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

Second year report of 1 July 2007

By

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DRAFT.

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1. Introduction

In accordance with the agreement of 18 August 2004 between Skagen Innovation Center (SIC) and the Danish Governmental Coastal Authority (KDI) a field test with the purpose of demonstrating the efficiency of the SIC vertical drain method as a mean for coastal protecting was initiated in a meeting 24 August 2004.

The test period is three years after which a final report has to be presented. The report shall contain an evaluation of the drain system with respect to qualitative and quantitative efficiency and environmental impact, as well as a related comparison with conventional coastal protection methods.

Besides the final report yearly reports have to be presented as well as a report half a year after the start of the field test.

For the evaluation the following two experts were retained

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

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

Besides the two experts the project group consists of

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

The present report, authored by the two experts, is the second year report, written as a stand-alone report for which reason it repeats substantial parts of the first year report of 20 November 2006.

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2. Preliminary conclusions

The changing wave and sea level conditions cause large natural fluctuations in the beach planform and volume. Moreover, coastline undulations moving along the coast in the direction of net sand transport might contribute to these fluctuations. The effect of the drains has to be detected from such "background noise" which is not easy during a short period, even if the drains might have a significant effect. For this reason the following conclusions are of preliminary character.

During the first one and a half year period the beach has increased its volume significantly in the two stretches where the SIC-drains have been installed. However, the most significant increase took place in Ref. III. Significant increase took place already in the first half of the one-year period. Out of three stretches without drains there has been significantly volume increase in one stretch, significant volume decrease in a second stretch, and balancing increase and decrease in volume in a third stretch. The storms, which occurred by the end of the second year period, caused erosion within all stretches with and without drains. The average changes in beach and dune volumes over each stretch are given in Table 1.

Table 2.1. Average changes in beach and dune volumes (m^3/m) in the period between July 2006 and January 2007 just after the storms.

Ref. III	Rør II	Ref. II	Rør I	Ref. I
+2	-49	-70	-40	-32

As seen there is not a clear correlation between the volume changes caused by the storms and the status of the stretches with respect to drains or not. It should also be noted that averaging over each stretch gives a too simplified picture of the performances as for example erosion of more than app. $90m^3/m$ took place in stations within all stretches. It is however clear that where in beforehand the beach is wider and higher there will be more resistance left after storm erosion.

A major effect in beach and dune development is caused by sand transport by the wind. This transport is both in cross shore and long shore directions which means that the sand, if not deposited on the beach and at the dune front, will be transported to the top and rear side of the dunes or along the beach not respecting the borders between the dedicated stretches. Due to lack of measurements of the dune top and rear slopes it is not possible to quantify the effect of wind-transport of sand not deposited on the beach and the dune front. We have to assume that the effect is almost equal for all stretches.

Although there seems to be some positive correlation between areas with beach volume increase and areas with drains, indicating a positive effect of the drains, it is too early to draw final conclusions. This is because a two-year observation period is still short seen in relation to the timescale of natural beach fluctuations. Moreover, theoretically based considerations and specific detailed field investigations have not yet explained a significant effect of the vertical drains.

July 1th 2007

Jørgen Fredsøe

Hans F. Burcharth

3. Dansk resumé.

Denne rapport beskriver baggrunden for og resultaterne af forsøgene med PEM-rørene (Pressure-Equalization-Modules) ved Vestkysten ved Skodbjerge syd for Hvide Sande.

Først beskrives hvorfor vi har valgt lokaliteten ved Skodbjerge, dernæst forklares lidt om strandens bevægelser, så forklares lidt om de foreløbige resultater, og endelig beskrives hvorfor vi ikke helt forstår at det skulle virke.

3.1 Lokaliteten.

SIC har ønsket at udføreet storskala forsøg på den jyske vestkyst, for at vurdere rørenes funktion. Nogle steder er vestkysten sikret af høfder og lignende, andre steder er der mange turister. KDI (Kystdirektoratet) fandt i planlægningsfasen frem til nogle områder, f.eks. Husby og Skodbjerge. Desuden er Skallingen en mulighed. Der er problemer med alle områder, den første fordi der her er lerlag i stranden, det andet fordi der her foretages sandfodring, og Skallingen fordi der kun er 6-7 km uforstyrret område, hvor forsøget kan udføres. Til sidst valgtes en 11 km lang strækning ved Skodbjerge.

Dette område er som lige nævnt ikke uproblematisk: Ca. 10 km nord for forsøgsområdets nordlige ende ligger Hvide Sande, hvor der er forbindelse mellem Ringkøbing Fjord og Vesterhavet. Her blokerer molerne delvist for sandtransporten langs kysten. I dette område er sandtransporten sydgående, og har i et gennemsnitsår en størrelse på godt 2 millioner kubikmeter per år.

Hvis man blokerer for sandtransporten får man erosion syd herfor. Derfor er der lagt kystparallelle bølgebrydere langs stranden de første knap 5 km syd for Hvide Sande. Nedstrøms dette område kan man forvente erosion, da bølgerne kan gnave af kysten, der samtidigt ikke får tilført sand nordfra. Derfor sandfodrer KDI kysten syd for havnen ved at dumpe sand, dels ude på en revle godt 500 m fra kysten, dels på selve stranden for at kompensere for den manglende tilførsel af sand nordfra.

Uden denne sandfodring ville der på forsøgsstrækningen – over mange år – ske tilbagerykning - erosion - i den nordlige del og fremrykning - aflejring - i den sydlige (se nedenstående figur).

Det har aldrig været muligt at få en fornuftig forklaring på hvorfor systemet skulle kunne virke, se også afsnit 4. Vi har derfor i forsøget fokuseret på følgende 2 punkter:

- prøvet lokalt at se om rørene har nogen virkning, og
- prøvet i større skala at se på om rørene samler sand.

Før disse 2 punkter beskrives vil vi kort beskrive lidt om problematikken ved forsøget.

3.2 Erosion og aflejring.

Langs den jyske kyst 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 samt vandspejls forhold, samt tilførsel 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 kystlinien, og det er vigtigt at betragte det samlede system. Under en stor storm eroderes en strand generelt. Da storme er hyppigst om vinteren opnår man det såkaldte 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 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.

Ovenstående beskrivelse er meget simplificeret. Specielt 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 betyder meget for strandens udseende.

3.3 Rørenes virkning i stor skala.

På den pågældende lokalitet har vi altså 2 problemer: en storm lige før forsøget startede, og sandfodring nord for forsøgs-området. Siden forsøget begyndte er der sket en opbygning af stranden, men det samme er også sket mange andre steder langs den jyske vestkyst i samme periode.

Det er derfor vor opgave at kunne påvise, at rørene er (en del af) årsagen til den konstaterede opbygning. SIC ønskede en lang sammenhængende forsøgsstrækning for at vurdere rørenes effekt (på trods af at SIC implementerer systemet mange steder på meget kortere strækninger).
På forsøgsstrækningen er kysten – over mange år – i tilbagerykning i den nordlige del og i fremrykning i den sydlige.

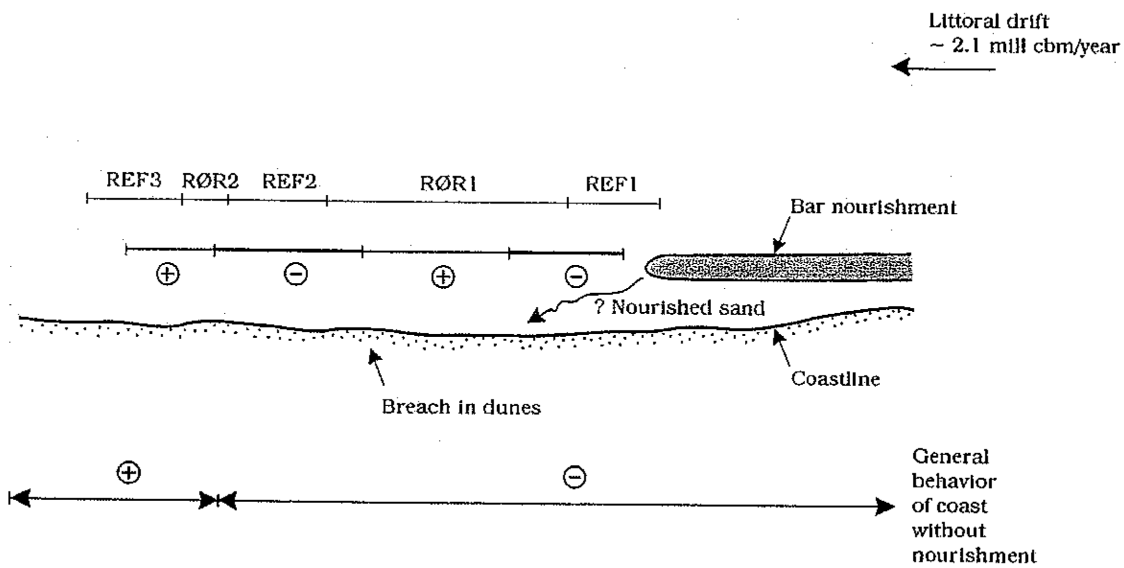
Rørene er anbragt på 2 strækninger, hhv 4.7 km (Rør 1, mod nord) og 0.9 km (Rør 2, mod syd) afbrudt af et område på 1.8 km (Ref 2) uden rør.. Nord for rørene er der er reference område 1, og syd for reference område 2, begge områder uden rør. Ideen var at vi gerne skulle observere større aflejring i rør områderne end i reference områderne.

Efter 2 år er hovedresultaterne som beskrevet i tabellen, der angiver de gennemsnitlige niveau ændringer dels af en 100 m bred strimmel målt fra klitfod i januar 2005, dels af et udenfor liggende 600 m bredt bælte. Det kan nævnes at stranden stedvis er både bredere og smallere end 100 meter.

	Reference 1	Rør 1	Reference 2	Rør 2	Reference 3
"Strand":100 m bredt bælte fra klitfod	-0.48	0.11	-1.02	0.47	1.04
"Hav" (600 m bælte udenfor de 100 m "strand")	0.41	0.05	0.57	0.43	0.35

Ændringer i niveau (m) af strand og havbund.

Går man mere i detaljer, giver observationerne efter to år et noget rodet billede af situationen. Der er mest aflejring mod syd, der i forvejen er et aflejringsområde. Her sker aflejringen både ud for rørene og syd herfor.
I det nordlige rørområde sker der både aflejring og erosion, sådan lidt varieret, og ikke fuldt korreleret med rørenes placering , se også figuren (nourishment=sandfodring).



I vort reference-område 2 uden rør i midten er der tydeligvis erosion, hvilket kunne tyde på at rørene kan have en positiv virkning. Men stranden var her allerede smal på en kortere strækning før forsøget begyndte, og siden hen har havet her brudt gennem klitten. Et sådant brud øger vindens mulighed for at transportere sand fra stranden op i baglandet, så den smalle strand fastholdes. Det er derfor svært at relatere opbygning/erosion udelukkende til rørene.

3.4 Lokal virkning af rørene

Effekten af rørene er ikke tydelig helt lokalt omkring rørene. Der er 100 meter mellem hver rørrække, og det kunne forventes - hvis rørene har en positiv effekt - at der foran hver rørrække i første omgang blev dannet en lokal sandpude. Noget sådant er ikke iagttaget. SIC hævder at en sådan bule har en høfdevirkning, hvilket vi har meget svært ved at forstå skulle være tilfældet. Når der end ikke kan konstatere lokal aflejring omkring hver rørrække er det svært at indse at der kan opstå en "høfdeeffekt". SIC hævder at rørene har en skylleeffekt på det omgivende sand, således at det fine materiale bliver bortskyllet, og man får det såkaldte grovere "vaskede sand", der har større stabilitet. Årsrapporten indeholder et appendiks, hvori det vurderes, at rørene nok lokalt øger hastigheden af grundvandsbevægelsen, men det er så lidt, at det kan negligeres, nemlig mindre end en tiende-del promille. Denne vurdering af hastighederne er der vist enighed om i gruppen, vi har i det mindste gang på gang bedt om at få målt hastigheden af vandet indeni røret, men der har været generel enighed om at disse hastigheder er så små, at de ikke kan måles. Når hastighederne inde i røret er små, er de meget-meget mindre udenfor, da hastighederne aftager med afstanden fra de enkelte rør. Oveni dette kommer så at rørets areal af det samlede strandareal er utrolig lille (et rør pr. parcelhushave).

Grunden til at vi ikke kan forstå, at rørene skulle have en drænende virkning er den simple, at rørene ikke er, som dræn normalt konstrueres, nemlig forbundet med et afløb, så vandet kan komme videre. For eksempel konstrueres et omfangsdræn omkring et hus konstrueres således, at vandet føres hen til en brønd (fagsprog: et område med lavt tryk). Et markdræn ledes normalt hen til en grøft, hvorfra vandet strømmer videre (fagsprog: et område med lavt tryk). Men PEM-røret ender blot dybt nede i sandet. Vandet der ledes gennem rørene skal jo også videre ud til havet, og der er der intet naturligt afløb (fagsprog: et område med lavt tryk) for enden af røret.

Man kunne forestille sig lag dybere nede med grovere materiale, hvorigennem vandet ville løbe lettere, men det ville vandet så også gøre uden rør. Her må man jo også forstå, at vand ikke har så svært igen ved at løbe gennem sand, hvad man sagtens kan forvisse sig om ved at tømme en spand vand på stranden, vandet forsvinder med det samme. I øvrigt ville mellemrummene i et lag bestående af småsten hurtig fyldes op med sand i en strand, og så ville det ikke være lettere for vandet at strømme her end alle andre steder.

4. Planning of the tests

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

4.1 Selection of test site

According to agreement between SIC and the Ministry of Transport a stretch of approximately 10 km on the Danish North Sea Coast should be selected for the tests.
Conditions with respect to hydrographic and geomorphological conditions should be as homogenous as possible along the stretch. Moreover, influence of man-made interventions should be as small as possible.
Two potential sites were discussed: A 15 km long stretch at Skodbjerge just south of the part of Hvide Sande, and a 7 km long stretch at Skallingen north of the town of Esbjerg.
The net-sediment transport is southwards at both site, but much larger at the Skodbjerge site. The Hvide Sande jetties north of the Skodbjerge site create leeside erosion for which reason some beach parallel detached rock structures are placed just south of the jetties. This coastal protection has been supplemented with beach nourishment and nourishment at the offshore bar approximately 600 m from the shore, cf. Fig. 4.1. Erosion decrease to the south so that just south of the 15 km stretch the beach is stable. Further south accretion takes place. Beach nourishment will not take place in the three years test period, but nourishment at the offshore bar will continue.

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

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

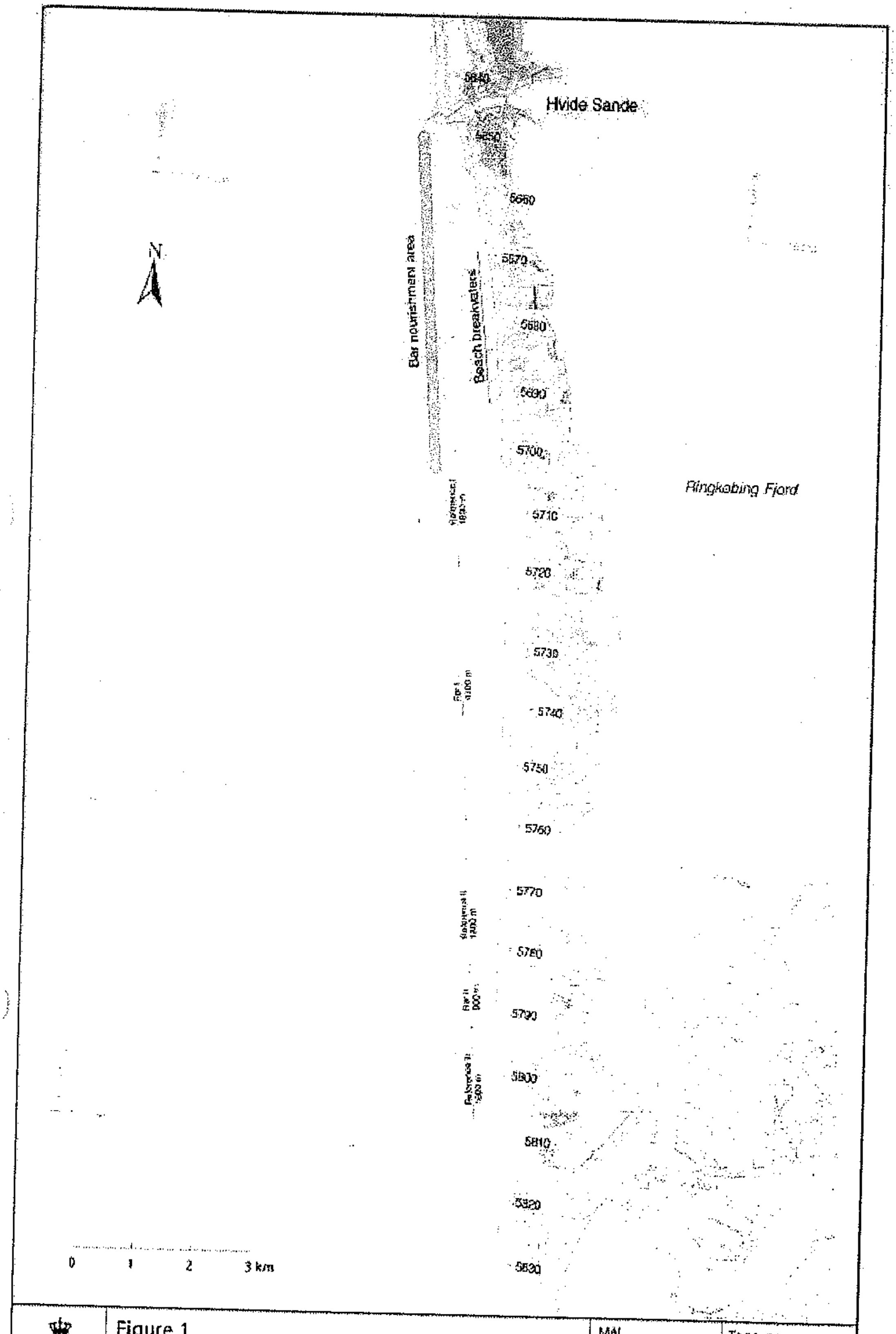


Figure 4.1 Bar nourishment

4.2 Planning of the test

The basis for the evaluation of the tests is a comparison of the morphological changes in stretches with and without drain pipes as well as more detailed investigations and calculations related to the function of the drains.

The total length of the Skodbjerge test site was limited to approximately 11 km in order not to come too close to the beach breakwaters to the North and the accreting coast to the South.
KDI and JF preferred a split of the site in a number of relatively short stretches (say 2 km) with alternating drains and no drains. SIC could not accept this as – based on experience – they wanted longer stretches, basically a 6 km stretch with drains and a 4 km stretch without drains. However, due to the gradient in erosion along the test site this was not acceptable and HFB proposed as a minimum stretches with no pipes on both sites of the drained stretch.
A compromise as shown in Fig. 4.2 was found in which two stretches of 4.7 km (Rør I, chainage 4019200 - 4014500) and 0.9 km (Rør II, chainage 4012700 - 4011800) respectively were drained, and three stretches of 1.8 km (Reference I, chainage 4021000 – 4019200), 1.8 km (Reference II, chainage 4014500 – 4012700) and 1.8 km (Reference III, chainage 4011800 – 401000) respectively were left undrained.

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

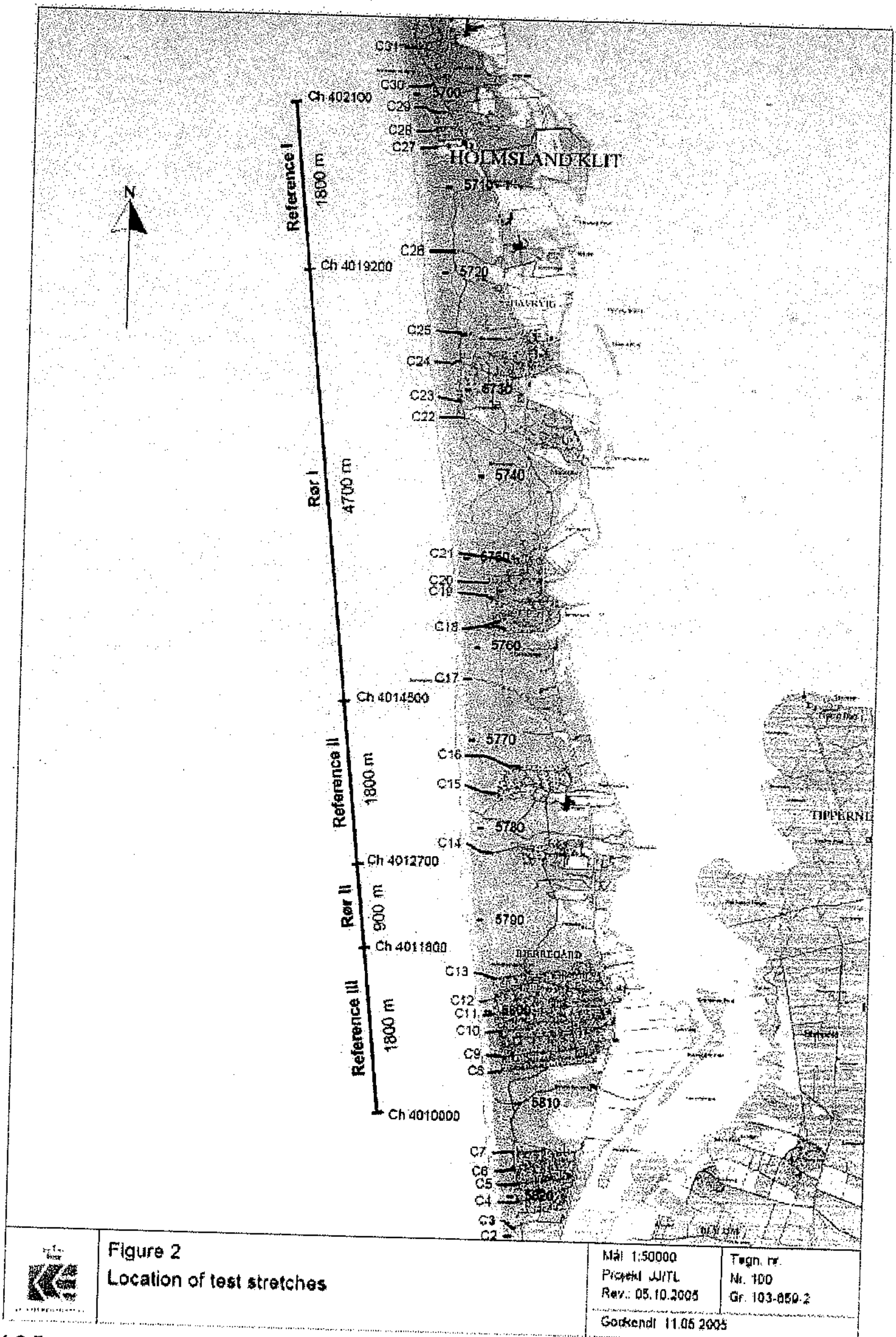


Figure 4.2 Location of the test stretches.

4.3 Monitoring of the test site

4.3.1 Surveying

Profiling per 100 m of the beach including the dune front four times per year was decided as well as soundings per 200 m of the seabed within 600 m from the shoreline. The first profiling took place in January 2005 just after placement of the drains. Since then four surveys have been performed in April, July and October 2005, and January, April, July and October 2006, and January 2007. Carl Bro A/S performs the landward surveying and KDI the depth sounding. Moreover, KDI has performed depth soundings along the North Sea west coast three times every year in lines spaced 1 kilometre and covering the nearshore zone from the beach to app. 8 metre water depth. Five of these lines cover the stretch just south of the Hvide Sande inlet and thereby also the stretch where bar nourishment takes place.

4.3.2 Monitoring of ground water levels across the barrier spit

According to SIC the function of the drain relates to changes in the ground water flow caused by pressure equalisation in the surroundings of the drains. For this reason a comparison between pressure fields near the drains and far from the drains is of importance. The method of instrumentation is under discussion.

As it is generally accepted that ground water outflow in the beachface affects the sedimentation, it was decided in 2005 to monitor in one line the ground water table across the narrow land spit between Ringköbing Fjord and the test beach. Application for permission 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.

4.3.3 Grain size analyses

In order to check the hypothesis of SIC that the drains increase the groundwater outflow through the beachface and thereby wash out the fine beach material, it was decided to investigate if changes in the composition of the beach material take place as a result of the installation of the drains. Five borings were taken app. three month after the installation of the drains in Rør I between chainage 4015500 – and chainage 401540. (SIC has raised the question if this was too late compared to the rapid development in accreation observed after placement of the drains).

Grain size analyses of the samples have been made and compared with samples taken in May 2006. The relative amount of very fine material with grain size smaller than 0.063 mm were 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.

4.3.4 Satellite images, aerial photographs, and airborne laser photogrametry

Nine sets of satellite images covering the period 9.10.2004 – 11.9.2006 have been obtained. The varying quality of the images makes an analysis difficult. Airborne laser photogrametry was tried but without success. Aerial photographs have not been of a frequency and quality which allow more systematic analyses.

4.3.5 Pressure measurements in the beach

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

The programme was carried out with additional consultancy of Dr. Peter Engesgaard, Geological Institute of University of Copenhagen. The report of Peter Engesgaard, attached as Appendix 3, concludes that the no effect of the drains on the surrounding water pressures could be detected on the observed pressure variations would be expected also without the drains.

5. Characteristics of the test site

5.1 Geomorphologic conditions

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

As to the coastal profile along the test site, the distance from the coastline at level 0.0 m (equal to mean water level) to the 6 m depth contour is approximately 650 m over the full length of the test site, i.e. an average slope of app. 1:100. This slope has remained almost constant during the last 20 years according to the profiling by KDI. The coastline has in the same period shown large fluctuations with changes in position ranging from 50 m to 100 m.
Grain size analyses of the sand in the foreshore and in the beach top layers shows medium to very coarse sand with grain diameter in the range 0.3-2.5 mm. Deeper borings show fine sand down to approximately 10-12 m below the surface. Underneath is very fine sand or silt, and in some places clay.
Several shore parallel bars, typically three, are formed along the coast. The net sediment transport in front of the test site is southwards amounting to approximately 2.1 million m^3 per year in average (ref. KDI). Most of the longshore transport takes place in the bar zones.

5.2 Hydrographic conditions

Water levels

At the coast the difference between mean high water and mean low water is 0.7-0.8 m. Storm surge caused by strong westerly gales and low pressures can give water levels of up to approximately 3.1 m above mean water level. Low water levels down to -2.0 m can occur during easterly winds.
In the Ringköbing Fjord lagoon the water level varies between -0.5 m and +0.5 m, dependent on the operation of the sluices and on the wind set-up.

A very severe storm with westerly winds of more than 26 m/s occurred 8-9 January 2005, shortly before the first survey took place in January 2005. Water levels up to 3.03 m above M.S.L. were recorded at the head of the jetties at Port of Hvide Sande. Wave set-up might have caused an even higher maximum water level at the beach face of the test site. No severe westerly storms occurred in the first year period. The maximum water level recorded in this period was +1.44 m on the 26.10.2005 in a situation with only moderate wind. In 2006 occurred only one stormy situation on the 27.10 with maximum water level +1.54 m and westerly winds of app. 20 m/s. However, in January 2007 occurred three storm situations, 1.1.07 max. water level +1.75m with winds just over

21 m/s, 11-12.1.07 max. water level +2.14m with winds over 21 m/s, and 14.1.07 max. water level +1.78 m with winds over 21 m/s.

The January 2007 survey was performed after this row of January storms.

Waves

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

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

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

Because of the protecting effect of the bars against beach erosion it is important to identify positions and holes in the bars, especially related to the inner bar. In case of holes much larger waves will reach the beach. It is therefore important to see if there is correlation between the bar topography and the beach erosion and beach accretion. It is however very difficult to get, within reasonable costs, information about the bar topography. Methods of obtaining this information are investigated. Fig. 5.1 and 2 show the one-year 2005 and 2006 statistics of significant wave height recorded by a directional waverider buoy in 15.5 m water depth offshore Nymindegab.

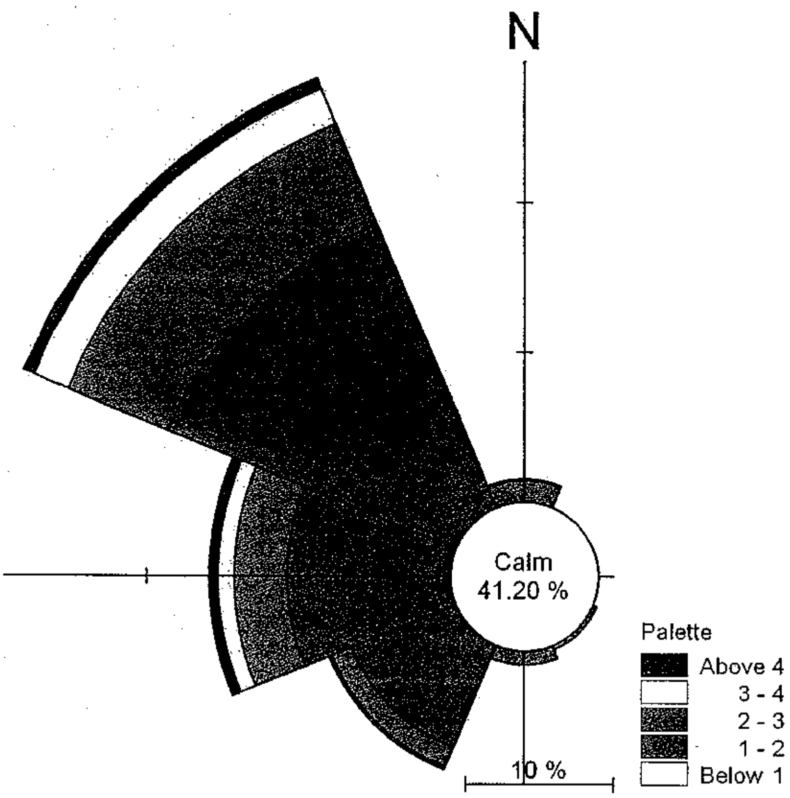


Figure 5.1 Wave rose year 2005

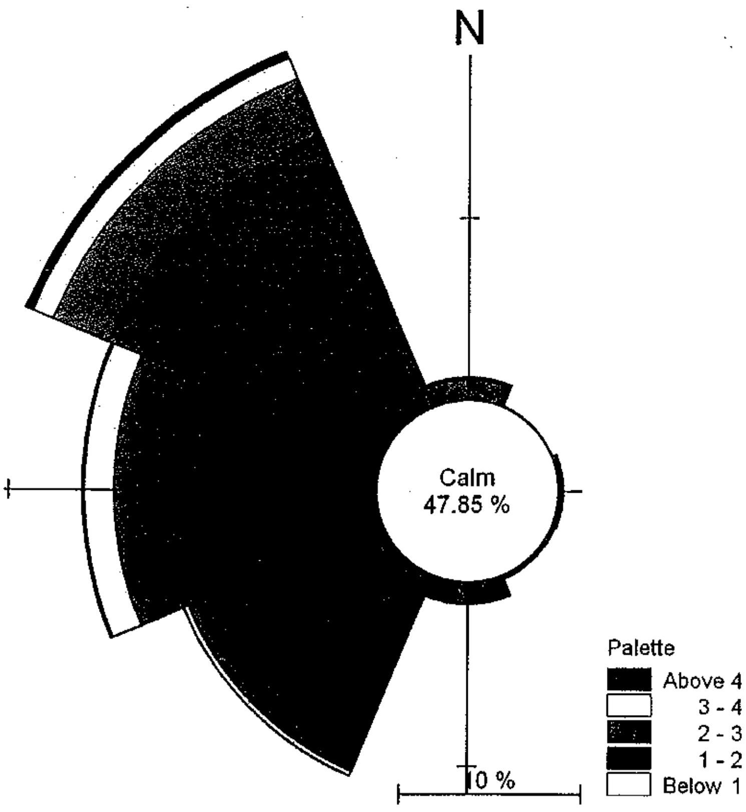


Figure 5.2 Wave rose year 2006

It is seen from Fig. 5.1 and 5.2 that the angle between the coastline and the dominating incoming waves is approximately 45°, thus causing a net-sediment drift in southern direction.

5.3 Former coastal changes and man-made interventions

The natural erosion (retreat of the coastline) is estimated by KDI to vary gradually from approximately 3.5 m/year just south of the Hvide Sande jetties to approximately 1.5 m/year at the southern end of the test site, calculated as averages over the years 1977-96.
The actual erosion is different due to man-made interventions. Actually the coastline has, apart from fluctuation, in average been stable over the last 5-10 years as documented by the KDI profiling of lines 5700-5810 (chainage 4010000-4021000). Table 5.1 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).

Table 5.1. Man-made interventions, 1977-2006

Volumes (m³)

	Årgab					Havrvig			Skodbjerge	
	dumping at dune foot	beach nourishment	beach scraping	nourishment foreshore	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					
Total	2.246.230	4.556.147	138.855	307.224	1.308.197	1.346.563	385.855	200.255	352.124	614.242

6. The functioning of the tubes

6.1 The near-tube flow.

Introduction

In this chapter we try to study the functioning of the tubes.

PEM stands for Pressure Equalization Modules, so as we understand it there must exist a pressure difference in the beach which can be equalized by the tubes. It is not easy to localize this point. In the following we restrict ourselves to consider where the tubes may improve the **drainage capacity** of the beach, since no pressure difference can be build up, because sand is able to breath .

It has not been possible for the experts to explain a significant drainage effect of the tubes.

In general a drain works as follows: The flow in the soil will always flow from a higher to a lower pressure. Such 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 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 we can not see why the system should have any kind of drainage effect.

The flow in the beach is usually quite complicated, and some simple cases will be outlined below and in the two Appendices 2 and 3 at the end of this report.

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 change 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 6.1a-c shows a number of sequences of the ground water level in the beach:
In figure 6.1a and 6.1b, 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.

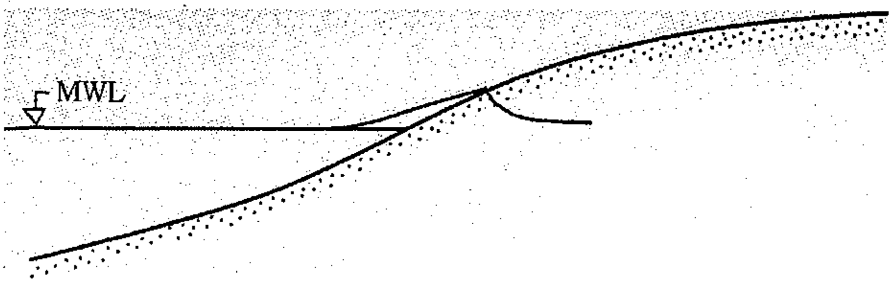


Figure 6.1a: Ground Water Level (GWL) during run-up of wind generated waves.

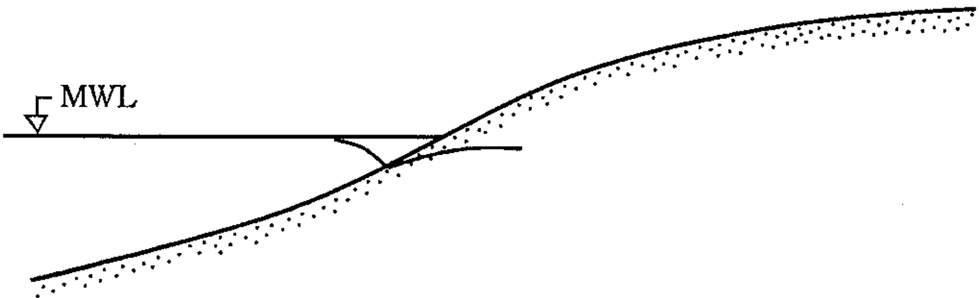


Figure 6.1b: Ground Water Level (GWL) during draw-down of wind generated waves.

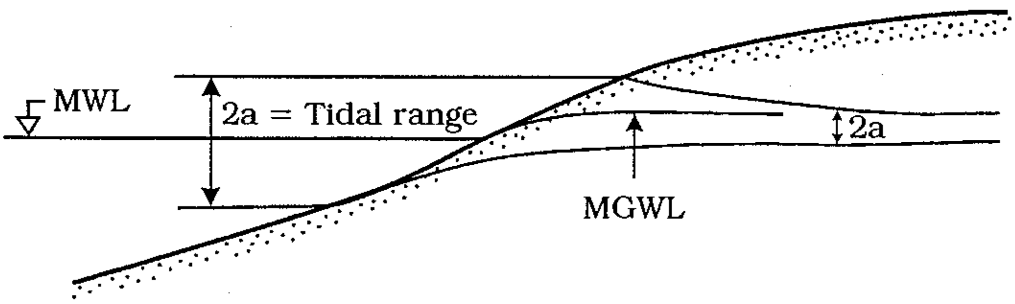


Figure 6.1c: Ground Water Level (GWL) due to long waves (tide)and storm surge. The dampening in the beach (the height of the tidal range 2a in the beach) is much weaker than in the case of wind generated waves.

In figure 6.1c 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 6.2a.

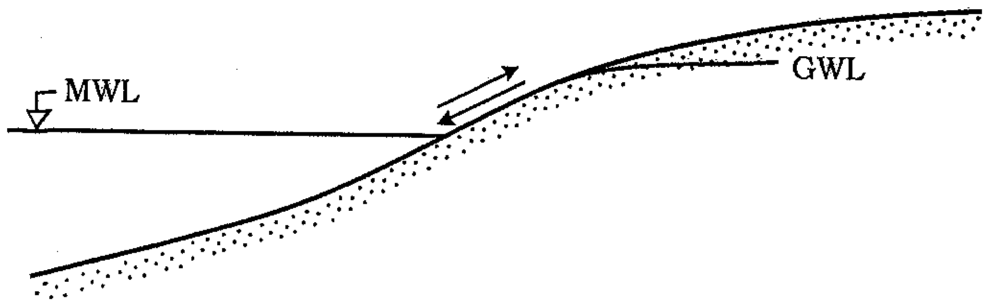


Figure 6.2a: The swash zone flow back and forth is more or less the same if the beach is saturated.

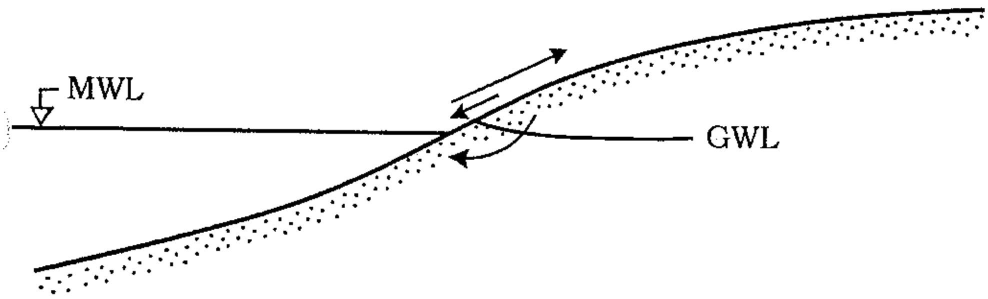


Figure 6.2b: The flow is stronger in the uprush-phase than in the downrush-phase if the beach is drained, because some of the uprush-water can filtrate into the beach..

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 6.2b. 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. Below we quote Peter Nielsen, Coastal Engineering 2002:

It is also reasonable to assume that the observed higher transporting efficiency of the uprush is due, in some part, to the presence of pre-suspended sediment from the bore collapse (Masselink and Hughes, 1998; Puleo et al., 2000; Butt et al., 2001). The importance of the pre-suspended is at present difficult to judge. It is very prominent when the process is viewed from above. However, it must also be kept in mind that sheet flow observations (e.g., Horikawa et al., 1982; Ribberink et al., 2000) show that the main contributions to the sediment transport come from a few millimetres around the undisturbed bed level where the concentrations are several hundred grams per litre. Very little is known about the dynamics of this layer in swash zones.

While pre-suspension may enhance the uprush transport, this may be partly balanced by the infiltration, which usually occurs during the uprush (Butt et al., 2001). However, the horizontal-bed-experiments of Nielsen et al. (2001) indicate that the infiltration effect is likely to be very weak. Their measurements showed a barely measurable effect although they used very strong infiltration, corresponding to head gradients of more than 2. Such strong head gradients are unlikely to occur in natural swash zones (cf. Baldock et al., 2001; Butt et al., 2001).

It is also not clear to what extent fluidisation plays a role in the swash zone sediment transport process. Fluidisation may be caused either by the horizontal pressure-head gradients near the uprush front, which seem quite likely to some times exceed the critical value of 0.6 suggested by Madsen (1974). It might also be caused by the mysterious upward pressure gradients which have been measured by Baldock et al. (2001), but not by Butt et al. (2001).

This reference suggests that the deposition in the swash zone is mainly due to presence of pre-suspended sediment, and not due to infiltration.

Other drain systems.

The idea of drainage has for instance been followed in the so-called Beach Management System (BMS), in which a tube is placed horizontally down in the beach as shown in figure 6.3.
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. 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. Such a 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.

Beach management system

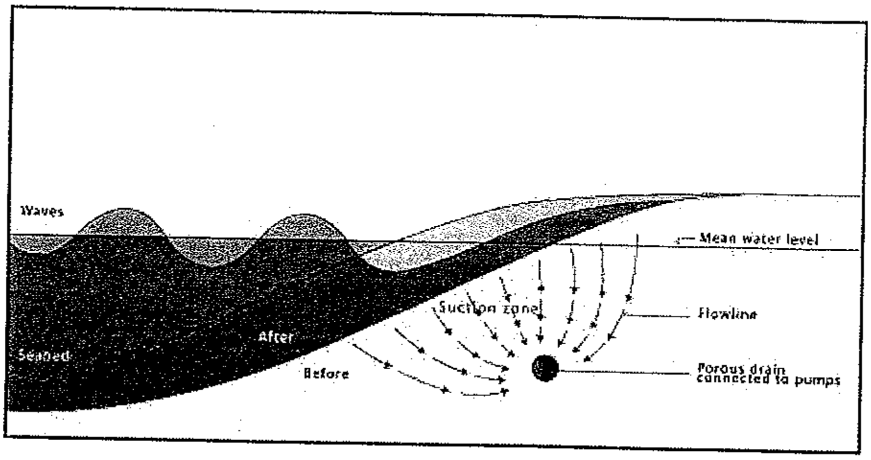


Figure 6.3. The Danish Beach Management System drains the beach by pumping through nearly horizontal tubes located parallel to the shore.

Another drain approach is Japanese, and shown in figure 6.4. 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.

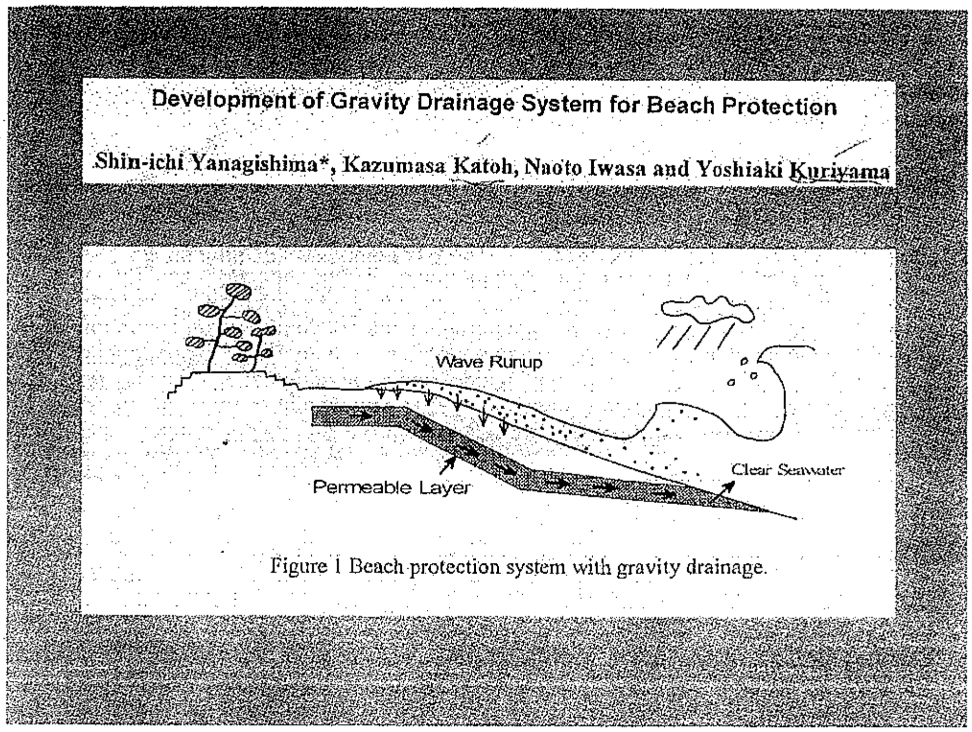


Figure 6.4. Japanese system to drain beaches: here the tubes are replaced by a highly permeable layer, which is emptied by gravity. Please note the sea-connection of the permeable layer.

In the gravity system shown in figure 6.4 accumulation of sand has also been observed, the magnitude being slightly smaller than that obtained by the BMS system.

The PEM-system

The flow in the PEM-system is as follows: A row of vertical perforated tubes is drilled down in the beach sand.
Figure 6.5 shows a single tube used in the present test, and figure 6.6 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 6.5 it might be noted that slots only are present only in the lower half of the tube. 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.

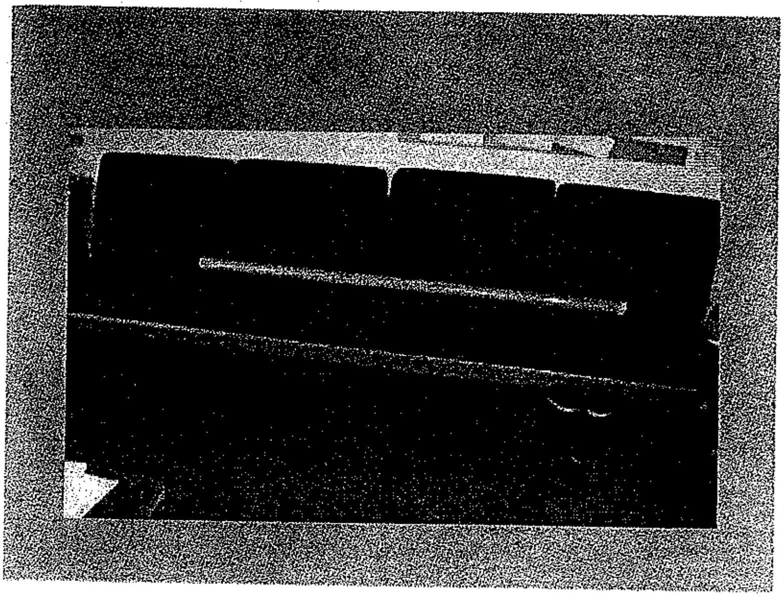


Figure 6.5: Photo of tube in full length. The tube is without slots in the upper half, but it is ventilated at top, so air can go through.

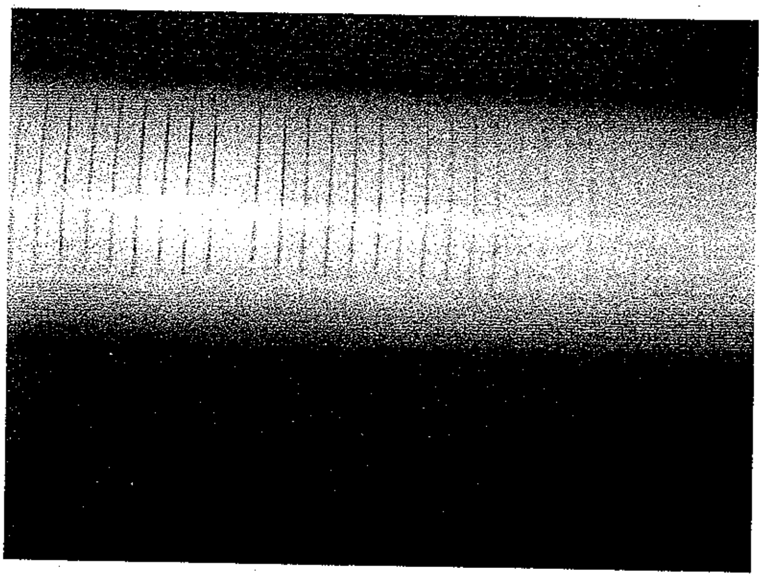


Figure 6.6 Blow up of the tube: Slots of 0.2 mm width are cut in the lower half of the tubes, so water can flow in or out.

The distance between each row of the tubes is 10 meter, and the distance in between the rows is 100 meters.

6.2. The homogeneous beach.

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 decrease 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 we agree (the experts and SIC) that the PEM-system does not have any impact, The oscillations caused by the tide and storm surge for which much more water will infiltrate the beach because of the slow changes in water level, cf figure 6.1 is therefore considered in the following.

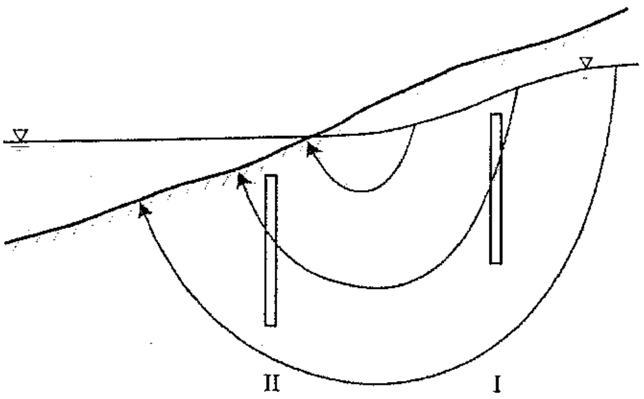


Figure 6.7: The flow introduced in the beach caused by tidal motion in the sea.

The analysis given in appendix 2 consider the tidal situation, where a vertical pressure gradient leads to a ground water motion very different from standing waves in front of a vertical wall, see figure 6.7. This will cause a negative vertical pressure gradient at tube I shown in figure 6.7, and a positive vertical pressure gradient at tube II. It has been measured (see appendix 3) 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 6.8 a and b.

The reason why the experts don't understand that the PEM-system should work is that there are no connection of the tubes to a low-pressure region at the end of the tubes,

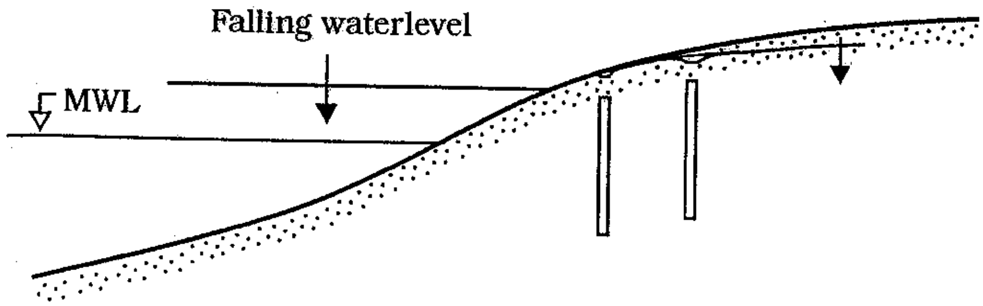


Fig 6.8a: During falling waterlevel (ebb flow or after a storm), the tubes will improve the drainage, the impact is however estimated to be insignificant, actually less than one per thousand.

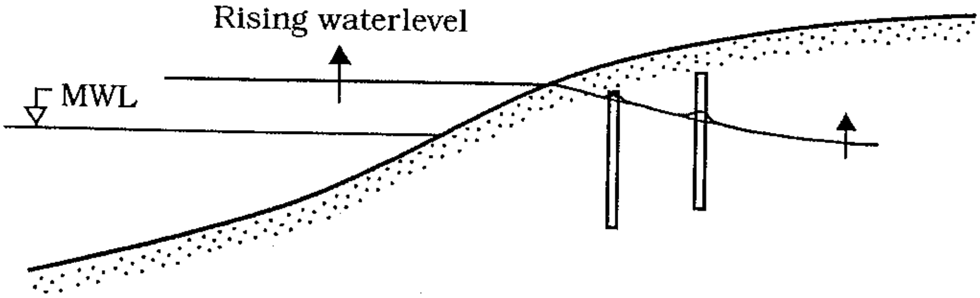


Figure 6.8b: During rising waterlevels (flood or storm surge), the beach is filled slightly faster with water, because the vertical tubes can lead the water easier to the beach. Like in the falling stage, the impact is insignificant; less than one per thousand.

So nearly no driving forces exist to activate the flow near the tubes. A simple estimate of the impact of the tubes is given in Appendix 2, in which it is demonstrated that there certainly is 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. 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. If we assume that the tubes shall drain the surrounding area in a radius of 5 m only around each tube, the improved drainage will be 0.01% (in case of very fine sand, where the impact is largest), corresponding to a change in the tidal range from 1.0000 m to 1.0001m.

6.3. 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 are discussed. For simplicity only one tube is shown in the beach, and we are considering the case of a falling watertable in the beach.

Figure 6.8 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.

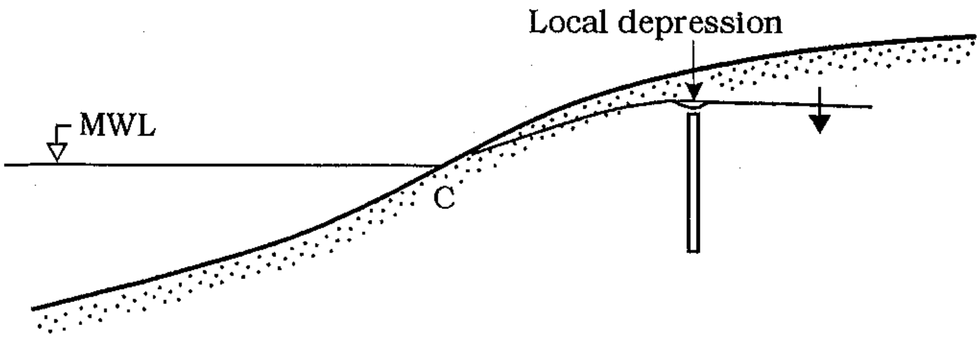


Figure 6.8: The drain will locally make a depression cone around the tube. However, the size of the cone is extremely small, and most of the beach water will flow directly rather through the tube towards the sea.

Figure 6.9 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 6.9 from a SIC report.

Vertical drains

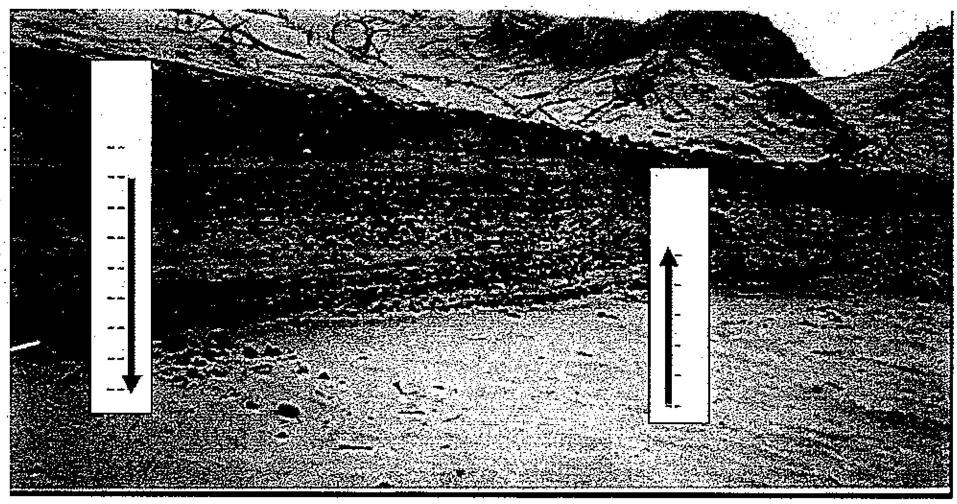


Fig. 3

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 6.9 SIC's explanation of trigger

Figure 6.9 illustrates one explanation given by SIC of the functioning of the drains in the presence of permeable layers.

As shown in figure 6.10, the presence of a horizontal-like permeable layer will in all cases improve the drainage of a beach, even without tubes installed. The requirement

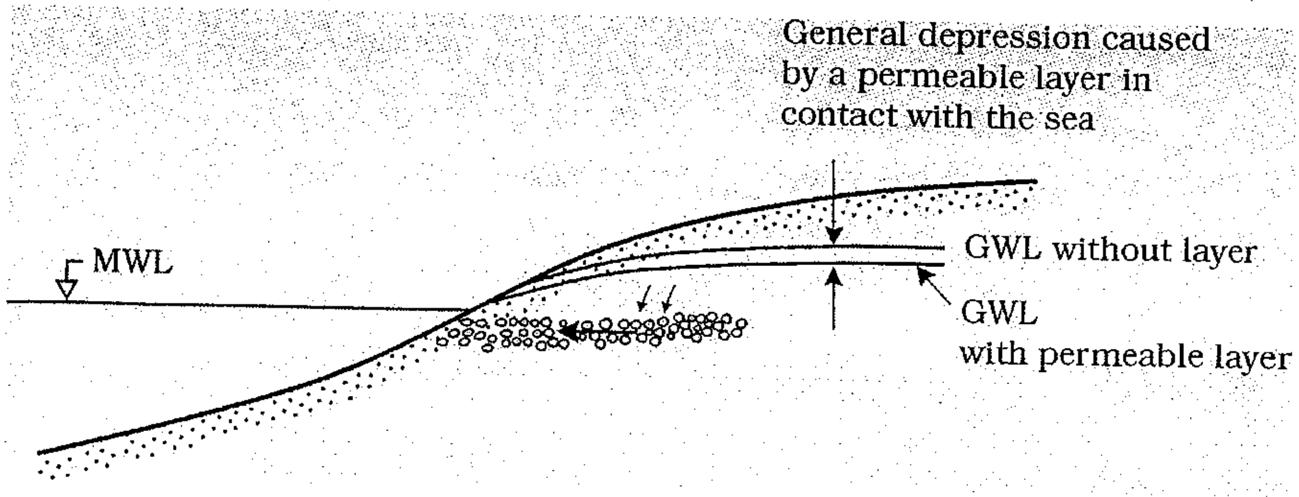


Figure 6.10: The presence of a sea-connected permeable layer will anyway improve the drainage of the beach.

will just be that the permeable layer will be sea-connected, so a low pressure can be established in the permeable layer. The layout in figure 6.10 is slightly different from the Japanese system shown in figure 6.4, 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 6.11 shows the same situation as that in figure 6.10, but with a tube installed. Now

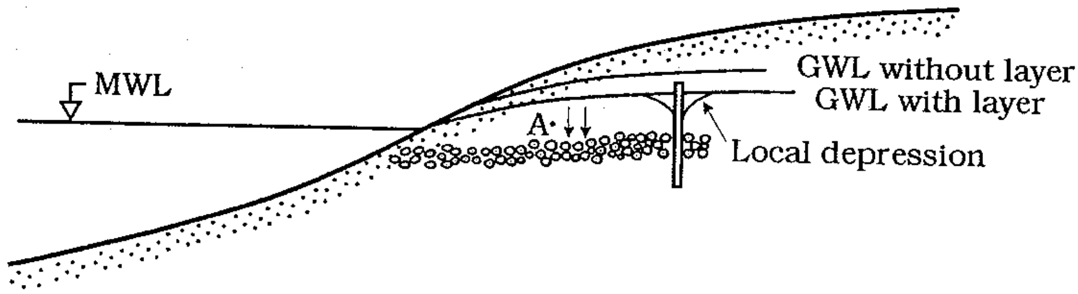


Figure 6.11: Tubes installed in a beach with sea-connected permeable layers will only have a local effect, because most of the water will go directly to the permeable layers.

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 6.11) 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 6.12a-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.

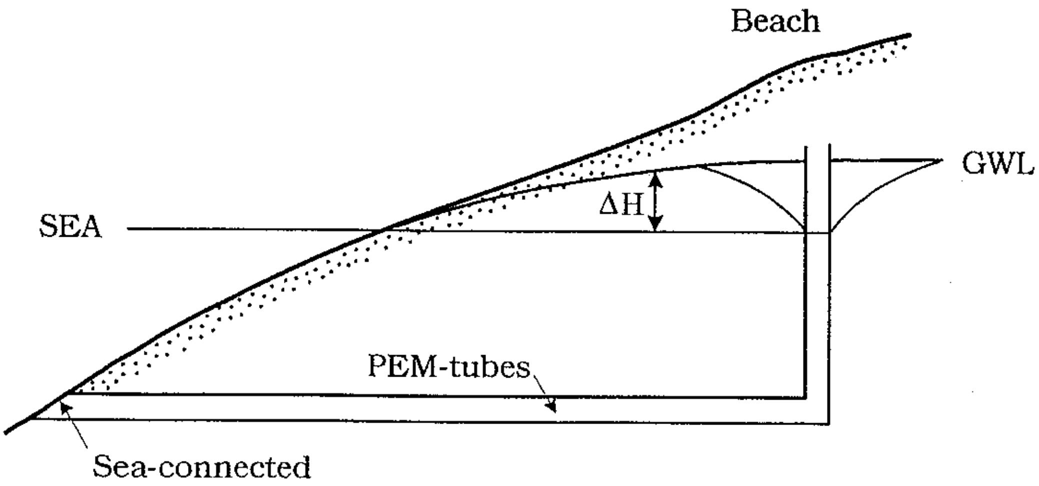


Figure 6.12a: An effective solution to drain the beach, if GWL is higher than Sea Water Level.

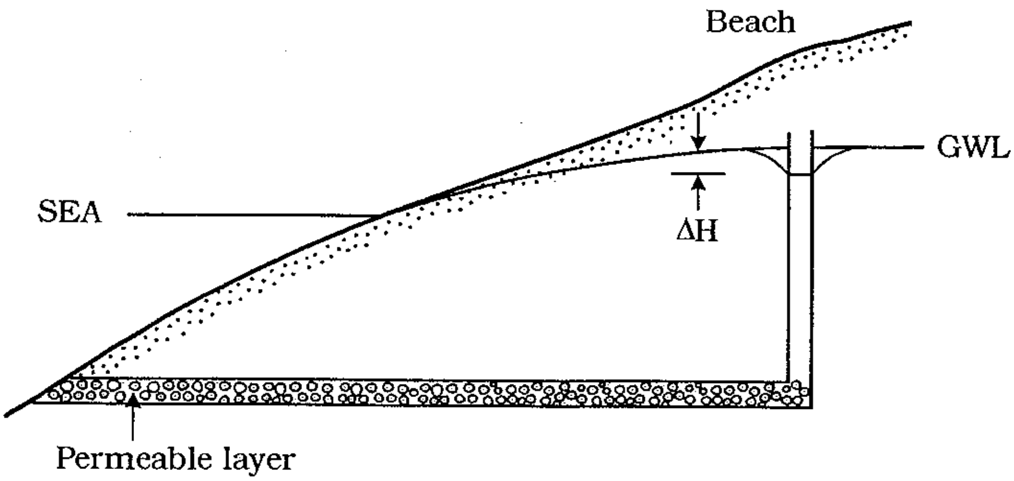


Figure 6.12b: the drainage capacity decreases if the sea –connection get a smaller permeability.

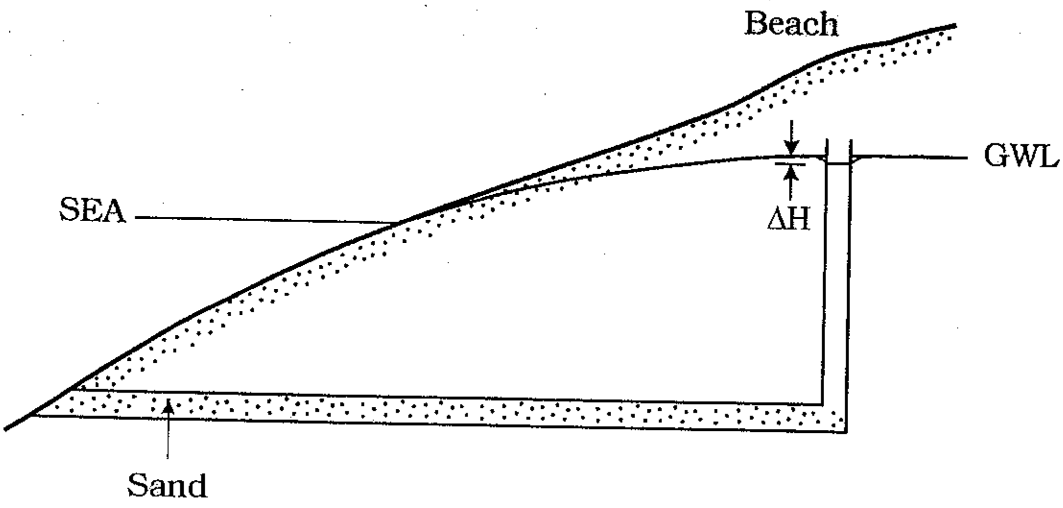


Figure 6.12c: in the case where the horizontal part of the drain simply consist of the same material as the original beach, the drainage effect disappear to be negligible.

In figure 6.12 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 6.12c the horizontal tube is filled with sand, and we are back to the situation shown in figure 6.8 with a very small local depression.
From the sketches in figure 6.12 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 6.13 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.

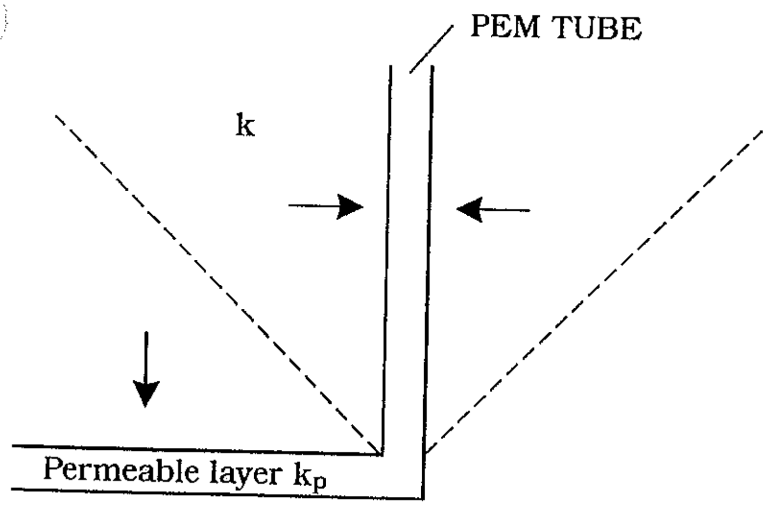


Figure 6.13: The water confined within the 45-degree cone will prefer to flow through the vertical tube if a sea-connected permeable layer exists.

Does permeable layers exists?

Permeable layers might be present in the beach, due to grain sorting by waves and wind. Figure 6.14 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.

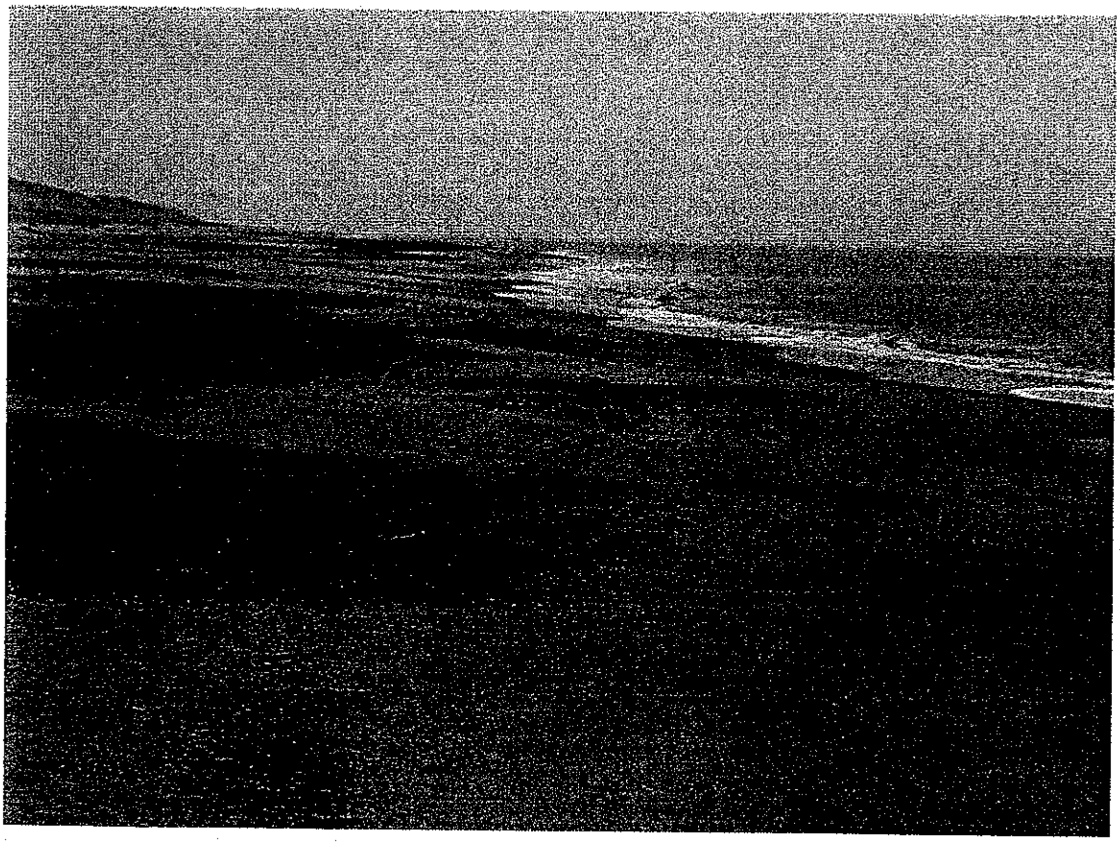


Figure 6.14: Layers of pebbles on the beach.

"Activation of Permeable layers".

As seen from figure 6.14, the distribution of pebbles on the beach is quiet "patchy" or 3-dimensional in its nature. So the situation as shown in figure 6.15a 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).

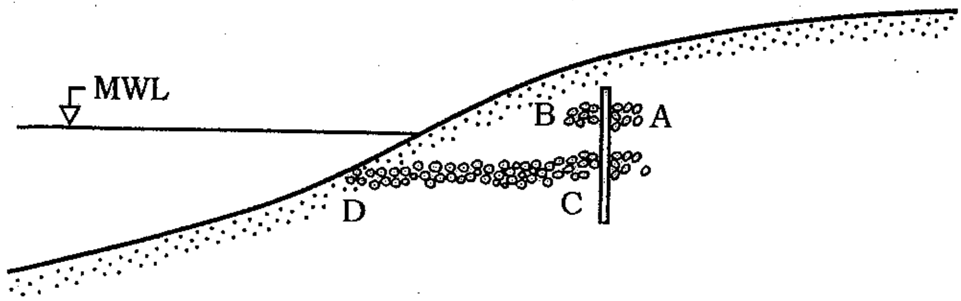


Figure 6.15a: The upper layer A-B will be drained better to the sea-connected layer CD by a vertical drain.

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 row effect: it could be asked whether an interconnection between a number of tubes might improve the drainage as shown on the photo figure 6.9 and in figure 6.15b and c, 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.

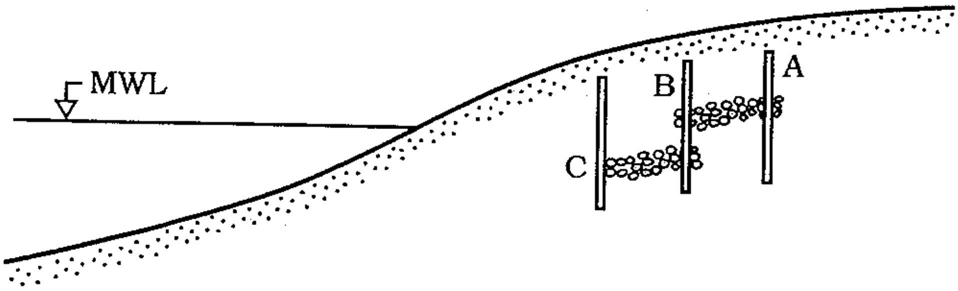


Fig 6.15b: A row of tubes can connect different permeable layers.

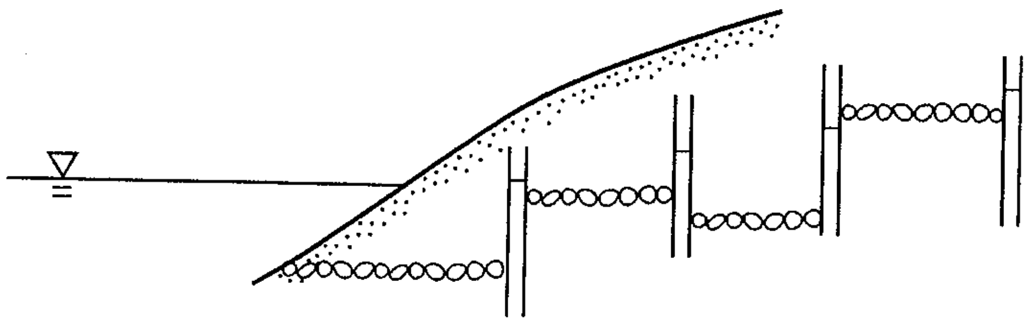


Figure 6.15c: To activate the different layers you need Sea-connection.

Will there be Sea-connection??

The situation with sea connection as sketched in figure 6.15a 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.

6.4. 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 6.7, 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 6.16.

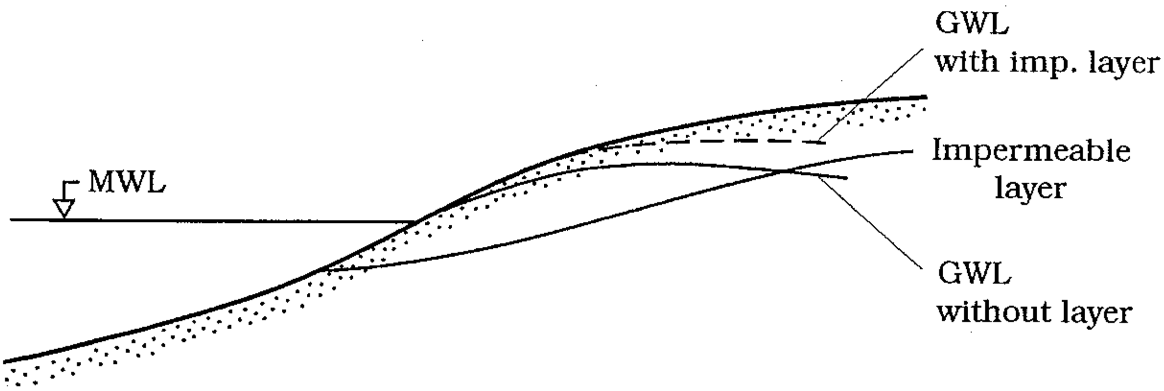


Fig 6.16: Impermeable layers will increase the ground water level in the beach during ebb flow because the flow will be more horizontally.

If a tube is installed, which penetrate the impermeable layer as shown in figure 6.17a, then the water can flow down through the tube if the pressure is lower below the impermeable layer than above.

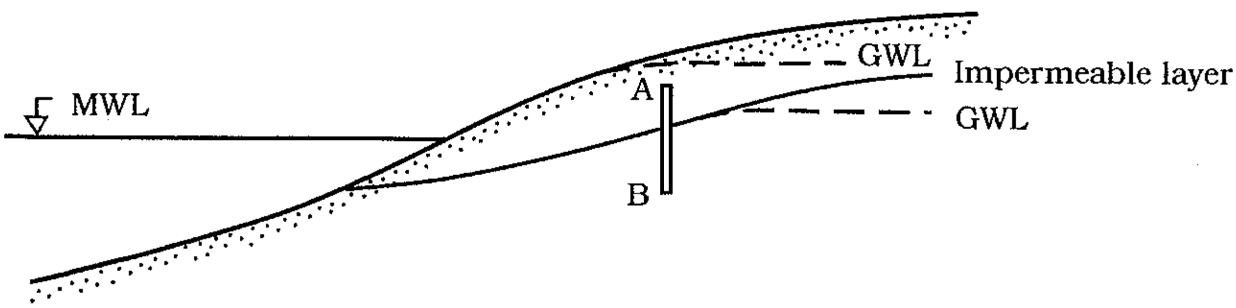


Figure 6.17a: The ground water level can be lowered if a tube penetrates the impermeable layer, and the pressure below this layer is lower than above the layer.

This will require that the extend of the impermeable layer along the coast is large, otherwise there will be a pressure-equilization through the sand outside the impermeable layer.

As sketched in figure 6.17a, 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 6.17b. If not the drainage improvement will be insignificant.

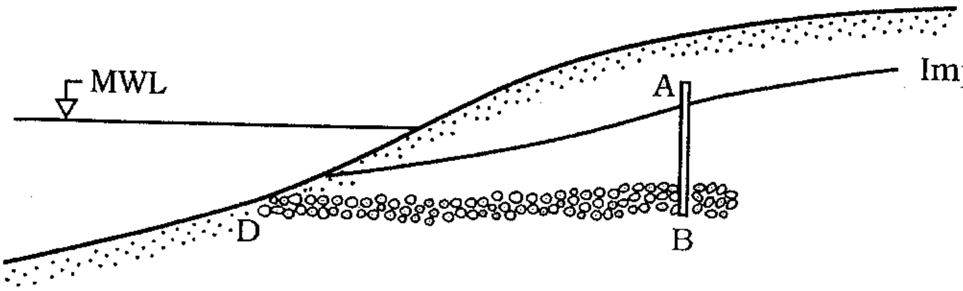


Figure 6.17b: a drain located in a Sea-connected high-permeable layer, and penetrating an impermeable layer above the permeable layer will improve the drainage above the impermeable layer. This will require a very special configuration in the beach.

6.5. Water suply from land.

One of SIC's major arguments for the functioning of the PEM-system is (or has been?) 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 6.18 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 (artesic 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. One positive effect might be, that if an impermeable layer like that depicted in figure 6.18 exists, this will lead to a concentration of the flow of the fresh water below the impermeable layer. Here a drain might have a small positive effect by reducing this outflow concentration.

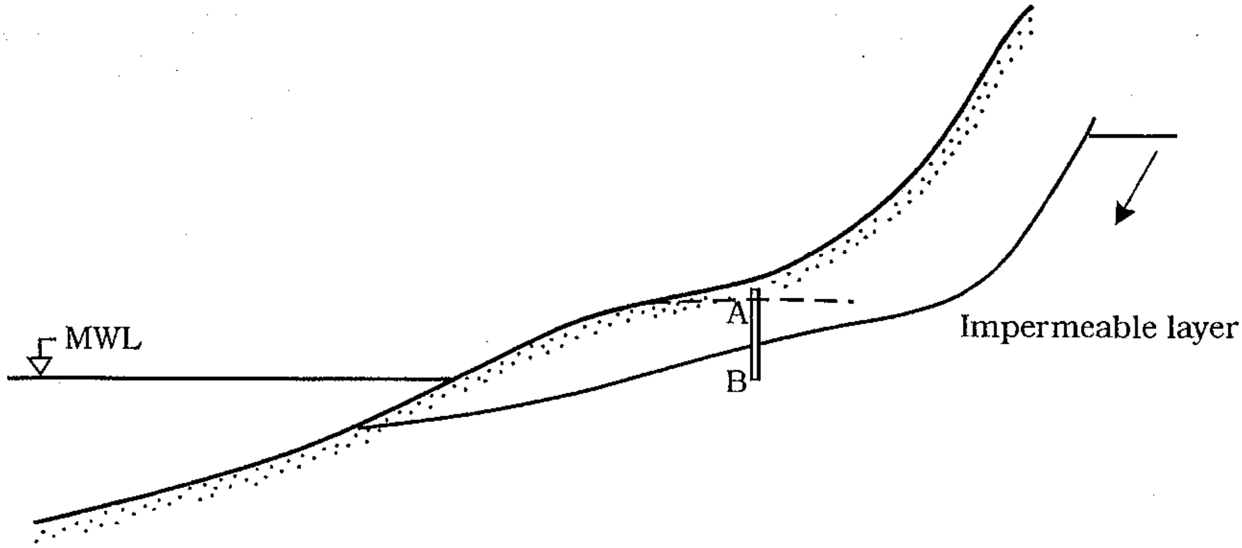


Figure 6.18: Supply of water from land will most probably flow *up* through the tubes (artesic pressure), and thereby make the beach more unstable.

6.6. Final remarks.

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. This means that you only have about one meter in height to make it possible to make a shortcut in between the high-permeable layers. Moreover in the case of impermeable layers, this must be located at the perforated part of the tube in order to function.

6.7 Field tests.

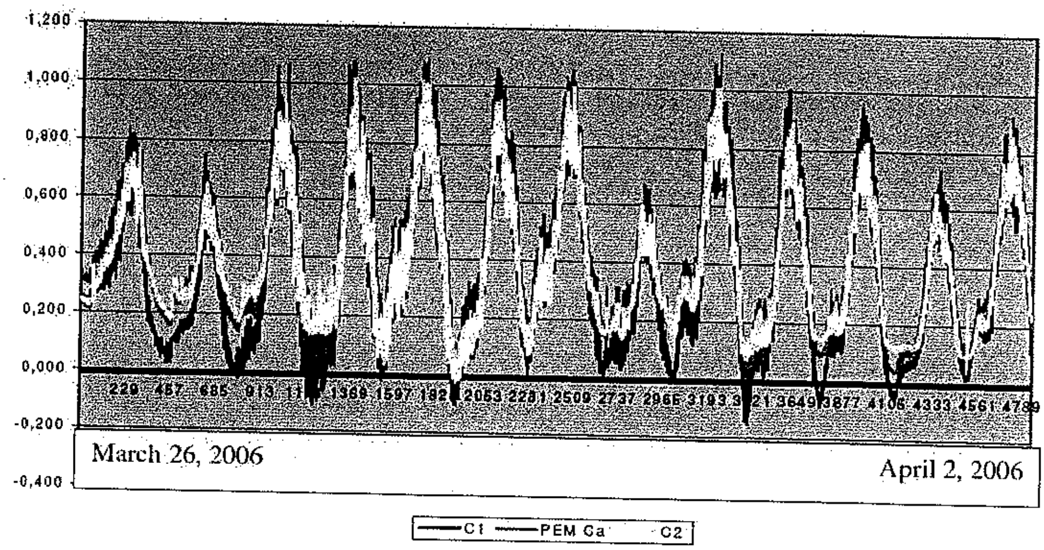


Figure 6.19: Example of Recording from the field test.

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 3.
The idea behind the test was to measure the groundwater level variation in two lines perpendicular to the coastline in two different environment: in one week without the PEM-system installed, and in the following week with the PEM-system installed. Figure 6.19 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 waterlevel fluctuate partly due to the windwaves (high frequency fluctuations) but more clearly the level is seen to follow the tide. In the present case the tidal range is around 1m, and it is seen that the watertable variation is more or less the same at all three locations, so the flow does not seems to change radically near the tubes. This is certainly not in favour of having a lot of impermeable layers!

Taking a closer look of figure 6.19 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 upper part of the tubes, and a corresponding outflow at the bottom of the tubes. This will improve the vertical drainage. This situation is considered in appendix 2, where the effect of a vertical pressure gradient is considered. Outside the tubes, the Darcy law determines the flow, while inside the tube the pressure is hydrostatic. For fine sand (0.10-.15 mm) it is demonstrated that the flow velocities might be 5-10 times as high as outside, but because the area of a tube is so small as compared to the area to be drained, the increase in drainage will be smaller than .1 per thousand, corresponding to a change in tidal range from 1.0000 m to 1.0001 meter.