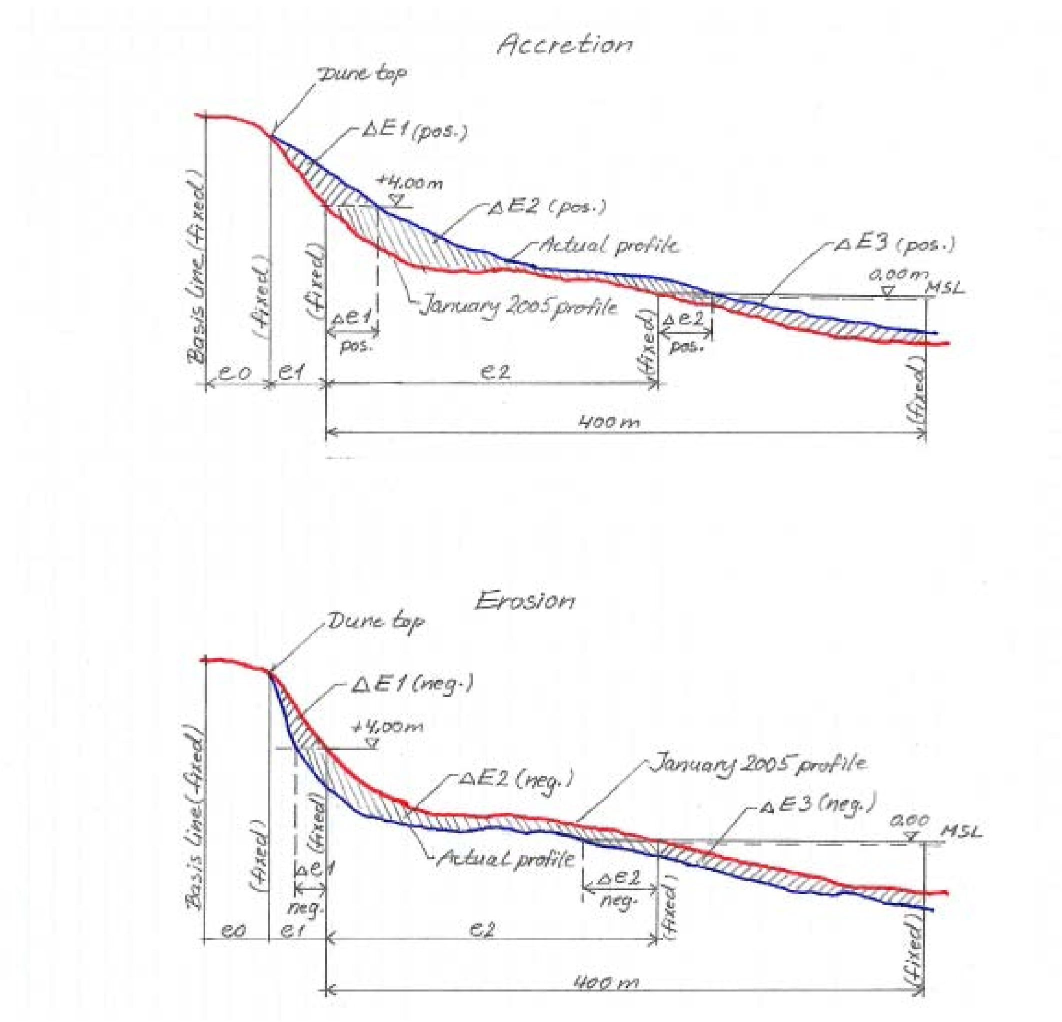


Figure 6.2 Definition of E-parameters. In this report, mainly the width e2 and Δe2 is applied.

The tubes were put in place in the middle of January 2005, and the recordings of the beach were done close to the following dates.

Dato
26-01-2005
27-04-2005
30-06-2005
07-10-2005
06-01-2006
06-07-2006
25-01-2007
07-02-2007
20-08-2007
03-01-2008

Table 6.1 Approximate dates for recording the profiles.

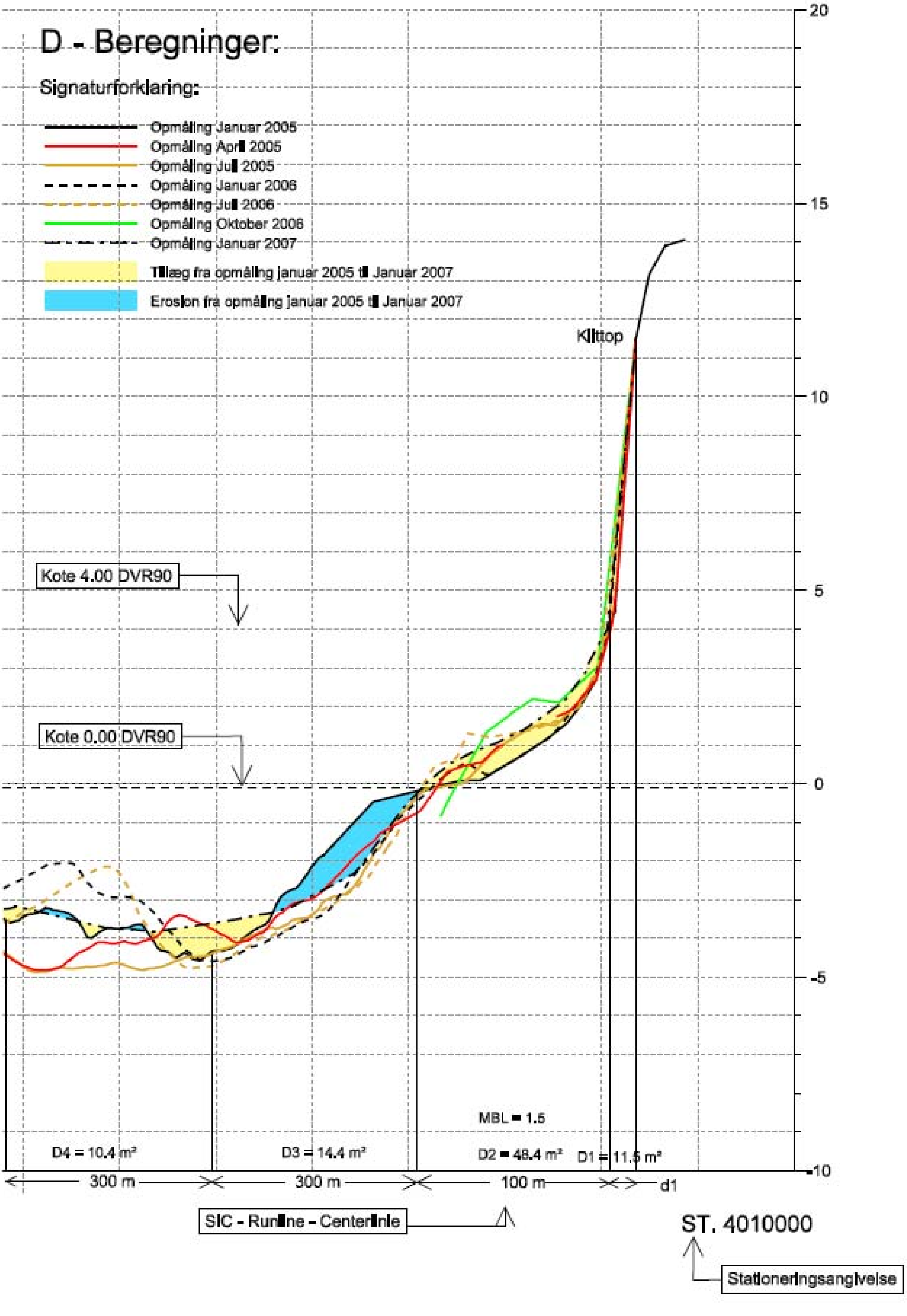


Figure 6.3 Typical example of a measured profile.

Grain size analyses

In order to check the hypothesis of SIC that the drains increase the strength of the groundwater flow and thereby wash out the fine beach material, it was decided to investigate if changes in the composition of the beach material takes place as a result of the installation of the drains. Whether this increase in strength is around the tubes or in the beach face is not clear to the expert, but it should be around the tubes: if it is in the beach face, then you will enhance erosion, and the opposite should be the aim of the system.

Five borings were taken app. three month after the installation of the drains in Rør I between chainage 4015500 – and chainage 401540. Grain size analyses of the samples have been made and compared with samples taken in May 2006.

The relative amount of very fine material with grain size smaller than 0.063 mm was determined from samples taken from each boring in three specific levels. The analysis revealed that in two of the five borings, one being located close to the drains, there was a clear decrease in the relative amount of fine material. In the other three borings, of which one was also close to the drains, there was not a clear picture, but the tendency was an increase in the amount of fine material. On this background no conclusion on the effect of the drains in terms of wash-out of fine materials could be made. Actually much more samples are needed to give any definitive answers.

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 proximity of the drains were performed in the spring of 2006, see appendix 1 written by SIC.

The programme was carried out with additional consultancy of Dr. Peter Engesgaard, Geological Institute of University of Copenhagen. The report of Peter Engesgaard, attached as Appendix 2, concludes that no effect of the drains on the surrounding water pressures could be detected. The observed pressure variations would be expected also without the drains.