EFFECT OF SUBMERGED VEGETATION UPON WAVE DAMPING AND RUN-UP ON BEACHES:
A case study on *Laminaria Hyperborea*

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Abstract

Effect of submerged vegetation upon wave damping and run-up on beaches have been studied using laboratory experiments. 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. The majority of the laboratory experiments were run with an experimental setup intended to represent conditions along sandy beaches along the Jæren coast in southwestern Norway. Two experimental setups were used. One with fixed sloping concrete bottom and one with sand shaped to represent the cross-shore area from offshore of breaking to somewhat beyond the dune top. A kelp field was simulated by 5000 artificial kelp plants in scale 1:10. When sand was present in the flume the kelp forest was put in the deeper part of the surf zone, giving a kelp-free area near the shoreline. The experiments confirmed that kelp reduces wave heights, and they also showed that the wave damping due to the kelp reduces wave breaking. It was also found that the breaking process reduces wave heights more rapidly than kelp. For a situation with kelp growing in less shallow water (water depth > about 2.5 m) a lot of the wave breaking takes place inshore of the kelp field for the wave conditions tested (H_{m0} <~ 2.5 m). The difference in wave heights with or without kelp was found to be minor in very shallow water. When the kelp grows in very shallow water (< about 2 m), run-up on a beach was also reduced with kelp in the flume.

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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. 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 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-sixties, the use of a kelp trawl was sufficiently successful to organize 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 harbors and increased erosion of sandy beaches and dunes as a result.

This paper is partly based on a reanalysis of data from laboratory experiments carried out by Kansy (1999) and is reported in more detail by Løvås (2000).

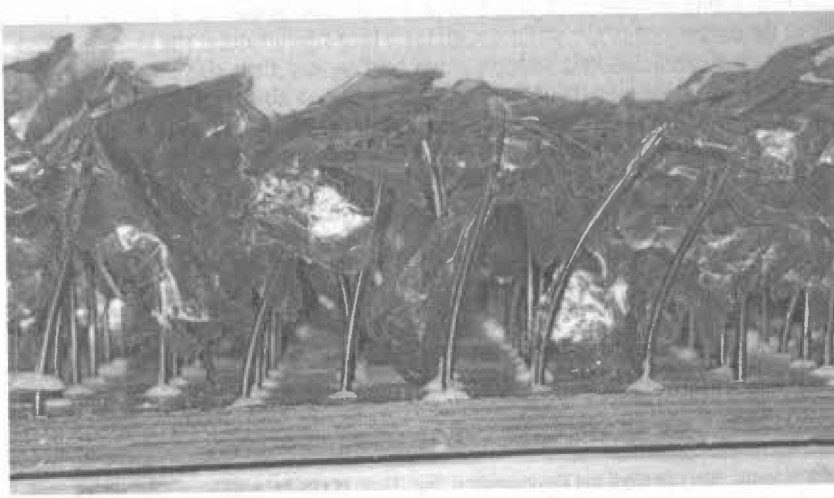

Figure 1 Model kelp plants

LABORATORY EXPERIMENTS

As part of a previous Ph.D. study (Dubi, 1995) 5000 model kelp plants were prepared. These plants were designed to replicate kelp plants sampled in the field and 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. 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 x 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 Figure 1). This technique reduced the efficient height of the stipes to approximately 9 cm.

The laboratory experiments with irregular waves on a solid slope were carried out in a 60-cm wide channel separated from the rest of a 40-m x 5-m wave flume by a plywood wall. The reason for this setup was to get uniform conditions across the 60-cm wide plywood plates (with or without model kelp plants). A surf zone was simulated by a slope of gradient 1:30 beginning at 12 m from the wave maker. Six cantilever conductivity wave gauges measured the surface elevation and two parallel wires acting as one stretched conductivity wave gauge measured the run-up at the beach. One wave gauge was located "offshore" and one shoreward of the kelp field, while the remaining four gauges were distributed along the kelp field (see Figure 2). The test program considered random wave simulations for five different peak periods. The selected peak periods represent 7.9 s – 14.2 s in full scale. The control signals for the wave generator are based on the JONSWAP spectrum with a γ-value of 3.3. While the variation of the wave heights is set by the control signal, the magnitude of the surface elevations are controlled by setting an amplitude amplification factor, e. A higher e-value gives higher waves.

After completing the experiments with solid sloping bottom, sand was put on top of the concrete, and in the upper part the sand was formed into a beach and a sand dune. The kelp field was also moved to the deeper part of the slope and the water depth was increased to simulate maximum storm surge level. The 9 cm model kelp plants were now located from about 30 to 50 cm depth giving a kelp height to water depth ratio of 0.3 to 0.18, which is the same as in prototype when the high water level in the model is taken into account. The distance from the shoreline to the kelp field and the length of the kelp field in the model represents about 65 m and 70 m (1:10 scale), which is smaller than in prototype. 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 m and 6.6 m. The maximum 'offshore' wave heights obtained in the model represent about 3.2 m in prototype scale and is hence somewhat 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) give a maximum wave height of 4.3 m (γ_b = 0.8), which is ~35% higher than in the model. The majority of the tests with this setup were run with a peak period of 3.5 s (11.1 s in full scale), and the number of wave gauges was increased to 9 along the slope.

RESULTS

The main energy dissipating process for waves propagating towards a shore is wave breaking. Visual observations during the experiments showed less wave breaking when kelp was present in the flume. The wave crests also moved slightly slower (lower celerity) with kelp in the channel. As the analysis of the time series did not show any increase in wave period over the kelp section, these observations indicate that although the wave lengths are reduced (lower celerity) the wave heights decrease even more since the reduced wave breaking is an indicator of lower wave steepness.

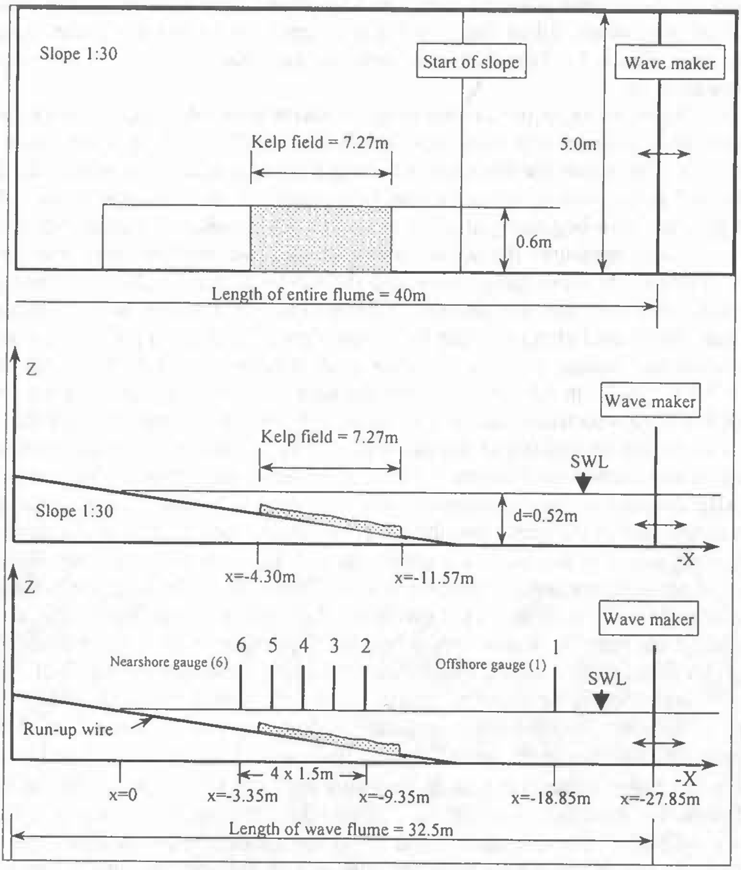

Figure 2 Wave flume layout. Top view and side view without/with instrumentation.

Wave height

Without kelp in the flume the H_{max}-values for all but the smallest waves are above the breaker-limit at all gauges along the slope (Figure 3, H_b based on Goda, 1974). The H_{max}-values of the smallest waves pass the breaker-limit between Gauge no. 3 and 5, which fits well with the maximum observed wave height. When there is kelp in the flume the largest waves are above the breaker height (Figure 4), while the H_{m0}- and H_s-values are below for all waves. These figures also show that although the range of H_{max}-values is very narrow at the innermost gauge without kelp in the flume, the scatter at the run-up

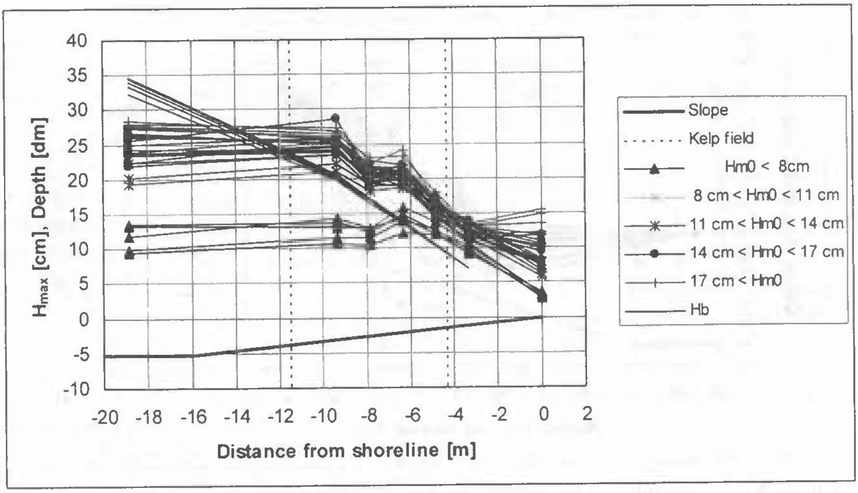

Figure 3 Variation in H_{max} towards the shore without kelp in the flume. The legend is based on the H_{m0}-values at the most offshore gauge.

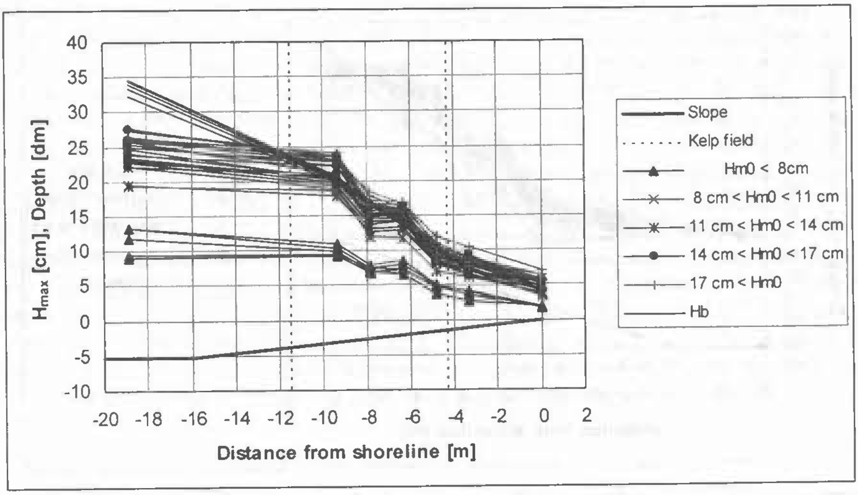

Figure 4 Variation in H_{max} towards the shore with kelp in the flume. The legend is based on the H_{m0}-values at the most offshore gauge.

wire is larger than with kelp. Hence, H_{max}-values after breaking does not seem to be a good indicator of the run-up. In general, at the run-up wire the scatter in the values of H_{max}, H_{m0} and H_s is less with kelp in the flume than without.

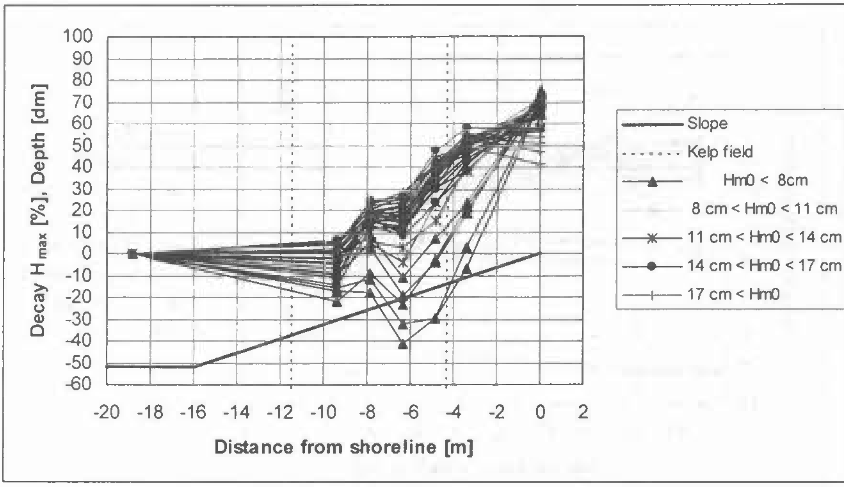

Figure 5 Relative reduction in H_{max} towards the shore without kelp in the flume. The legend is based on the H_{m0}-values at the most offshore gauge.

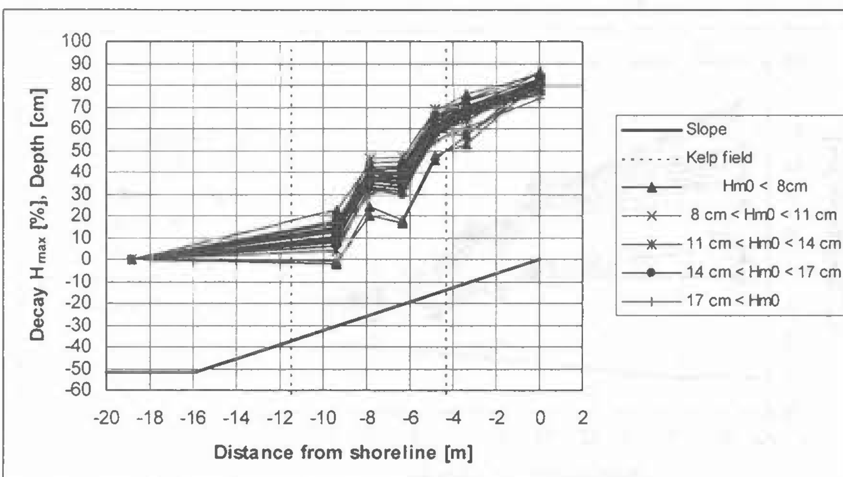

Figure 6 Relative reduction in H_{max} towards the shore with kelp in the flume. The legend is based on the H_{m0}-values at the most offshore gauge.

Figure 5 and Figure 6 show the relative reduction in H_{max}-values towards the shore without and with kelp in the flume. Due to shoaling H_{max} of the smallest waves increase (visualised as negative decay) up to more than 40% (without kelp in the flume) before they break, while with kelp there is hardly any increase at all. At the run-up wire the H_{max}-values are reduced by 80% ±6% with kelp in the flume, and between 41% and 76% without kelp. In general the smallest offshore H_{max}-values are reduced most, but the difference between Kelp and NoKelp conditions are greatest for the highest offshore H_{max}-values. This conclusion is the opposite of what would be the conclusion if one compared values from the gauges along the slope. This clearly shows the difficulty in isolating the effects of wave breaking, shoaling and the fixed kelp field on the wave transformation process along the slope.

The main purpose of putting a sand layer on the bottom of the slope was to study dune erosion. The change in wave height was however also studied. The values at each gauge represent the median from all test series with similar test conditions. All wave heights are given in model scale and should be multiplied by 10 to get full scale wave heights. The dotted lines shows the location of the kelp field when present in the flume, while the thicker black lines show the bottom slope and the breaker heights based on Goda (1974), In addition to the extreme cases with or completely without kelp in the flume a case with every other 48.5-cm plate removed was tested. This case was termed '50 % kelp' and was intended to show some effects of a kelp field with a significant amount of kelp trawling tracks.

Figure 7 shows changes in maximum down-crossing wave height (median values) for different 'offshore' wave heights for a model peak wave period (Tp) of 3.5 s. The legend shows H_{max} at the most offshore gauge, which was located at ~79 cm depth. The increase in wave heights at the gauge 2.5 m from the shoreline is due to wave reflection (incoming wave crest and the crest of the reflected wave met approximately at the gauge). It is clearly seen how the reduction of maximum wave heights begins in deeper water with kelp in the flume. The results for 50% kelp are closer to 100% kelp than without kelp in the flume. The figure also shows that at the shoreward end of the kelp field the difference in H_{max} with and without kelp in the flume is larger for the smaller waves. The reason seems to be the shoaling of the smaller waves without kelp in the flume. The differences decrease shoreward of the kelp field.

Figure 8 show the changes in H_{m0}. The differences at the shoreward end of the kelp field are about the same for the two settings of the wave amplification factor (e = 2.0 and 3.5). There is still a difference in H_{m0}-values at the most shoreward gauges. As the H_{m0}-values is an indicator the energy in the waves, this means that although the wave breaking rapidly reduces the differences observed in the shoreward end of the kelp field there is still an effect of kelp present close to the shore. As the energy in the waves is proportional to the square of the wave height, the differences in H_{m0} mean that the energy level is about 21% (e = 3.5, H_{m0} ~ 20cm in model scale) and 38% (e = 2.0, H_{m0} ~ 12cm) lower with kelp in the flume at the gauge about 4 m from the shoreline.

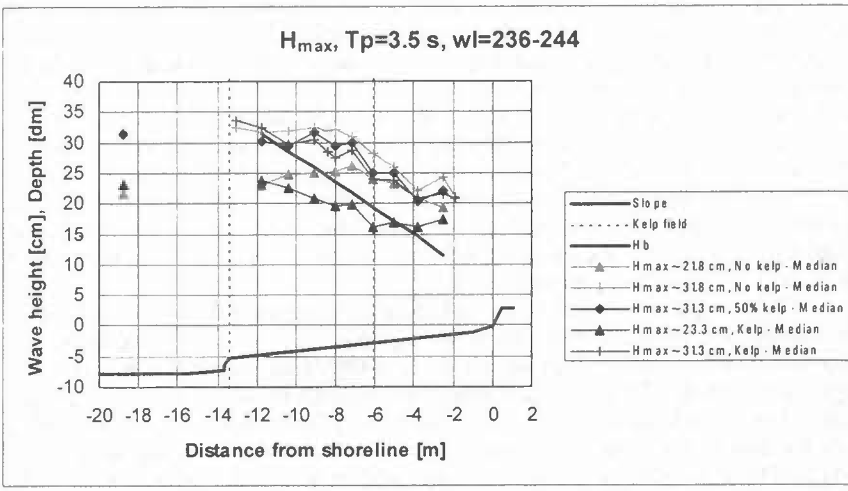

Figure 7 Changes in maximum (down-crossing) wave height for different initial wave heights when $Tp = 3.5$ s.

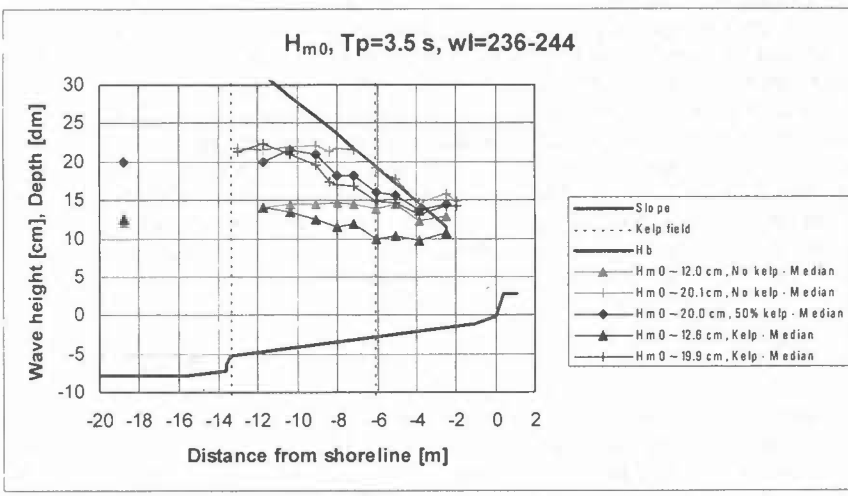

Figure 8 Changes in estimated significant wave height (H_{m0}) for different initial wave heights when $Tp = 3.5$ s.

Set-up/Set-down

Radiation stress is caused by the excess flow of momentum due to the incident wave field. From linear theory the radiation stress due to normally incident waves are estimated as (e.g. Dean and Dalrymple, 1984)

$$S_{xx} = E\left(2\frac{Cg}{C} - \frac{1}{2}\right) = \frac{1}{8}\rho g H^2\left(\frac{1}{2} + \frac{2kh}{\sinh[2kh]}\right) \quad (1)$$

showing that the radiation stress depends on wave height, wave length and local water depth. The variations in these parameters thus cause variations in radiation stress. A horizontal force balance between shoreward radiation stress, the pressure on the sloping bottom and bottom friction gives

$$\frac{\partial \overline{\eta}}{\partial x} = \frac{1}{\rho g(h+\overline{\eta})}\left(\overline{\tau}\frac{\partial h}{\partial x} - \frac{\partial S_{xx}}{\partial x}\right) \quad (2)$$

where $\overline{\eta}$ is the mean surface elevation (deviation from stillwater level). As the bottom friction (e.g. due to kelp) is directed against the propagation direction of the waves (positive x-direction) and the water depth decrease (negative slope), the bottom friction term is positive and causes the mean water level to rise (or decrease the fall). Outside the surf zone the wave heights increase due to shoaling and the *kh*-term also increases. Hence, the radiation stress increases and the mean water level falls (set-down). In the surf zone the wave breaking cause energy dissipation and decreasing radiation stress. The mean water level therefore rises. When the mean water level becomes higher than the stillwater level, the difference is termed set-up.

The mean set-up and set-down was removed from the time series during the initial data processing, but the values are stored and shown in Figure 9 and Figure 10. The values represent the mean of an entire time series, and not e.g. the extreme values from a moving average analysis. It is interesting to see that while Figure 9 shows the anticipated set-down in the breaker zone and set-up closer to the shore, Figure 10 shows that the set-up begins already in the kelp field. In fact the maximum set-up is observed at the shoreward edge of the kelp field. The set-up with kelp is substantially larger than without kelp until very close to the shore, but at the shore (the run-up wire) the set-up is significantly larger without kelp in the flume.

Without kelp in the flume, the major energy dissipation is due to the wave breaking and the bottom friction term can be neglected. However, the kelp may cause significant energy dissipation in deeper water than the region where the most intense breaking occurs without kelp in the flume. Then the mean water level rises in deeper water with kelp in the flume. In addition comes the rise due to the bottom friction term. Shoreward of the kelp field the set-up remains approximately constant, which means that the radiation stress is approximately constant. This again means that the energy dissipation is approximately balanced by the rise in the *kh*-term.

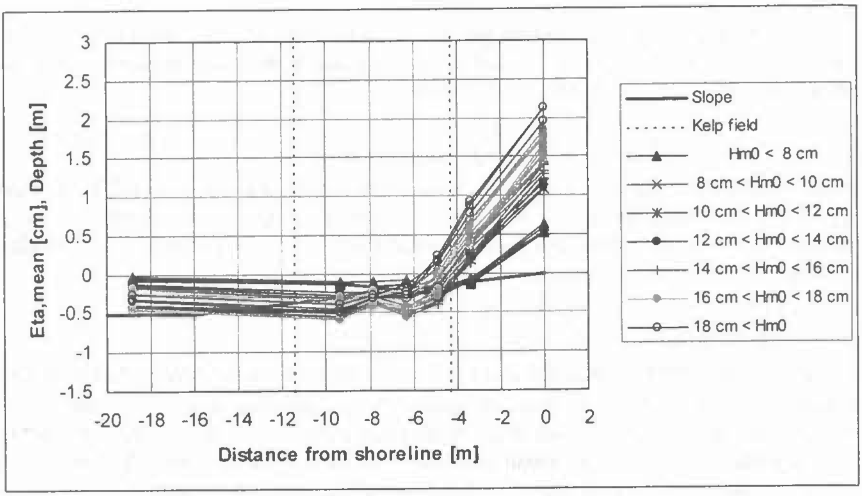

Figure 9 Average surface elevation without kelp in the flume. The legend is based on the H_{m0}-values at the most offshore gauge.

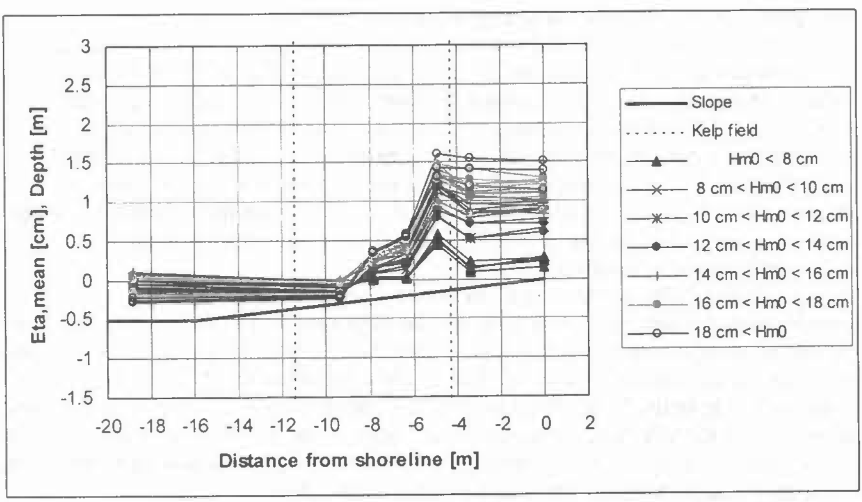

Figure 10 Average surface elevation with kelp in the flume. The legend is based on the H_{m0}-values at the most offshore gauge.

Run-up

That the sea water reaches the dune front is a simple but necessary requirement to induce erosion of the dune. The water level and the speed of the water reaching a dune front are important parameters to estimate the degree of erosion. Overton et al. (1988) showed that the volume eroded from a vertical planar dune was a function of swash force, where the swash force is defined as the product of fluid density, the uprush (run-up) velocity[3] squared and the height of the uprush at the moment of impact. The swash force is hence a kind of drag force where the fluid density and uprush velocity forms the dynamic pressure and the height of the uprush is the projected area per unit width along the beach.

In the experiments the water level at the beach is measured as the maximum vertical elevation along the run-up wire (see Figure 11). The mean set-up is included. The maximum run-up (vertical axis) with kelp in the flume is from 53% to 66% of the values without kelp and the difference increases (nearly linearly) with wave height (H_{m0}). It should be mentioned that the results are valid for the used slope angle (1:30) only and for fairly small waves (H_s less than 2.5m full scale), and that the kelp field is located in rather shallow water, but the differences are still quite remarkable. For steeper beaches and especially for dune fronts it is expected that the run-up will decrease more rapidly and that the differences due to the presence of kelp become smaller.

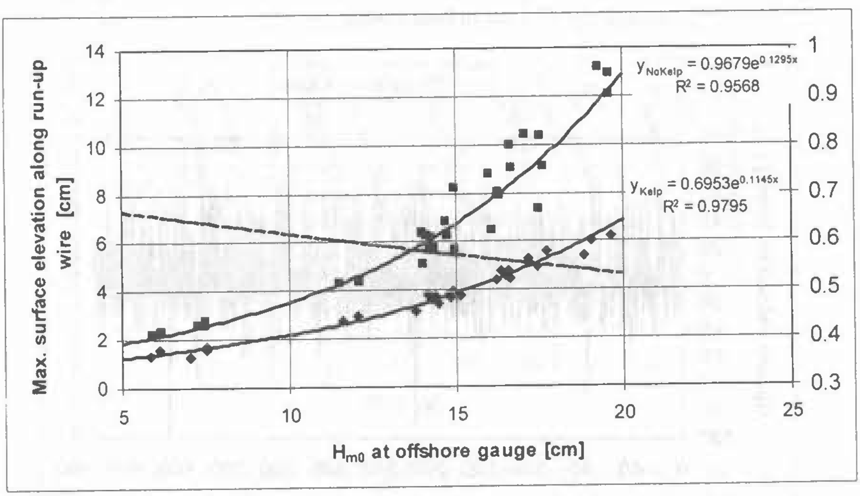

Figure 11 Measured values of maximum surface elevation along the run-up wire. Average set-up is included. The dashed line shows how the Y_{Kelp}/Y_{NoKelp}-ratio (right-hand Y-scale) varies with the H_{m0}-values at the most offshore gauge. The ratio is calculated from the exponential trendlines fitted to the measured data.

[3] The uprush (run-up) velocity is the velocity of the water front as it climbs the beach. This velocity may differ from the water particle velocity, but at the water front they are assumed to be approximately equal. Negative uprush velocities are termed downrush (run-down) velocities.

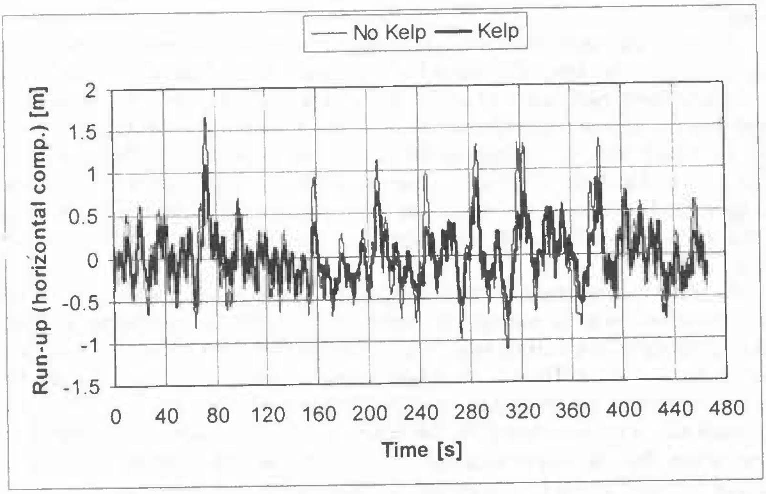

Figure 12 Difference in run-up (horizontal component) with and without kelp in the flume. Peak wave period is 4.5s and H_{m0} at the most offshore gauge is approximately 17.5 cm in both cases.

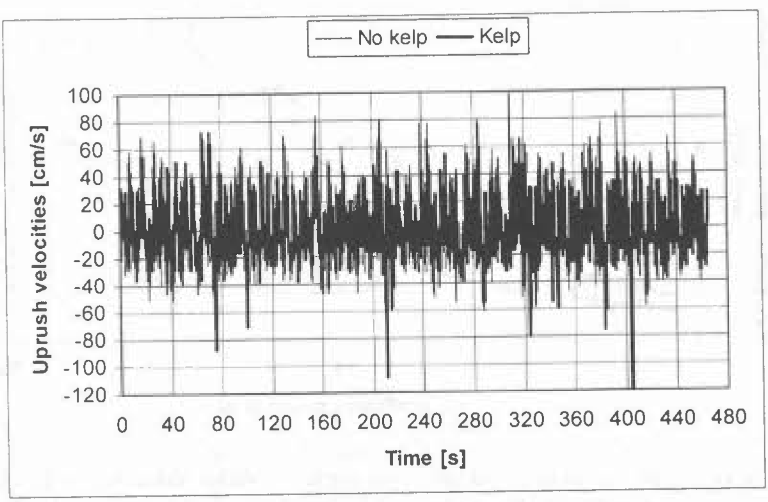

Figure 13 Difference in run-up velocity along the beach slope with and without kelp in the flume. Peak wave period is 4.5s and H_{m0} at the most offshore gauge is approximately 17.5 cm in both cases.

Figure 12 compares the run-up (horizontal component) with and without kelp in the flume for the highest tested waves. The figure shows that all the higher peaks are reduced with kelp in the flume, while the differences are much less for the smaller fluctuations.

Figure 13 shows the run-up velocities[4] for the time series shown in Figure 12. The figure shows that the kelp has less effect on the run-up velocities, but the highest velocities are reduced. Following the findings of Overton et al. (1988) the reduced run-up and run-up velocities leads to reduced swash forces and hence reduced dune erosion with kelp in the flume. Figure 14 includes an extract from Figure 12 and Figure 13, and shows how the run-up velocities increase rapidly when the next wave approaches and starts to decrease again when water front has passed the mean water level region. As the run-up velocities decrease and the elevation of the beach increases towards the point of maximum run-up, also the uprush will decrease with increasing run-up. This means that the swash force decreases rapidly above the mean water level region, and that this provides an explanation of the importance of the storm surge level compared to wave height. Figure 14 also shows that the effect of the kelp is not constant. The run-up peaks at about 10 s and 40 s are about the same without kelp in the flume, but while the peak at 10 s is much smaller with kelp in the flume the peak at 40 s is about the same as without kelp.

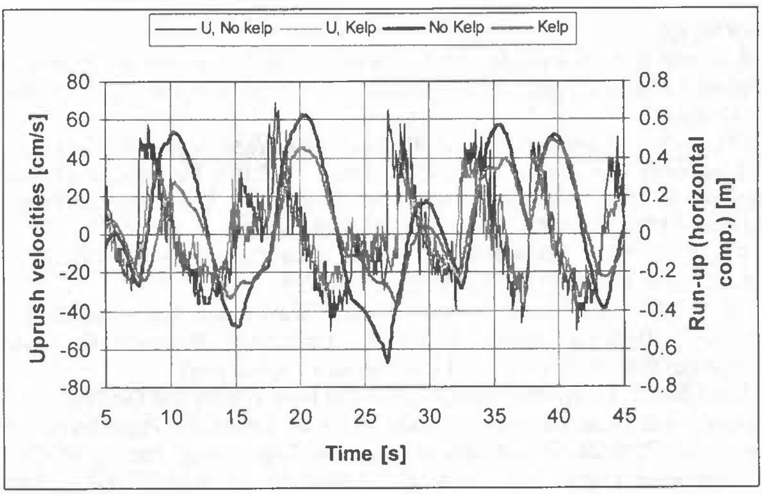

Figure 14 Run-up velocities (thin lines) and run-up (thick lines) with and without kelp in the flume. Peak wave period is 4.5s and H_{m0} at the most offshore gauge is approximately 17.5 cm in both cases.

[4] The run-up wire was calibrated to give vertical elevation values. This means that the actual run-up lengths on the sloping shore are $\sqrt{(1^2 + 30^2)} = \sqrt{(901)} \sim 30.02$ times greater than the values derived from the time series (slope 1:30). The run-up velocities (speed of the waterline fluctuations on the shore) are calculated as the gradient ($d\eta/dt = d\eta * df = d\eta * 20Hz$) in the run-up time series multiplied with $\sqrt{(901)}$.

CONCLUSIONS

The experiments carried out in this study confirm that kelp reduces wave heights, and that the wave damping due to the kelp reduces wave breaking. It was also found that the breaking process reduces wave heights more rapidly than kelp. For a situation with kelp growing in the outer part of the surf zone (water depth > about 2.5 m) and waves with H_{m0} <~ 2.5 m, a lot of the wave breaking takes place inshore of the kelp field. The difference in wave heights with or without kelp was then found to be minor in very shallow water. When the kelp grows in very shallow water (water depth < about 2 m), the presence of kelp reduces the run-up on a sloping beach.

These conclusions are primarily valid for conditions similar to those along the Jæren coast, and care must be exercised before using any of these conclusions in areas with different conditions, such as further north along the western coast of Norway. Here the sea bottom is rocky and more irregular and the kelp may grow closer to the shoreline.

ACKNOWLEDGEMENTS

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