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Effect of the kelp *Laminaria hyperborea* upon sand dune erosion and water particle velocities

Stig Magnar Løvås *, Alf Tørum

Department of Coastal and Ocean Engineering, Civil and Environmental Engineering, SINTEF Fisheries and Aquaculture, Klobuveien 153, N-7465 Trondheim, Norway

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Abstract

This paper presents a set of results from a laboratory study on water wave propagation above submerged vegetation growing in the surf zone and the effect of submerged vegetation on dune erosion. The study has focused on the kelp *Laminaria hyperborea*. The reason is that this kelp is commercially harvested along the Norwegian coast and there is a need to obtain better knowledge on the possible consequences of this harvesting. Experiments were run with irregular waves over a sloping bottom, and a kelp field was simulated by 5000 artificial kelp plants in a 1:10 scale. The experiments primarily focused on the effect of kelp upon erosion of a sand dune, wave damping and water velocities. It was found that the water level is a very important factor to the degree of dune erosion, while the kelp has only a minor effect. The kelp does, however, cause significant wave damping and the degree of wave breaking is reduced. It was also found that the kelp modifies the water velocity profile. In a region above the kelp canopy layer, the time-averaged water velocity was shoreward, while the seaward undertow was confined to a region higher up in the water column. © 2001 Published by Elsevier Science B.V.

Keywords: Dune erosion; Particle velocity; Kelp; *Laminaria hyperborea*; Surf zone; Swash force

1. Introduction

In Norway, industrial use of algae started about 100 years ago. The main industrial product is alginate, which is a biopolymer occurring naturally in the skeleton structure of alga plants. Today, alginate products find applications in a wide range of industries, such as pharmaceutical, food, petfood, textile and in the functional food and agro sectors. The most important alga plant to the Norwegian alginate industry today is the kelp *Laminaria hyperborea* (Gunnerus) Foslie, which consists of a holdfast (whorls of root-like growths), a rigid, erect stipe, and a laminate blade (frond) divided into finger-like segments. The frond is annual, while the holdfast and the stipe are perennial. A common stipe length is 1–1.5 m. The frond may reach a similar length. The number of grown-up species per m^2 bottom area is on an average approximately 10.

The kelp grows on rocks/boulders or rocky sea bottom down to the limit of light penetration. Several harvesting methods were tested before in the mid-

* Corresponding author. Fax: +47-73592376.
E-mail addresses: stig.m.lovas@fish.sintef.no (S.M. Løvås), alf.torum@bygg.ntnu.no (A. Tørum).

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1960s, the use of a kelp trawl was sufficiently successful to organise a kelp trawling fleet. In 1976, a modified kelp trawl was introduced. Instead of cutting the kelp stipes, the new trawl just tears the kelp loose. This trawl is still the preferred tool for harvesting kelp.

From the beginning, kelp trawling became a controversial issue. Fishermen claimed that the trawling scared the fish away and that fishing nets were damaged. Also those trawling for shrimps, crab or lobster complained. A trawling law separating the sea into zones for differing harvesting purposes reduced the criticism, but during recent years the criticism has increased again. There are several controversial issues. The kelp fields are habitats for different fish and animals. Some claim that the harvesting of kelp damages or destroys the good habitat conditions provided by the kelp forest. The kelp forests are also supposed to have a wave damping effect. When the kelp is harvested, this wave damping effect may be reduced with increased wave activity in harbours and increased erosion of sandy beaches and dunes as a result. Especially along the Jæren coastline, located in the southwestern part of Norway (see Fig. 1), kelp harvesting has been claimed to be causing increased dune erosion.

The work presented in this paper was carried out as part of a Dr.ing.-Study (Løvås, 2000) at the Norwegian University of Science and Technology. This study comprised both laboratory experiments and analytical work. The present paper focuses on a part of the experimental work.

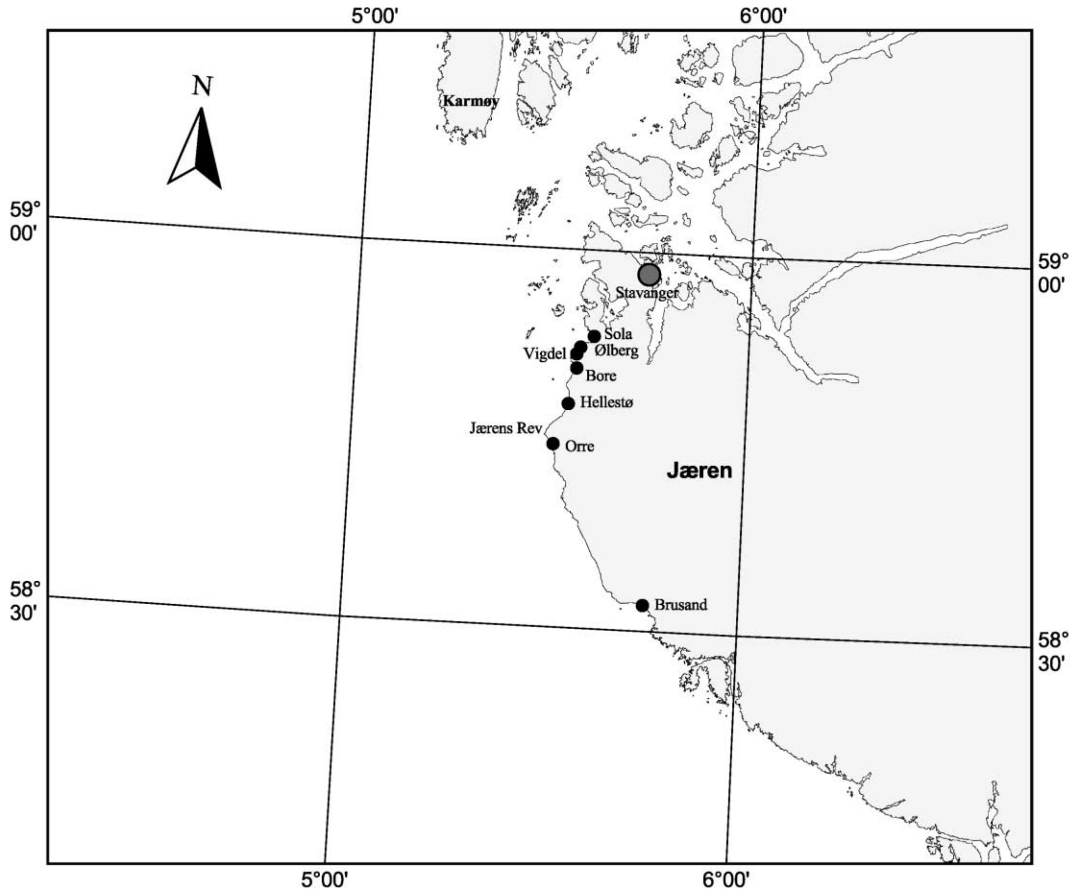

Fig. 1. Location of the main beaches along the Jæren coast.

2. Previous investigations

Beach and dune erosion have been studied by many (see e.g. Bruun, 1954; Dean, 1977, 1987; Kraus, 1992; Vellinga, 1986; Steetzel, 1993), but there have been few investigations on the effect of kelp harvesting on dune erosion. Sivertsen (1985) and Berg and Munkejord (1991) carried out some investigation on the effect of kelp harvesting on dune erosion along the Jæren coast. However, none of these addressed the basic issues on waves, wave kinematics, wave damping and the effect of water levels on dune erosion.

Price et al. (1968) investigated the effect of artificial seaweed on beach erosion. He concluded that artificial seaweed can build up beaches by promoting an onshore transport of material. Elwany and Flick (1996) investigated the effect on beach erosion from Southern California giant kelp (*Macrocystis pyrifera*). They concluded that there was no clear correlation or consistent pattern indicating that offshore kelp beds have any direct influence on adjacent-beach width. However, the *M. pyrifera* is a very different species than *L. hyperborea* (Gunnerus) Foslie. To our knowledge there are no previous studies on the effect on beach or dune erosion of submerged vegetation with similar properties as *L. hyperborea* (Gunnerus) Foslie.

Several investigations have been carried out on wave damping by sea vegetation on non-breaking waves over a horizontal bottom, e.g. Asano et al. (1993), Kobayashi et al. (1993), Dubi and Tørum (1994, 1996), Elwany et al. (1995), Dubi (1995), Mork (1996a,b), Øie Nilsen (1997). Otherwise there have been a number of studies on the wave forces on sea plants, e.g. Koehl (1982, 1984, 1986), Seymour et al. (1989), Utter and Denny (1996) and Dubi (1995).

It has clearly been shown that sea vegetation, and especially *L. hyperborea* (Gunnerus) Foslie, may damp the waves significantly, depending mainly on the wave length/water depth ratio. However, in the surf zone, with *L. hyperborea* (Gunnerus) Foslie, there are two strong mechanisms for wave damping, namely wave breaking and damping due to the kelp plants. Nothing is known on the simultaneous effect of these two damping effects and thus on the effect of kelp on beach and dune erosion. It was hence felt that a separate study was necessary to throw more light onto what extent kelp harvesting influences beach and dune erosion.

Different strategies could be used for such an investigation. Only theoretical work was deemed not to be sufficient, because it would include assumptions that might not be valid. Field investigations were at this stage felt to be costly and might not be successful because of the complexity of the problem. Hence, it was decided to carry out a laboratory experimental wave flume study. There might be scale effects present during small-scale laboratory model tests, especially on beach and dune erosion. However, in view of the very good control one has in laboratory studies and the easy change of wave parameters that can be done compared to field studies, laboratory experiments, coupled with theoretical analysis, were deemed presently with limited budget to give the best insight in the complex interactions in a wave surf zone with kelp. Due to the concerns at the Jæren Coast the study also put priority on the dune erosion issue.

3. Laboratory experiments

3.1. Experimental set-up

The main purpose of these experiments was to study the effect of kelp upon erosion of a dune front. Another objective was to obtain water velocity profiles to see how kelp may affect water motion in the surf zone. The experiments were carried out in a 40-m-long and 5-m-wide wave flume at SINTEF, Trondheim (Fig. 2). The walls and the bottom of the flume are made of smooth concrete. To simulate a surf zone a slope of gradient 1:30 begins about 14 m from the wave generator. The wave-maker is of the piston type with a plane paddle. The paddle is hydraulically driven and can generate both regular and irregular waves. A number of measurements carried out prior to the actual tests confirmed the high repeatability of the generated wave motion. The wave-maker is, however, not equipped with any means for suppressing generation of spurious free long waves or absorbing reflected long waves.

As part of a previous Dr.ing.-study (Dubi, 1995), 5000 model kelp plants were prepared. These plants

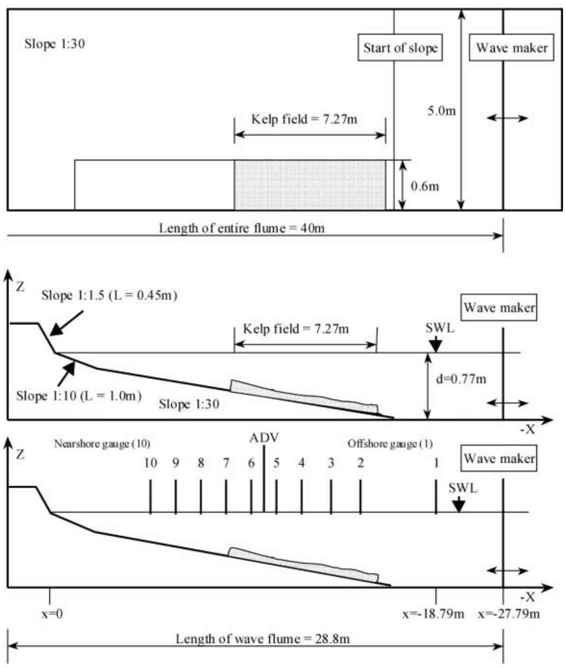

Fig. 2. Wave flume layout. Top view, side view and side view with instrumentation. The slope begins about 14 m from the wave generator.

were designed to replicate kelp plants sampled in the field. Current drag forces and bending stiffness of these plants were measured and formed the basis for making model plants in a 1:10 scale. The model plants were prepared from a plastic liquid which had the correct density for casting model stipes with the right shape (diameter smaller at the top than at the bottom) and stiffness (Dubi and Tørum, 1994). The artificial plants have 10-cm-high stipes and 10-cm-long fronds with a corresponding full-scale surface area of approximately 0.6 m^2 (scale 1:10) and are attached to 60 cm $\times$ 48.5 cm plates in a uniform distribution representing a full-scale plant density of 12 plants/m^2. The plates are 2-cm-thick plywood plates and the stipes were attached to the plates by drilling 1-cm-deep holes, filling them with glue and putting the bottom of the stipes into the holes (see Fig. 3). This technique reduced the efficient height of the stipes to approximately 9 cm.

To get a sufficiently long kelp forest, the available kelp plates were fixed in one row. A plywood wall was built to separate the kelp plates from the rest of the flume. The reason was to get uniform conditions across the 60-cm-wide plywood plates (with or without model kelp plants). Both ends of the plywood plates were provided with inclining metal sheets to minimise edge effects. The kelp field was put in the deeper part of the model slope. The 9-cm model kelp plants were located from about 30 to 50 cm depth, giving a kelp height to water depth ratio of 0.3 to 0.18, which is about the same as in prototype when the high water level in the model is taken into account.

To model a real beach, sand was put on top of the concrete (slope 1:30). Above the mean water level shoreline, the slope was increased (1:10) towards the dune foot. The front of the sand dune was shaped with a slope of 1:1.5 and a height of 30 cm, resembling a 3-m full scale. Most of the sand dunes at Jæren are higher than this and thus provides more protection towards erosion. However, no significant overtopping of the model dune occurred with the wave heights that could be generated (see Section 3.2).

The readily available sand used in the model has size $D_{50} = 220$ μm and $D_{90} = 300$ μm, and the density is 2650 kg/m^3. A few measurements obtained by the Norwegian Hydrotechnical Laboratory (now a part of SINTEF Fisheries and Aquaculture) showed $D_{50} \cong 400$ μm both at Boresanden and Orresanden. This means that the scale of the fall velocities (approximately 1:2) is somewhat larger than it should be from Froude scaling (1:$\sqrt{10}$), but even if we had access to a somewhat finer sand, we do not believe that this would change the overall conclusions on the effect of kelp upon dune erosion. Otherwise, the model beach cross-section was formed

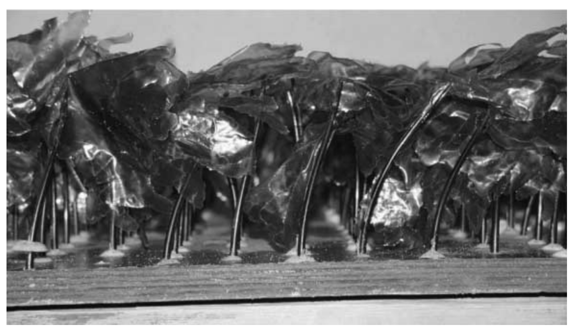

Fig. 3. Model kelp plants.

following to some extent Vellinga (1986) and Steetzel (1993).

A laser (DME 2000 from SICK Optic Electronic) was used to measure the sand profiles. This laser measures distances with 1-mm resolution with an accuracy of ± 1–3 mm over the relevant measuring range (approximately 500–1000 mm). The distance (height) is measured every 5 mm. The laser can, however, only measure reliable distances in air. This means that it cannot produce any sand profiles in the submerged part of the model.

A total of 10 cantilever conductivity type wave gauges were used to measure surface elevations (see Fig. 2), while an Acoustic Doppler Velocimeter (ADV) with a 3D side-looking probe from Nortek (Nortek, 1997) was used to measure water particle velocities in three dimensions. The ADV probe is fixed to a thin (0.8-cm diameter) 45-cm long circular stem, which again is fixed to a thicker (6.35-cm diameter) circular ADV Signal and Condition module. In most of the test series, the ADV was located in the same place. When the kelp field was in place, this position was in the shoreward part of the kelp field. However, to check the velocity profile closer to the beach, the ADV was moved to obtain a few velocity profiles from two positions shoreward of the kelp field before the final test series. One location was 30 cm shoreward of the kelp field, while the other location was only about 1.5 m from the stillwater shoreline. For these additional test series, two wave gauges were also moved to the region closer to the shoreline to get more data on set-up/set-down. During these tests it was found that the ADV-signal was stable even when lowering the ADV to a level below the canopy layer without flattening any plants. It was also found that it was necessary to add seeding material several times during a day to maintain a stable ADV-signal.

Fig. 2 shows the experimental set-up.

3.2. Water level and wave height

The water level (storm surge level) seems to be the most important hydraulic factors for erosion of sand dunes with no kelp outside, e.g. Steetzel (1993). The maximum water level recorded in Stavanger in the years 1979–1997 is 112 cm above the mean sea level. It is believed that this is also representative for the conditions along the Jæren coast. In the model the still water level used in most of the tests was therefore about 11 cm above the change between 1:10 and 1:30 slope, which is supposed to represent the mean sea level. Then the stillwater level barely reaches above the dune foot. This means that the model (scale 1:10) represents well the maximum water level for 10–15-m-wide beaches with a 1:10–1:15 slope between the shoreline at mean sea level and the dune foot. The distance from the berm crest to the dune foot was estimated to vary from 15 to 80 m (October 1999) at the Jæren beaches, with 40–50 m as an estimated average. Hence, the erosion found in the model could therefore be regarded as a maximum of what could be expected in nature for the modelled wave heights.

The water depth outside the model slope represents about 8-m depth in prototype scale. The maximum wave height at breaking, H_b, is often taken as $H_b = \gamma_b h$, where h is the water depth and γ_b is in the range 0.55–0.83 depending on the bottom slope. Hence, the maximum wave height should be between 4.4 and 6.6 m. The maximum 'offshore' significant wave height and "maximum" wave heights obtained in the model represent about $H_{s,max} = 1.7$ m and $H_{max,max} = 3.2$ m, respectively, in prototype scale. Outside the Jæren coast in deep water the 100-year significant wave height is $H_{s,100} \approx 10$–12 m. Hence, the "deep" water waves we could obtain in the model (scale 1:10) is thus much less than can be expected in nature. However, if instead of comparing offshore wave heights one compares wave heights at the seaward end of the kelp field, the water depth here (~ 5.4 m) gives a maximum wave height of 4.3 m ($\gamma_b = 0.8$), which is $\sim 35\%$ higher than could be obtained in the model.

4. Test program

The test program considered random wave simulations for two different peak periods, 2.5 and 3.5 s. The selected peak periods represent 7.9 and 11.1 s in full scale. The control signals for the wave generator are based on the JONSWAP spectrum with a target peak enhancement factor (γ-value) of 7.0. The wave height can be set/varied by changing an amplitude amplification factor for the control signal. Depending on water level and wave period the same amplitude amplification factor may produce somewhat different wave heights. For each wave peak period, tests were run for two different amplitude amplification factors ($e = 2.0$ and 3.5). The highest amplification factor ($e = 3.5$) was the maximum allowed by the length of the piston rod of the wave generator and produced waves with offshore $H_{m0} \sim 18–22$ cm (depending on water level and wave period), while the lower value produced waves with offshore $H_{m0} \sim 12–14$ cm. The same test combinations were used for the wave runs with and without kelp present in the flume. The length of each wave run was 15 min and sampling frequency was 20 Hz. For each combination of wave period and amplitude amplification factor, a number of wave runs were made. In order to test the effect of partial removal of kelp, every other 48.5-cm plate with kelp was removed. Between the remaining kelp plates, sand was filled until the top surface of the sand was similar to the top surface of the plates. In the Results this case is called '50% kelp'.

A laser mounted on a beam and moving with constant speed along the beam was used to measure sand profiles from the back of the sand dune and up to 2700 mm in the seaward direction. The profiles were spaced 5 cm apart. Profiles were obtained after each of the first wave runs. As the erosion rate decreased profiles were obtained after two or more consecutive wave runs (this was done to save time as each profiling sequence took 45 min with 1700-mm-long profile lines). The initial profile (before the first wave run) and the final profile of each test series (same wave period and amplitude amplification factor) was obtained without water in the flume and for the total length (2700 mm) of the beam. The intermediate profiles were obtained with water in the flume and were only obtained for a length of 1700 mm (well into the water). The reason for using shorter profiles was that the laser profiles are anyway only reliable above the water level and it saved about 30 min for each profiling sequence.

The regular procedure for each test series was that the sand was first reshaped into the initial profile. Then, the laser was used to obtain the initial profile before the flume was filled with water up to the bottom (foot) of the dune front. The flume was then left overnight for the water to reach a stable temperature. The tests next day started with calibration of the wave gauges before a number of wave runs with subsequent profiling were made. After completing the tests the water was drained from the flume, the final profile obtained and the sand reshaped into the initial profile again. The first test series consisted of 6 to 11 wave runs, which with Froude scaling represents 4 h 45 min up to 8 h 40 min. The majority of these test series consisted of nine wave runs, which with Froude scaling represents 7 h 7 min. Vellinga (1986) found that using constant hydraulic conditions similar to the maximum of the North Sea storm surge hydrograph gave the same amount of erosion above storm surge level as varying hydraulic conditions resembling the North Sea storm surge hydrograph. If this finding is representative also for storms at the Jæren coast, the length of each test series should be sufficient to obtain erosion quantities representative to the complete duration of storms. However, to obtain velocity profiles (1–2 cm resolution in height) covering as much as possible of the water depth (from about 4 cm above the bottom to 9 cm above the stillwater level) test series with up to thirty-two 15-min wave runs were carried out.

The water level (storm surge level) seems, as mentioned, to be the most important hydraulic factor for erosion of sand dunes (see e.g. Steetzel, 1993). Storm duration (or successive storms) is also important, while wave height and wave period are of lesser importance. As the main purpose of the experiments was to study the effect of kelp, the presence or absence of kelp was an additional variable. To study whether presence of kelp may cause reduced erosion in the presumed worst conditions, the water level in the model was chosen to represent the maximum observed water level at Jæren. A number of initial tests were run with different combinations of the two wave periods and wave heights, with and without kelp in the flume. As will be shown in the Results, repeated series where the test conditions were presumably the same showed varying degree of erosion. To obtain knowledge on the range of the variations, the number of repeated series had to be increased, but as each test series took 1–2 days to complete the number of variables had to be limited in order to finish the test program in time. The majority of the test series was therefore run with almost the same water level, a wave period of 3.5 s and wave height amplification factor of 3.5. To see the effect of the water level, tests with and without kelp were also run at two lower water depths. The full test program is listed in Table 1. With the present knowledge later similar studies should probably start with an equilibrium beach profile. However, we believe that the results of the present study give an insight in the

Table 1
Overview of test series with sand in the wave flume

Test no.	Tp (s)[a]	e[b]	No. of runs[c]	Water level[d]	Location of ADV[e]	Kelp[f]	Profiling[h]	Comments
1	2.5	2.0	11	230	20.13	0	x	
2	2.5	2.0	9	240	20.13	100	x	
3	2.5	2.0	10	~ 240	20.13	100		
4	2.5	3.5	10	235	20.13	0	x	
5	2.5	3.5	13	225	20.13	100	x	
6	2.5	3.5	9	241	20.13	100	x	
7	3.5	2.0	9	244	20.13	0	x	
8	3.5	2.0	20	239	20.13	0	x	
9	3.5	2.0	9	240	20.13	100	x	
10	3.5	2.0	10	~ 240	20.13	100		
11	3.5	3.5	6	244	20.13	0	x	
12	3.5	3.5	20	239	20.13	0	x	
13	3.5	3.5	20	241	20.13	0	x	
14	3.5	3.5	14	~ 240	21.98	0		
15	3.5	3.5	11	~ 240	25.65	0		
16a	3.5	3.5	6	236	20.13	100	x	Sand reshaped after six runs
16b	3.5	3.5	4	240	20.13	100	x	
17	3.5	3.5	1	240	20.13	100	x	Wave generator failure in 2nd run
18	3.5	3.5	5	242	20.13	100	x	
19	3.5	3.5	10	~ 240	20.13	100		
20	3.5	3.5	13	244	20.13	100	x	
21	3.5	3.5	22	240	20.13	100	x	
22	3.5	3.5	28	239	20.13	100	x	
23	3.5	3.5	32	240	21.98 25.65	100	x	
24	3.5	3.5	21	241	21.98	100	x	
25	3.5	3.5	9	250	20.13	50	x	
26	3.5	3.5	26	241	20.13 20.05	50	x	ADV moved after 15 runs
27	3.5	3.5	15	240	20.05	50	x	
28	3.5	3.5	22	164	20.13	100	x	
29	3.5	3.5	22	164	20.13	0	x	
30	3.5	3.5	27	201	20.13	100	x	
31	3.5	3.5	27	201	20.13	0	x	

[a] Peak wave period of the wave generator control signal. The measured period was very close to this period.
[b] Wave amplitude amplification factor.
[c] Number of 15-min wave runs.
[d] Output laser value (mm) of the stillwater level. The foot of the dune front slope is at 233. Higher values represent higher water level.
[e] Horizontal distance (m) from the wave generator.
[f] Percentage kelp: 0 means no kelp in the flume, 50 means every 2nd 48.5-cm plate removed and 100 means that the entire kelp field is present.
[h] Indicate whether any erosion profiles were obtained.

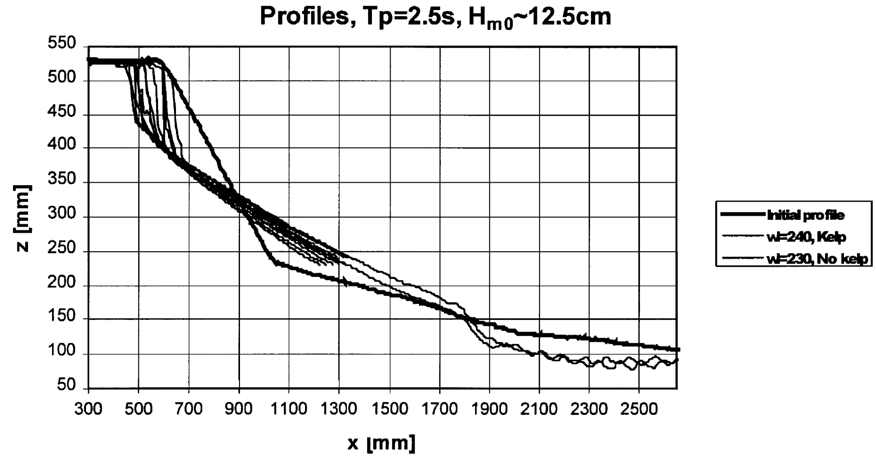

Fig. 4. Median laser profiles for Tp = 2.5 s and H_{m0} ~ 14 cm (model scale) at the most offshore gauge. The stillwater levels are indicated in the legend.

major mechanism for dune erosion with and without kelp.

5. Data processing and analysis

The laser profiles were used to analyse erosion and accretion of sand above the stillwater level. Erosion is here defined as the area where the profile is *lower* than the initial profile, while accretion is defined as the area where the profile is *higher* than the initial profile.

To calculate erosion and accretion volumes the first step was to find the location, X_{cross}, where each profile crossed the initial profile (above the stillwater level). Using the part of the profiles from $X = 0$ to $X = X_{cross}$, the eroded volume was calculated as the difference between the sand volume below the initial profile and the sand volume below the measured profiles. The accreted volume was calculated simi-

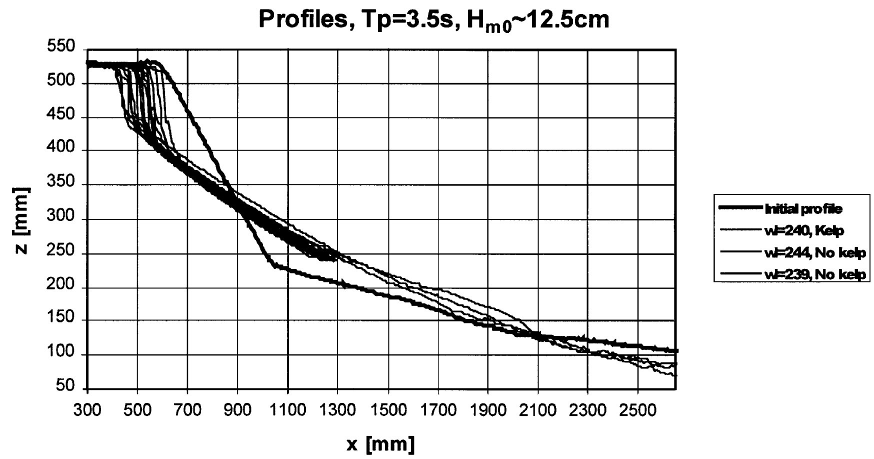

Fig. 5. Median laser profiles for Tp = 3.5 s and H_{m0} ~ 12.5 cm (model scale) at the most offshore gauge. The stillwater levels are indicated in the legend.

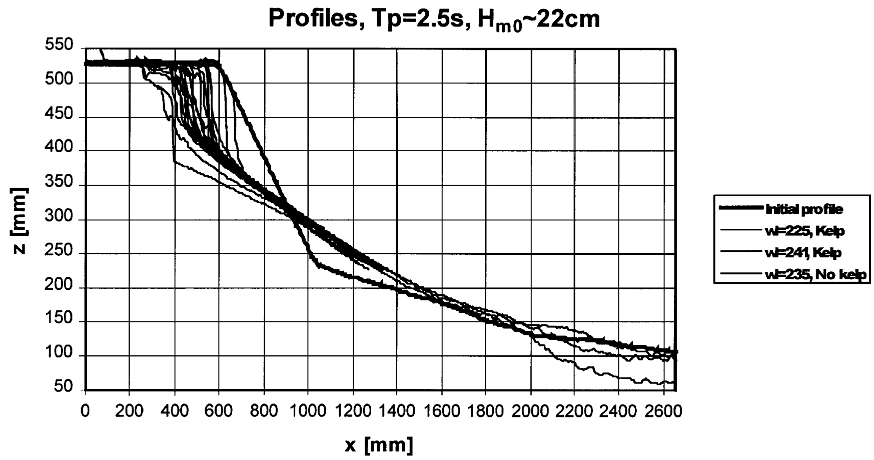

Fig. 6. Median laser profiles for Tp = 2.5 s and H_{m0} ~ 22 cm (model scale) at the most offshore gauge. The stillwater levels are indicated in the legend.

larly using the part from $X = X_{cross}$ to the location where each profile crossed the stillwater level. This means that the erosion/accretion that takes place below the stillwater level is not included, but to study effects of kelp upon dune erosion that is not necessary. The calculated volumes were used to show the time development of eroded sand volume, $V(t_0 = 0) - V(t)$, accreted sand volume, $V(t) - V(t_0 = 0)$, and erosion/accretion rate, dV/dt. It should be mentioned here that the erosion/accretion rates are calculated from the already calculated erosion/accretion volume. This is not quite correct. If e.g. the eroded area is just shifted shoreward, the present method would give zero erosion rate (since $\Delta V(t_I) = 0$), while in reality there is a balance between erosion and accretion in the erosion region ($\Delta V_{erosion}(t_I) = \Delta V_{accretion}(t_I)$). If the crossings between each profile and the previous profile were used instead of the crossing with the initial profile, the rates would be correct. The reason for using an

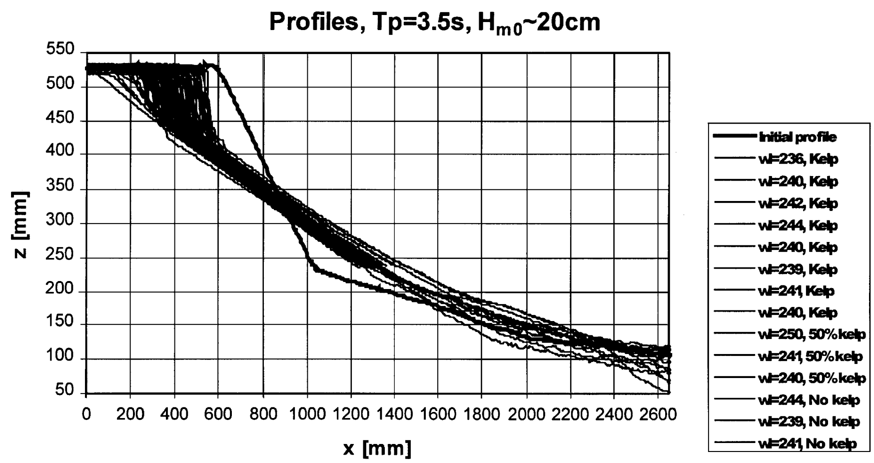

Fig. 7. Median laser profiles for Tp = 3.5 s and H_{m0} ~ 20 cm (model scale) at the most offshore gauge. The stillwater levels are indicated in the legend.

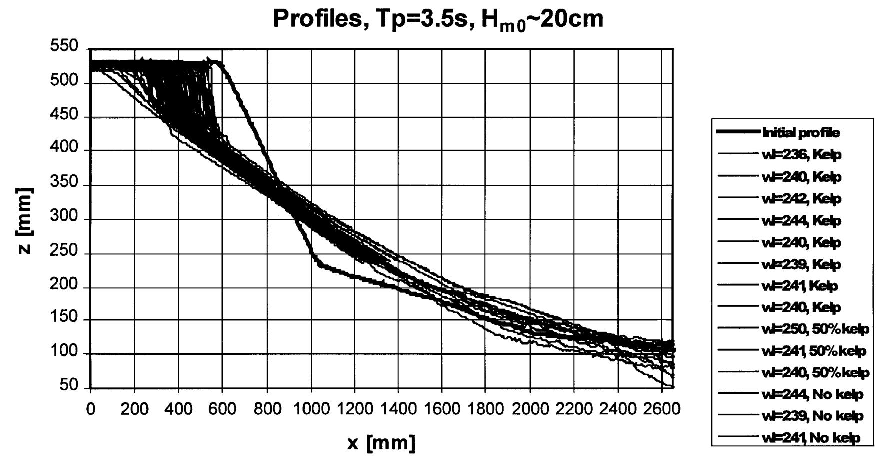

Fig. 8. Median laser profiles for Tp = 3.5 s and H_{m0} ~ 19 cm (model scale) at the most offshore gauge. The stillwater depth is ~ 30 cm (full scale) below the dune foot.

'incorrect' method is that it is much simpler to use and that it is believed to be sufficiently correct to see any effect of kelp on dune erosion.

Especially during the first test series, there were problems with non-uniform erosion across the flume. Looking towards the shore there was generally more erosion at the right side of the sand dune. The plywood wall separating the test channel from the rest of the flume is believed to be cause of the problems. Partly because it was smoother than the concrete wall on the other side of the test channel, but mainly because difference in wave height and phase between the test channel and the rest of the flume caused the wall to vibrate slightly. This caused a crack pattern to develop from the plywood wall and into the sand dune, which again caused increased erosion. Two actions were taken to reduce the problem. First, the plywood wall was made stiffer around the shoreline section. Secondly, in the volume analyses a test was added to exclude (from the right)

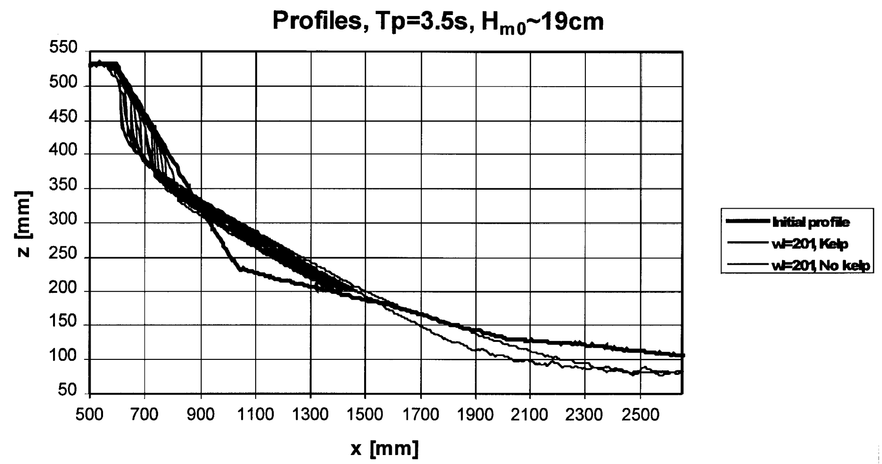

Fig. 9. Median laser profiles for Tp = 3.5 s and H_{m0} ~ 18 cm (model scale) at the most offshore gauge. The stillwater depth is ~ 70 cm (full scale) below the dune foot.

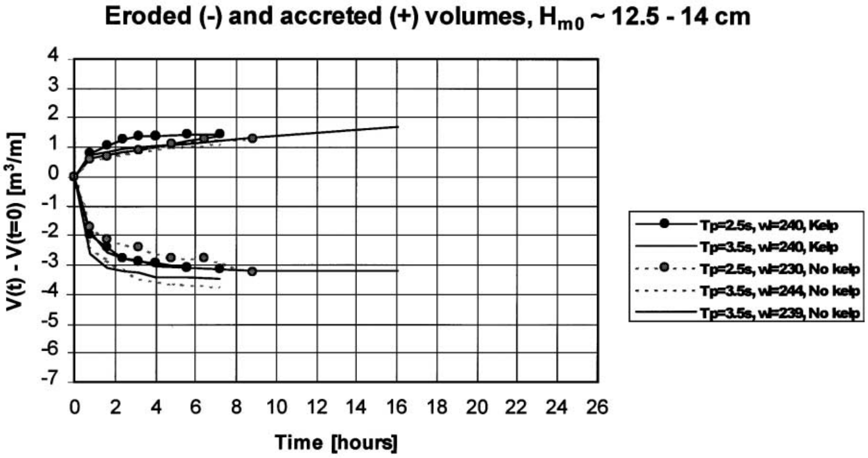

Fig. 10. Eroded and accreted volumes for Tp = 2.5 and 3.5 s. H_{m0} ~ 14 and ~ 12.5 cm (model scale) at the most offshore gauge.

profiles causing the x-axis difference between the most and least eroded profile (at each time step) to exceed 7.5 cm near the top of the sand dune.

6. Results

6.1. Dune erosion

This section focuses on erosion of the modelled dune due to different amounts (0%, 50% and 100%) of kelp in the flume. As described in Section 4, 50% kelp means that every other 48.5-cm kelp plate is removed. Erosion and accretion is quantified as volumes derived from height profiles. These volume figures cannot be used directly to obtain a mass balance, as this would require assuming uniform bulk density in the sand. This would not be correct as the compactness, and hence the bulk density, of the sand in the slope formed by the wave action is higher than in the dune front initially. Hence, the mass of the sand remaining above the still water

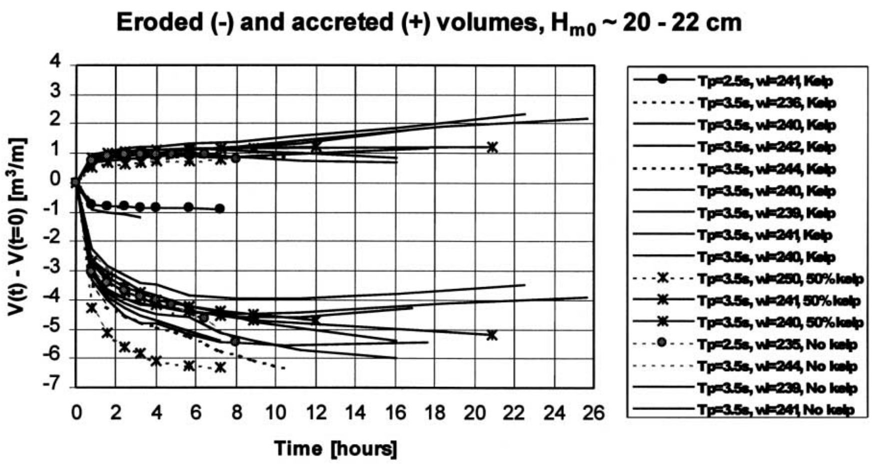

Fig. 11. Eroded and accreted volumes for Tp = 2.5 and 3.5 s. H_{m0} ~ 22 and ~ 20 cm (model scale) at the most offshore gauge.

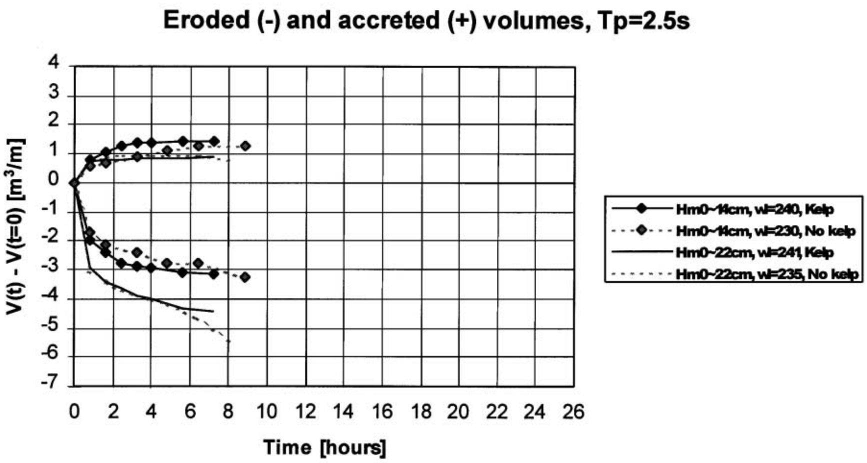

Fig. 12. Eroded and accreted volumes for Tp = 2.5 s. $H_{m0} \sim 14$ and ~ 22 cm (model scale) at the most offshore gauge.

level after each wave run is higher than indicated by the remaining sand volume. This also means that less sand is moved offshore than indicated by the differences between eroded and accreted sand volumes.

However, as this study is more concerned with the effect of kelp on dune erosion and differences between presence and absence of kelp conditions, this issue is not pursued further. It would also be difficult, as it must be expected that the initial compactness also varies somewhat and it would anyway require special and time-consuming tests, as obtaining samples to measure compactness/density would destroy the beach/dune profile.

The source data for the evaluation of erosion are the laser profiles. As these are only reliable above the water level, the focus of this section is changes in eroded and accreted sand volume above the water level and changes between the initial and final profile when the water was drained from the flume. Figs. 4–9 show the changes in the median profile for all time steps. Except for the initial and final profiles only the part above the stillwater level is included.

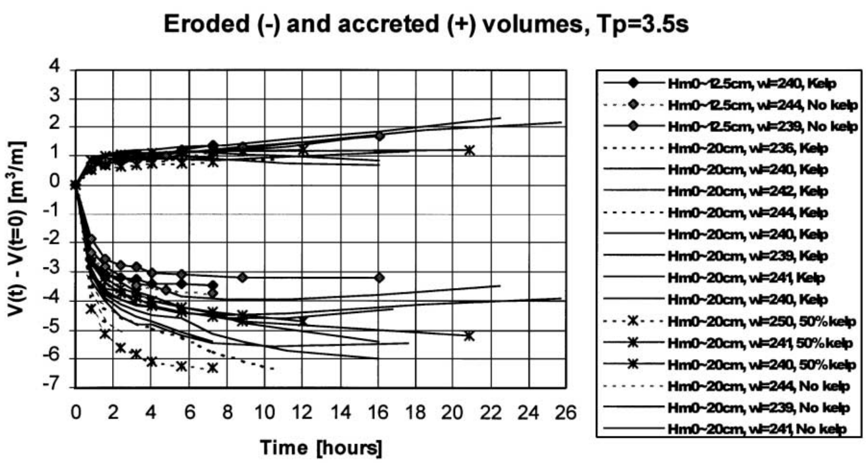

Fig. 13. Eroded and accreted volumes for Tp = 3.5 s. $H_{m0} \sim 12.5$ and ~ 20 cm (model scale) at the most offshore gauge.

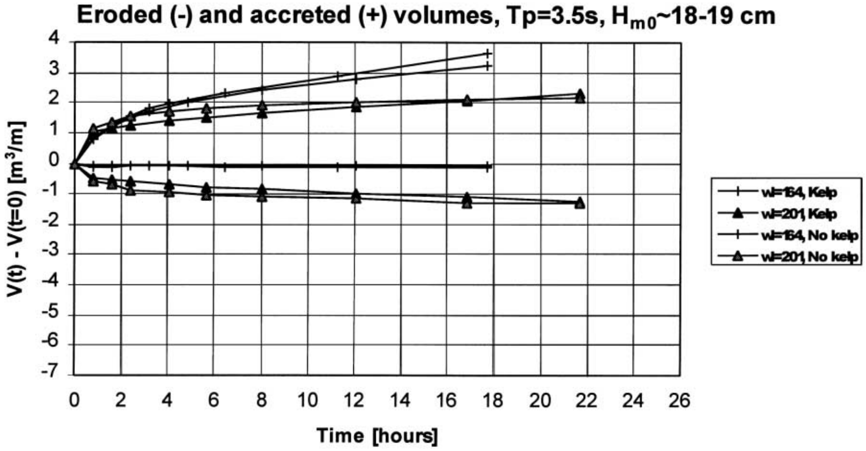

Fig. 14. Eroded and accreted volumes for Tp = 3.5 s. $H_{m0} \sim 18$ cm and ~ 19 cm (model scale) at the most offshore gauge, and the stillwater level is about 30 and 70 cm below the dune foot (full scale).

Figs. 10–15 show the changes in eroded and accreted volumes as a function of time.

The figures are intended to reveal differences due to different wave period, offshore wave height and stillwater level. The wave period is specified by the target peak period (Tp), the offshore wave height by the amplitude amplification factor (e) (wave generator setting), and the stillwater level (wl) by using the same millimetre scale as the vertical axis in the median profile figures. The offshore wave height varies somewhat by wave period and water level and the approximate median values are shown in Table 2. The profile figures are shown in a model scale based on the millimetre values provided by the laser, while in the volume figures the volumes and time have been converted to full scale using Froude scaling.

For the smallest tested wave heights ($H_{m0} \sim 12.5$ cm and $H_{m0} \sim 14$ cm), Figs. 4 and 5 show little difference between the "Kelp" and "No kelp" cases. The slope in the swash zone is only slightly steeper without kelp in the flume. There is more difference due to the wave period, especially below the stillwa-

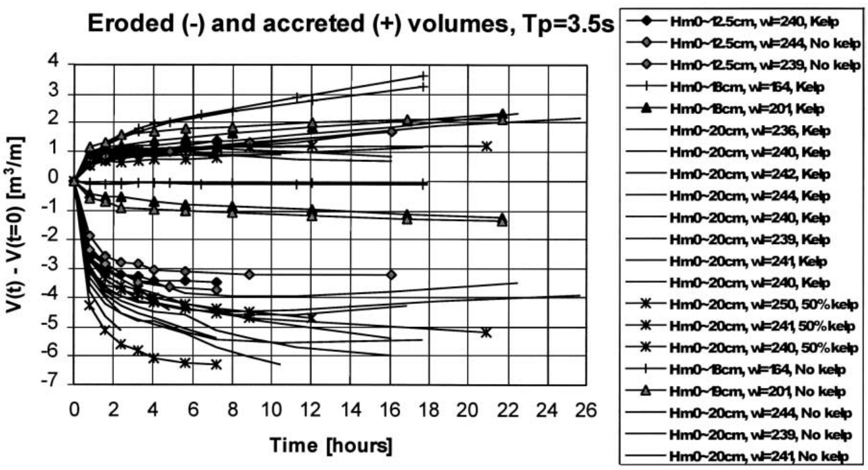

Fig. 15. Eroded and accreted volumes for Tp = 3.5 s. $H_{m0} \sim 12.5$ and ~ 18–20 cm (model scale) at the most offshore gauge, and the stillwater level is just above and about 30 and 70 cm below the dune foot (full scale).

Table 2
Variation in offshore wave height (H_{m0}, median values)

Tp (s)	e	wl (mm)	H_{m0} (cm)
2.5	2.0	~ 240	14
3.5	2.0	~ 240	12.5
2.5	3.5	~ 240	22
3.5	3.5	~ 240	20
3.5	3.5	201	19
3.5	3.5	164	18

ter level. A berm is formed at the seaside of the swash zone when there is kelp in the flume and also for Tp = 2.5 s without kelp. For Tp = 3.5 s without kelp in the flume a berm is not visible. The difference in the location of the berm indicates that the swash zone is wider for Tp = 3.5 s than for Tp = 2.5 s. This is to be expected as the wave length also increases with wave period. For the highest waves tested (H_{m0} ~ 22 cm and H_{m0} ~ 20 cm), a berm is also formed for Tp = 2.5 s when there is kelp in the flume (Fig. 6). The most shoreward berm is formed when the water depth is lower (wl = 225). For Tp = 3.5 s (Fig. 7) no berm is observed within the area covered by the laser. Except for the formation of a berm or not, the main difference due to kelp is found in Fig. 7 where the slope formed is less steep with kelp in the flume. As the final profiles with kelp is generally located above the ones without kelp, it seems that more of the sand eroded from the sand dune is found in the slope with kelp in the flume. The 50% kelp profiles are located between the "Kelp" and "No kelp" profiles, except for the profile with the highest water level (wl = 250), which shows the most erosion in the top part of the sand dune. The profiles for the two lower water depths (Figs. 8 and 9) show a similar picture with less erosion below the water line and a less steep slope with kelp in the flume. Fig. 9 shows that for this water level (wl = 164), where the wave run-up barely reaches the sand dune, the waves erode slightly higher up in the sand dune without kelp in the flume.

Fig. 10 shows the effect of wave period upon eroded and accreted volumes for the smallest tested waves. The differences due to kelp or wave period are small. Fig. 11 shows larger differences due to percentage of kelp in the flume. The dashed lines show results of tests where the stillwater level deviated more than 3 mm (model scale) from wl = 240. As seen the highest water level (wl = 250) gives most erosion despite 50% kelp in the flume. Vellinga (1986) found that a period of about 5 h with constant hydraulic conditions equal to the maximum in the North Sea storm hydrograph gives similar erosion quantities as a naturally varying North Sea storm hydrograph. A period of 8–10 h is therefore equal to the duration of about two storms with maximum wave heights similar to the ones used in the experiments. The experiments show that for tests with sufficiently equal water level, there is clearly less erosion and more accretion with kelp in the flume

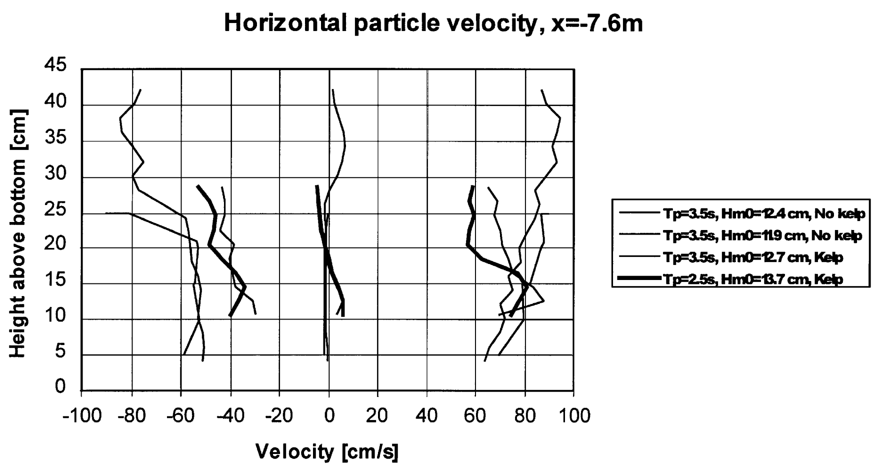

Fig. 16. Minimum, mean and maximum horizontal particle velocities in the shoreward part of the kelp field. Local stillwater level ~ 34 cm.

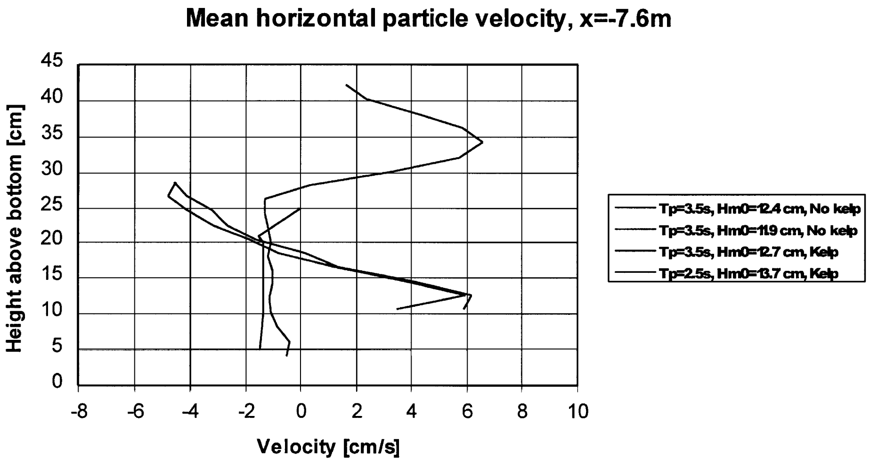

Fig. 17. Mean horizontal particle velocities in the shoreward part of the kelp field. Local stillwater level ~ 34 cm.

from 8 to 10 h. A negative rate of change of eroded volume means that there is less erosion than accretion in the upper part of the slope (the part defined as eroded area, see Section 5). Similarly, a negative rate of change of accreted volume mean that sand build up in the lower part of the slope (the part defined as accreted area, see Section 5) is being eroded. Without kelp in the flume, the eroded volume continues to increase beyond 8 h while the accreted volume starts to decrease. This indicates a net offshore transport of sand from the sand dune. With kelp in the flume the picture is the opposite, as after 8–10 h the eroded volume decreases and the accreted volume increases. This indicates that the sand eroded from the sand dune remains in the beach slope and the beach in general is being rebuilt. With 50% kelp in the flume the eroded volume continues to increase while the accreted volume remains the same. Hence, also for this case there is a net offshore transport of sand from the sand dune.

Fig. 12 shows the effect of the offshore wave height for Tp = 2.5 s, while Fig. 13 shows the same

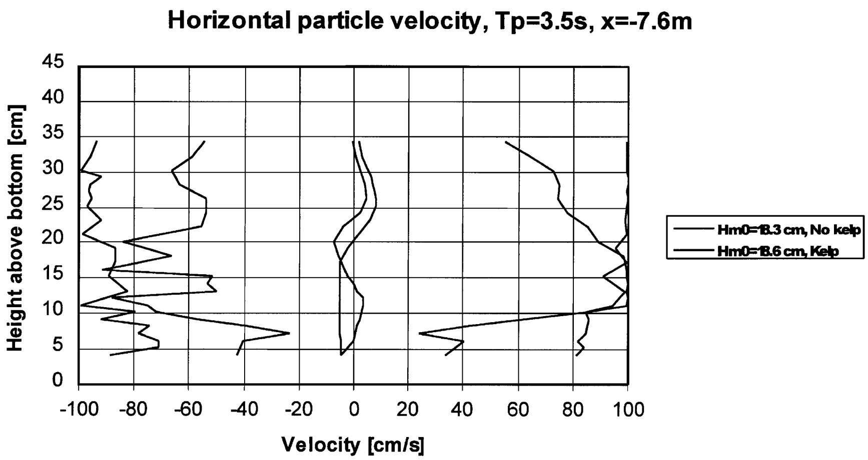

Fig. 18. Minimum, mean and maximum horizontal particle velocities in the shoreward part of the kelp field. Local stillwater level ~ 26 cm.

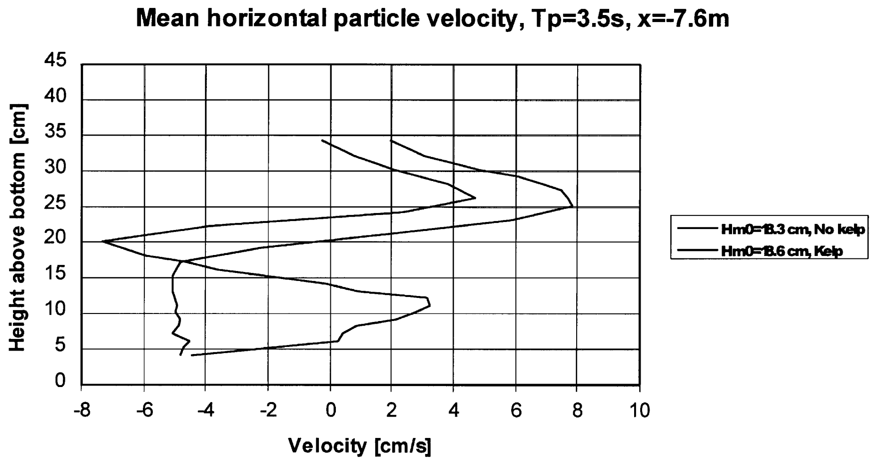

Fig. 19. Mean horizontal particle velocities in the shoreward part of the kelp field. Local stillwater level ∼ 26 cm.

information for Tp = 3.5 s. As expected there is less erosion with lower offshore wave height, and the accretion is higher. For Tp = 3.5 s the accreted volume continues to increase beyond 8 h for lower offshore wave height also without kelp in the flume.

Fig. 14 shows the effect of reduced water level, while Fig. 15 shows the effect of both water level and offshore wave height for Tp = 3.5 s. For the two lower water levels (about 30 and 70 cm below the dune foot; full scale) there is considerably less erosion and more accretion than when the water level is just above the dune foot. The effect of the kelp is, however small, but the slightly higher accretion rates indicate a faster build-up of the beach with kelp in the flume. The figures also show that the effect of the reduced water level is much greater than the effect of lower offshore wave height, even though the reduction in offshore wave height (∼ 80 cm full scale) is comparable to the reduction in water level (∼ 40 and ∼ 80 cm full scale).

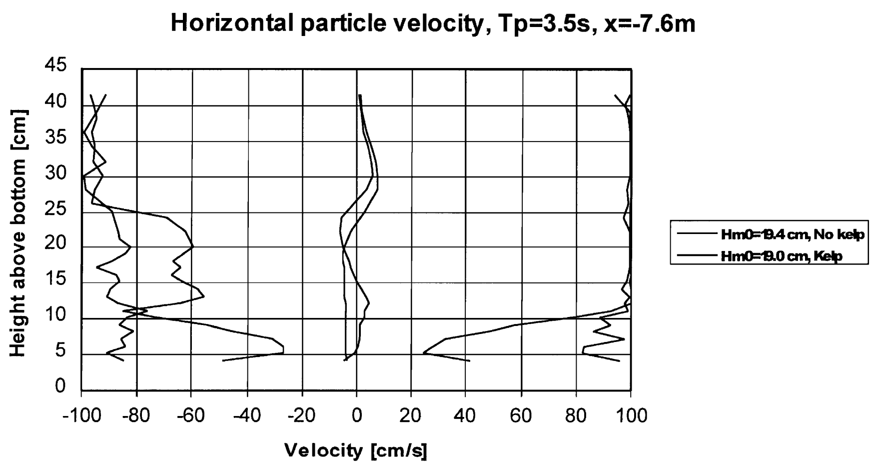

Fig. 20. Minimum, mean and maximum horizontal particle velocities in the shoreward part of the kelp field. Local stillwater level ∼ 30 cm.

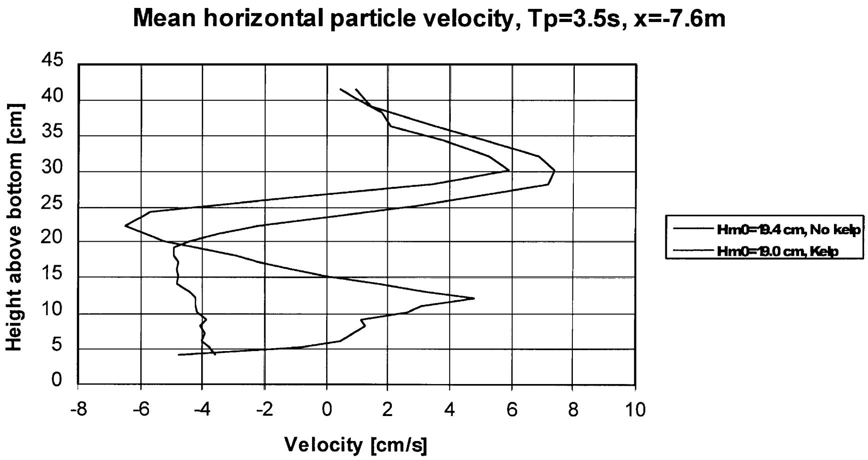

Fig. 21. Mean horizontal particle velocities in the shoreward part of the kelp field. Local stillwater level ~ 30 cm.

6.2. Particle velocities

The theoretical models on wave damping are based on a Morison force formulation (Morison et al., 1950) with an assumption of some reduction of the water particle velocities within the vegetation, e.g. Asano et al. (1993), Dubi (1995). But how valid is this assumption? In order to throw some more light on this issue, water particle measurements were carried out above and in between the kelp plants.

This section focuses then on how the presence of kelp affects water particle velocities. For simplicity and because it does not affect the findings, all quantities are shown in model scale. Using Froude scaling, all length scales should be multiplied by 10 and all velocities by the square root of 10 to convert to full scale.

Figs. 16–23 show mean, minimum (maximum seaward) and maximum (maximum shoreward) horizontal Eulerian velocity profiles for different water

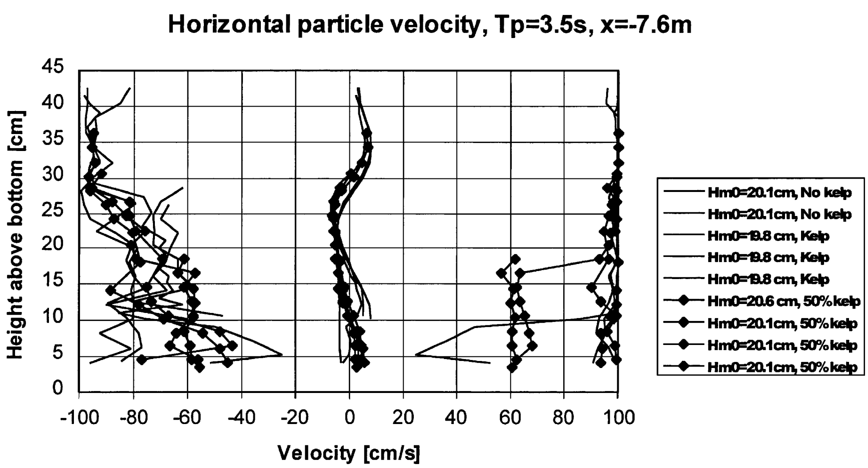

Fig. 22. Minimum, mean and maximum horizontal particle velocities in the shoreward part of the kelp field. Local stillwater level ~ 34 cm.

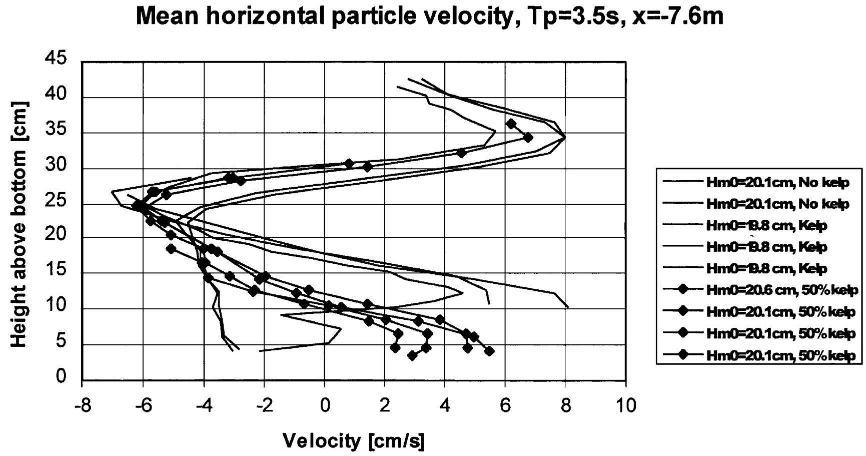

Fig. 23. Mean horizontal particle velocities in the shoreward part of the kelp field. Local stillwater level ~ 34 cm.

levels and wave conditions when the ADV sensor was located about 1.5 m seaward of the shoreward end of the kelp field. The legend for each curve shows the median H_{m0}-value as derived from the sea surface elevation time series at the offshore gauge. Figs. 24–27 show the same information when the ADV sensor was located about 0.3 and 4 m shoreward of the kelp field. Figs. 28–31 show mean, minimum (maximum downward) and maximum (maximum upward) vertical Eulerian velocity profiles for different water levels when the ADV sensor was located about 1.5 m seaward of the shoreward end of the kelp field. Figs. 32 and 33 show the same information when the ADV sensor was located about 0.3 m shoreward of the kelp field. The velocity profiles were prepared by taking the minimum, mean and maximum values from the entire time series at each level the ADV was located. However, the ADV can only produce reliable results when the sensor is submerged in water (and there is sufficient seeding

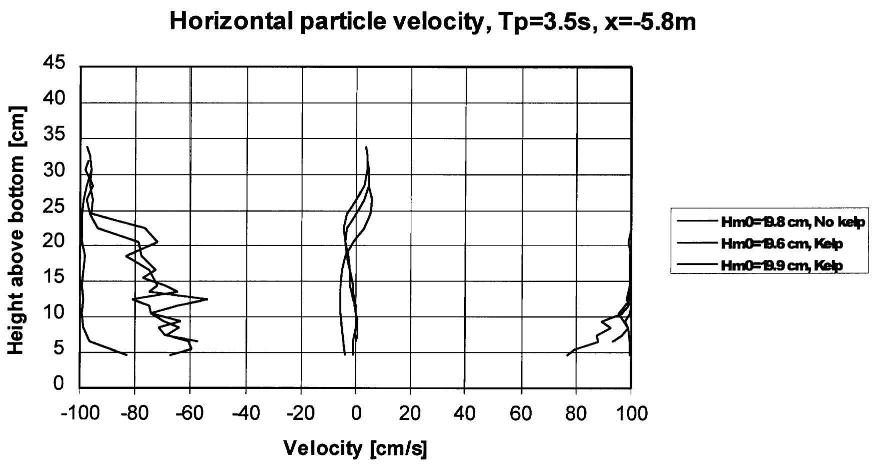

Fig. 24. Minimum, mean and maximum horizontal particle velocities about 0.3 m shoreward of the kelp field. Local stillwater level ~ 28 cm.

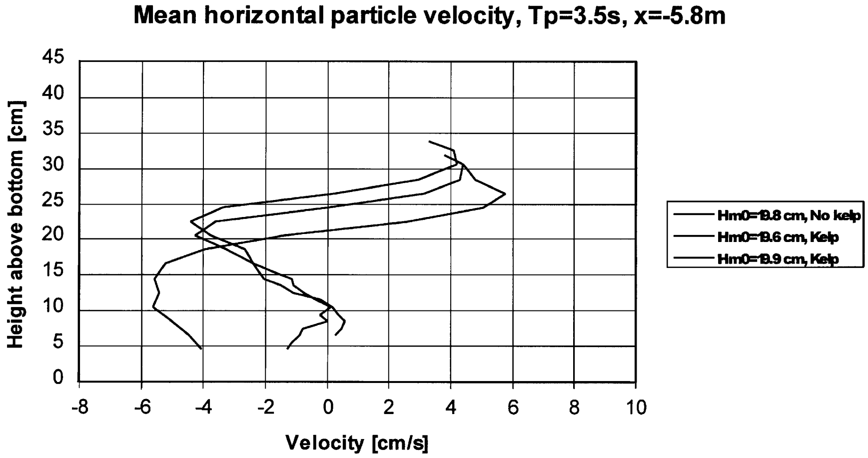

Fig. 25. Mean horizontal particle velocities about 0.3 m shoreward of the kelp field. Local stillwater level ~ 28 cm.

material in the water). When the ADV is above water only noise is measured. The part of the minimum and maximum velocity profiles where noise affects the measurements has not been removed. Hence, maximum velocities are not reliable when the ADV is located above the wave crest and minimum velocities are not reliable when the ADV is located above the wave trough. The mean values from a time series when the ADV is above the water level in parts of the time series are therefore a mean of real values and noise. The mean values are therefore only useful if one can assume that the mean of the noise is zero. The figures show that this is a reasonable assumption. Another problem with the ADV measurements was that only values within the range ± 100 cm/s was saved on file. The ADV software did however display the real measured values on the monitor and horizontal particle velocities up to 160–180 cm/s were observed. As the maximum velocities occur below the wave crest, this means that the

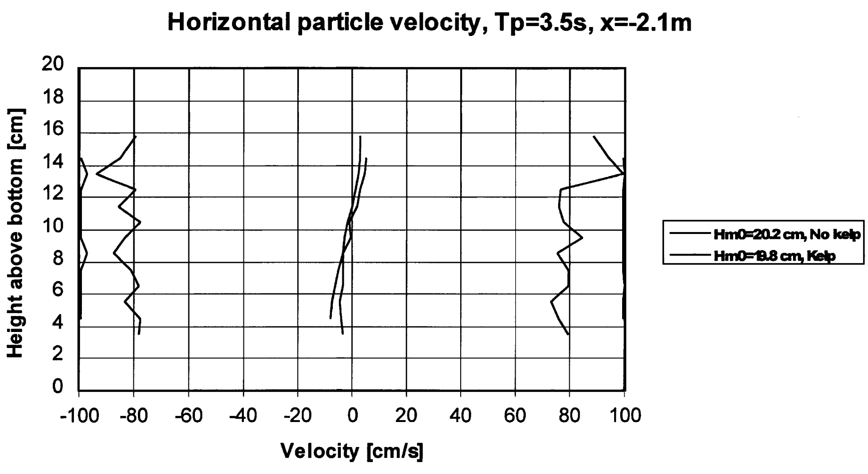

Fig. 26. Minimum, mean and maximum horizontal particle velocities about 4.0 m shoreward of the kelp field. Local stillwater level ~ 16 cm.

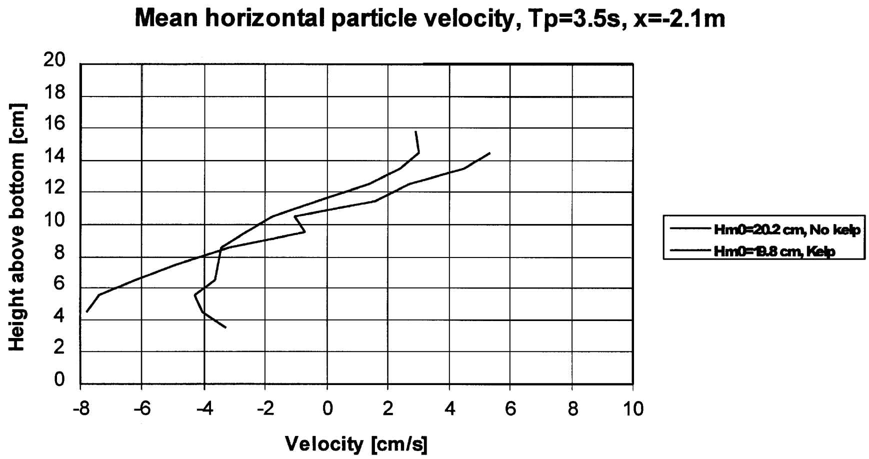

Fig. 27. Mean horizontal particle velocities about 4.0 m shoreward of the kelp field. Local stillwater level ~ 16 cm.

mean values are somewhat low when the ± 100 cm/s range was exceeded (as then only ± 100 cm/s would be recorded in the file).

The figures show both expected and "unexpected" results. Looking first at the smaller of the tested waves, Fig. 16 shows how the extreme velocities decrease, as expected, toward the bottom when there is no kelp in the flume. Fig. 17, which enables a closer look at the mean horizontal velocity profile, shows the expected shoreward velocities in the region between wave crest and wave trough and seaward velocities (undertow) below the wave trough. Also Figs. 18–27 show similar shape of the horizontal velocity profiles without kelp in the flume. When there is kelp in the flume the picture is quite different. The maximum (and minimum) velocities are higher just above the kelp layer than higher above the bottom. It is also seen that the maximum seaward velocities are smaller compared to the maximum shoreward velocities when there is kelp in the flume. In the figures where the kelp velocity profiles contain data above the stillwater level, it is seen that the

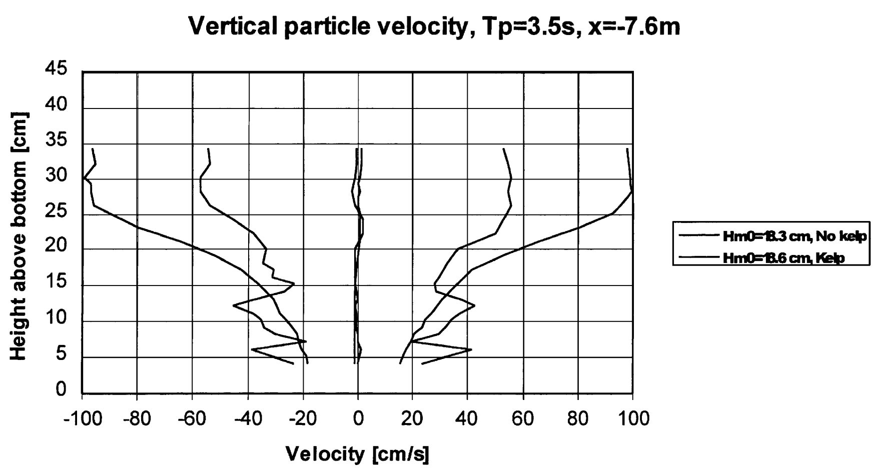

Fig. 28. Minimum, mean and maximum vertical particle velocities in the shoreward part of the kelp field. Local stillwater level ~ 26 cm.

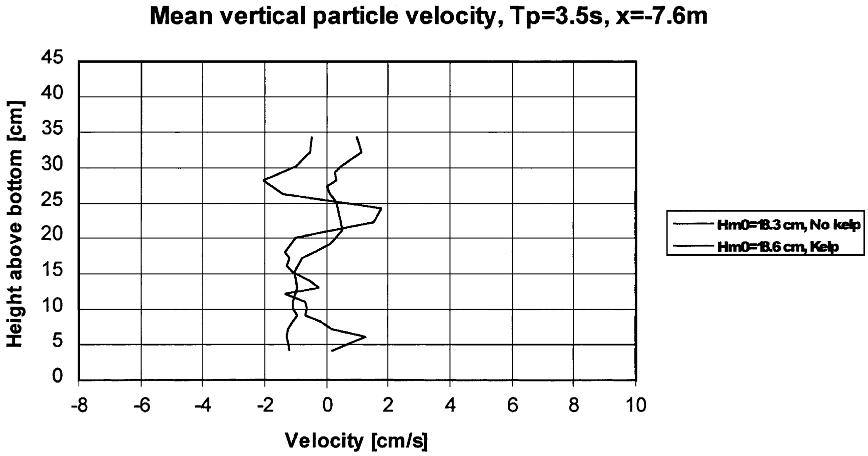

Fig. 29. Mean vertical particle velocities in the shoreward part of the kelp field. Local stillwater level ∼ 26 cm.

onshore mean velocity above the kelp layer is about the same magnitude as above the wave trough. For the shallowest water depth tested (Figs. 18 and 19), the maximum velocity is even higher 10–25 cm above the bottom than in the crest region. As water particles have a tendency of following the “path-of-least-resistance”, the observation that the streamlines near the top of a dense vegetation layer are deflected to the region just above the vegetation is actually what one might expect. An effect of this is also that the undertow is confined to a narrower depth region and the magnitude is therefore larger than without kelp. In the figures including velocity measurements closer than 10 cm to the bottom, the minimum and maximum horizontal velocity curves show a minimum (meaning closest to zero) at a level of 5–7 cm above the bottom. This probably corresponds to the vertical distance from the bottom to canopy layer when the plants are bent.

The velocity profiles showing higher velocities above the kelp layer also show that one cannot estimate energy dissipation due to kelp by just ac-

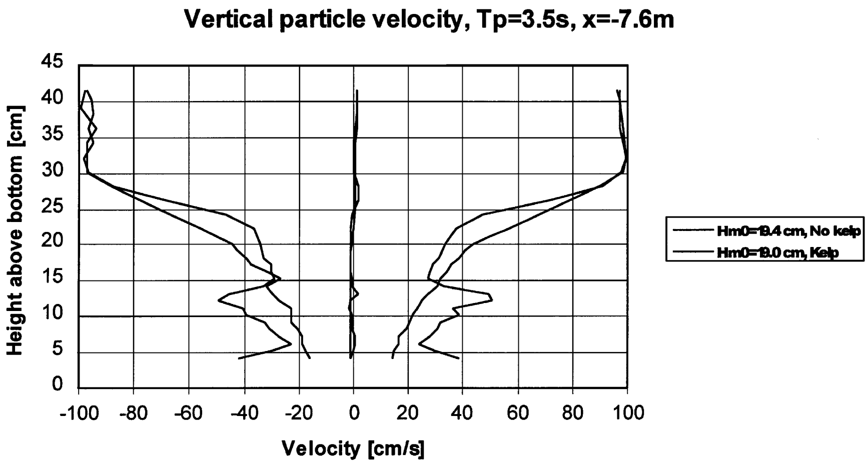

Fig. 30. Minimum, mean and maximum vertical particle velocities in the shoreward part of the kelp field. Local stillwater level ∼ 30 cm.

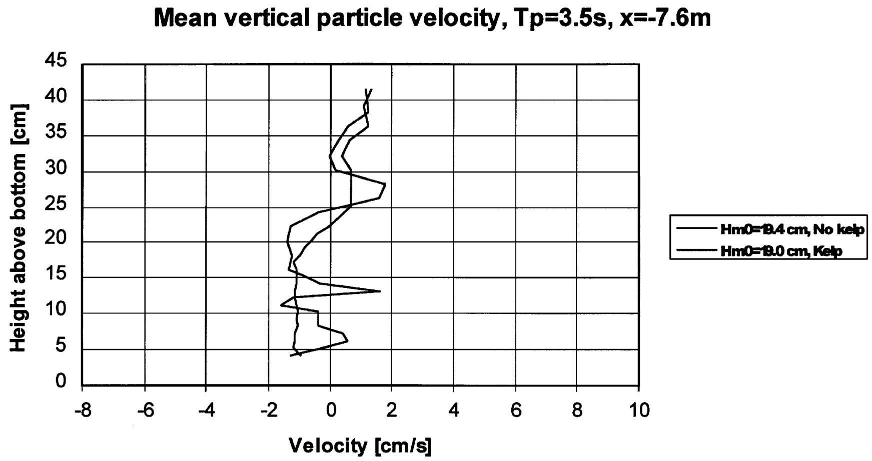

Fig. 31. Mean vertical particle velocities in the shoreward part of the kelp field. Local stillwater level ∼ 30 cm.

counting for energy loss in the vegetation layer. Some of the energy loss in the canopy layer zone is due to the deflected streamlines causing increased kinetic energy above the vegetation layer.

Figs. 22 and 23 also includes velocity profiles from the tests when every other 48.5-cm kelp plate was removed from the flume. In the first two 50% kelp tests, the ADV was located 7–8 cm before a kelp plate. To reduce any effects of the kelp plates, the ADV was moved to 15 cm before the kelp plate for the next two 50% kelp tests. The effect of moving the ADV is seen in the maximum velocity profiles, but less in the mean velocity profiles. Despite being located in a kelp-free area, the mean velocity profile with 50% kelp have similar shape as the profiles when all the kelp plates are present in the flume. The main difference is that close to the bottom, the maximum onshore velocities are located 4–7 cm above the bottom, compared to 10–13 cm with 100% kelp. As seen in Figs. 24 and 25 the effect of kelp upon the horizontal velocity profile is also observed 30 cm shoreward of the kelp field. The

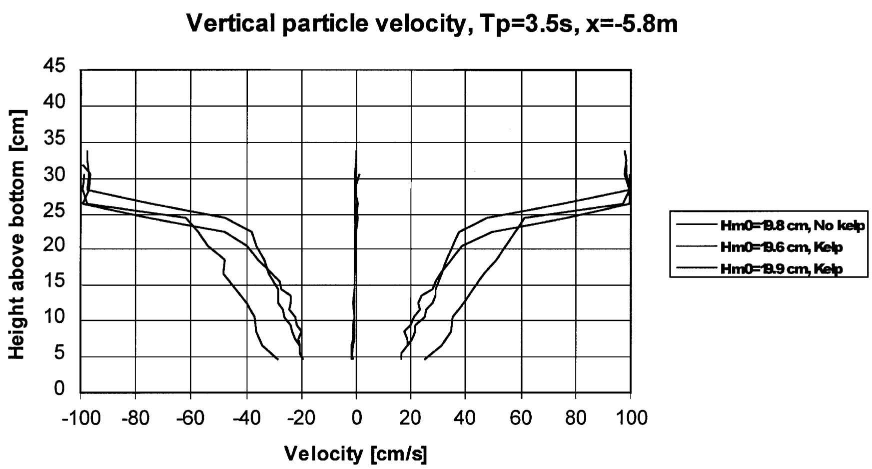

Fig. 32. Minimum, mean and maximum vertical particle velocities about 0.3 m shoreward of the kelp field. Local stillwater level ∼ 28 cm.

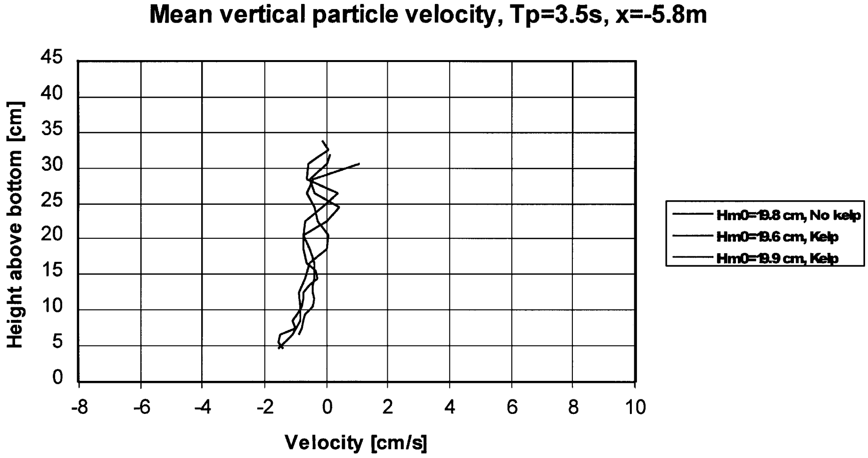

Fig. 33. Mean vertical particle velocities about 0.3 m shoreward of the elp field. Local stillwater level ~ 28 cm.

level where the maximum velocities are observed is somewhat lower than in the kelp forest, and this is in line with the measurements with 50% kelp. Even 4 m shoreward of the kelp field (see Figs. 26 and 27) there is a difference in the horizontal velocity profile with and without kelp in the flume.

Figs. 28–31 show vertical velocity profiles within the kelp field for the two lower water levels. In the upper part of the water column the vertical velocities are lower with kelp in the flume. However, in a region above and below the canopy layer, both the maximum upward and downward velocities are

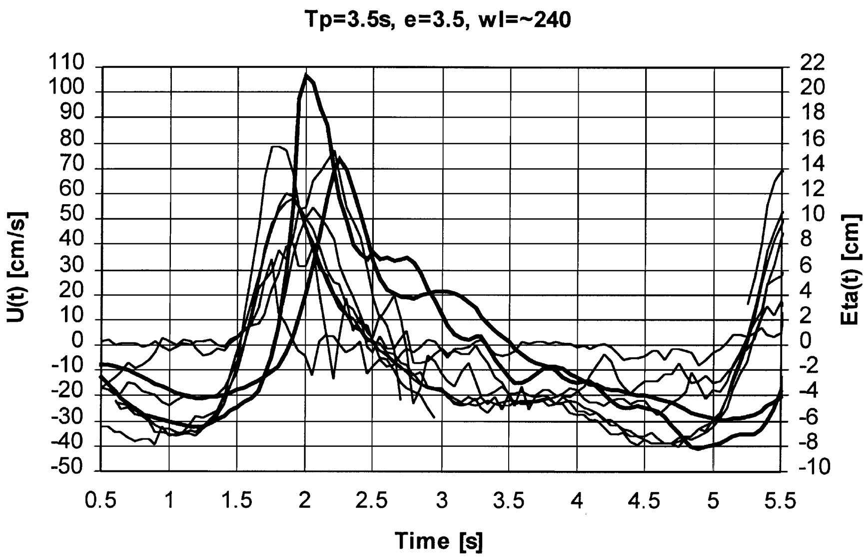

Fig. 34. Comparison of horizontal particle velocities and surface elevation; with and without kelp in the flume. The velocities are from below, in and just above the kelp canopy layer and just above the stillwater level. The surface elevations (thick lines) are from the gauge shoreward of the ADV. The darker lines show results from test series without kelp in the flume.

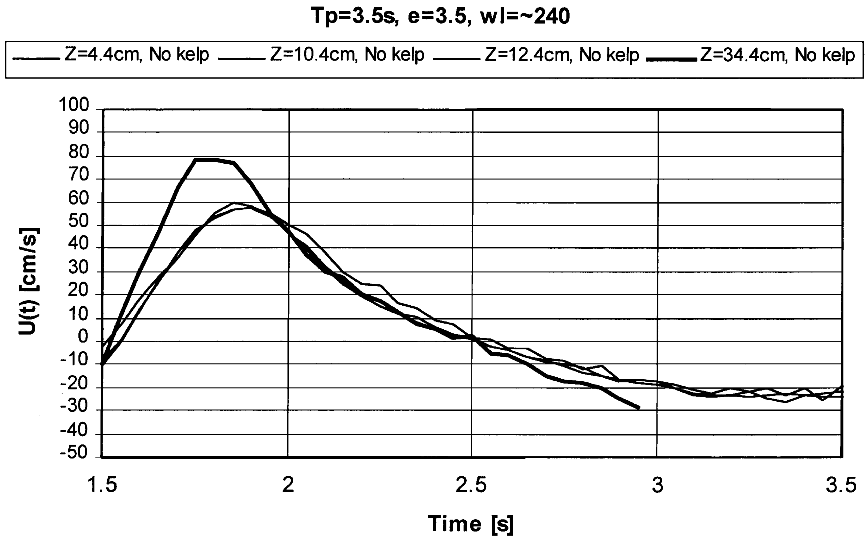

Fig. 35. Comparison of horizontal particle velocities without kelp in the flume. The velocities are from below, in and just above the kelp canopy layer and just above the stillwater level.

higher than without kelp in the flume. This is another indication of turbulent boundary layers. In the location 30 cm shoreward of the kelp field (Figs. 32 and 33), there is less difference due to kelp, but the maximum upward and downward velocities are lower up to the wave trough level with kelp in the flume.

As the control signal is the same and the wave generator starts in the same location for all tests, it is also possible to look at phase differences between time series. Fig. 34 shows how the wave passes the ADV (and the wave gauge) earlier without kelp in the flume than with. The wave is also higher without

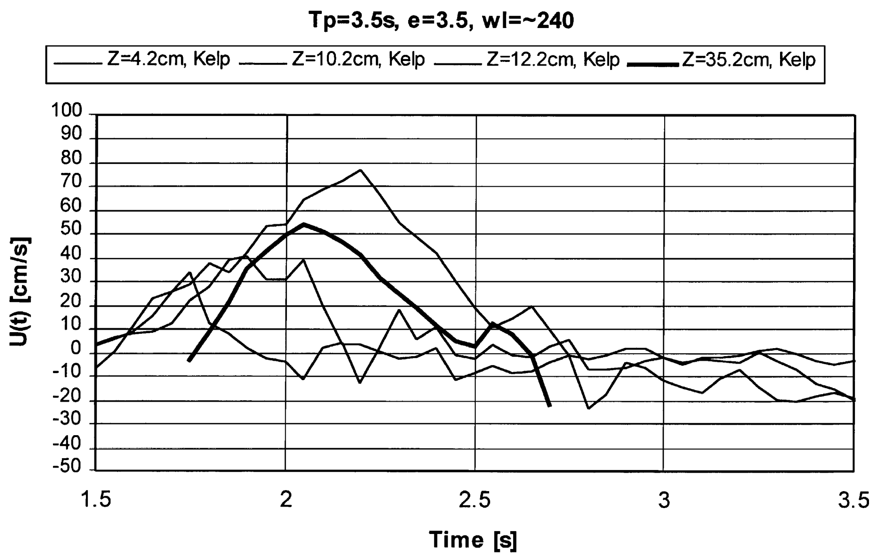

Fig. 36. Comparison of horizontal particle velocities with kelp in the flume. The velocities are from below, in and just above the kelp canopy layer and just above the stillwater level.

kelp in the flume. It is also seen that except for the crest region the horizontal particle velocities are about the same for all depths without kelp in the flume. With kelp in the flume the velocity time series show more fluctuations (partly noise, and partly turbulence), but they also show how the velocities differ at the different depths during the entire wave cycle. To enable a closer study of the velocity, Fig. 35 shows velocity time series without kelp in the flume while Fig. 36 shows velocity time series with kelp in the flume. From the level above the still water level, only velocities measured when the ADV was submerged is included. Fig. 35 shows as expected highest maximum velocities near the water surface and smaller velocities towards the bottom. There is also a phase delay from the wave crest towards the bottom. When there is kelp in the flume the picture is quite different. When the wave approaches the ADV, the velocity near the kelp layer starts to increase before the velocity near the stillwater level. For this wave, the maximum velocity at about 12 cm above the bottom is even higher than the maximum velocity near the stillwater level, but this is not always the case. As it can be assumed that the wave crest passes the ADV about when the velocity near the stillwater level is at its maximum, Fig. 36 also shows that the maximum velocity at about 12 cm above the bottom is reached after the wave crest has passed the ADV. It is also seen that the velocity at about 10 cm above the bottom reaches its maximum long before the wave crest passes the ADV. The reason might be that the kelp has swayed to its most extreme position and the dense canopy layer blocks the passage of water at this level.

7. Discussion and conclusions

7.1. Dune erosion

Results from experiments with various combinations of initial wave height, water level and wave period are presented. The initial wave height varies with water level, but for the water levels used in these tests the variation is so small that the initial wave height is treated the same as long as the wave amplitude amplification factor (e) is the same. This means that there are two initial wave height cases, identified by $e = 2.0$ ($H_{m0} \sim 12$–14 cm) and $e = 3.5$ ($H_{m0} \sim 18$–22 cm). The tests also comprised two wave periods: Tp = 2.5 s and Tp = 3.5 s. The water levels used (~ 240, 201, and 164) are thought to represent, respectively, the highest water level observed at Jæren (~ 90 cm above mean high water), and ~ 50 and ~ 10 cm above the mean high water at Jæren (see also Section 3.2).

The experiments confirm that the water level is very important to sand dune erosion. One reason is, e.g. as along the Jæren coastline, where the beaches are rather flat shoreward of the berm crest, until close to the sand dune where the beach slope steepens. Hence, when the water level rises above the berm crest, the distance from the shoreline to the foot of the sand dune decreases rapidly. Another reason why the water level is so important to dune erosion is the variations in the height and velocity of the water front as it rushes up the beach (Løvås and Tørum, 2000), and hence the variations in the swash force (Overton et al., 1988).

The experiments also showed that when the water level is high enough to enable severe damage to a sand dune, a kelp field in less shallow water (water depth > about 2.5 m) does not significantly affect the level of initial damage. Given successive storms, without significant rebuilding in between, the presence of kelp reduces the time until an equilibrium is obtained and dune erosion ends. The level of damage is then reduced.

7.2. Particle velocities

The laboratory experiments presented in this paper have shown that the presence of kelp has a major effect on Eulerian water velocity profiles, especially in the region from the sea bottom up to about two times the kelp height. Without kelp in the flume the horizontal velocity profiles are as expected, with shoreward time-averaged water velocity above the wave trough and a seaward undertow below. With kelp in the flume there is a time-averaged horizontal water velocity in the shoreward direction also in the region above the kelp canopy layer, while the undertow is confined to a region higher up in the water column.

Price et al. (1968) carried out laboratory and field experiments using artificial seaweed and they reported a net drift near the bed in the direction of wave propagation, i.e. towards the shore. They also reported net onshore sediment transport with artificial seaweed in the wave flume. The field experiments were partly destroyed by several severe storms, but despite the storms a small increase in the sand level was found in the lee of the artificial seaweed installation.

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