Artificial seaweed

Coastal and submarine-pipeline protection studies with stretched polypropylene foam strands (*)

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1 — Introduction

Light-weight polypropylene foam strands for artificial-seaweed applications are made via a process, named "extruder-gassing". The work carried out at Shell Plastics Laboratorium Delft, Holland, on the development of the extruder-gassing process dates back to about 1964; in principle, it consists in directly injecting a low-boiling liquid into the polymer melt on an extruder. Initially this work was directed to the manufacture of light-weight foamed products in the form of more or less thick polystyrene sheets. On the other hand, at that time a considerable amount of development work was done on the manufacture of PP tapes and yarns; small wonder that both techniques have led to the idea of combining the process such as the manufacture of light-weight foamed PP tapes, which could possibly be used in artificial seaweed. It has been found that synthetic tapes or yarns with a density of less than that of water can be suitably anchored to the sea bottom, the flow rate of the water near the bottom will be reduced, thus giving a certain degree of control over the migration of bottom material. Consequently, erosion of the bottom can be suppressed and deposition of suspended solids is enhanced in a relatively simple and not too expensive way.

Bottom stabilisation and coastal protection by traditional methods is usually extremely expensive. One simple mole with a length of about 200 m costs, for instance, more than Nfl. 1,000,000.—, while bottom stabilisation with "willowmattresses" involves an expenditure of Nfl. 70-150/m^2. Hence, there is a definite need for less expensive alternatives.

Since 1965 companies in the U.K. and the U.S.A. have carried out performance trials on a limited scale using unfoamed or slightly expanded PP tapes as artificial seaweed. In the U.K. experiments were successful in that a definite accumulation of sand took place at the location of the weed field, but it was found difficult to anchor the weed properly and in a practical manner to the sea bottom. In the U.S.A. experiments were less successful: neither a beneficial effect on bottom and coastal erosion nor accumulation of suspended sand particles was established.

In the Netherlands, Rijkswaterstaat started experimenting in cooperation with Nicolon. Fairly soon the good anchorage was found to constitute a major problem; the trials resulted in new and practical concepts. In the same period K.S.P.L.D. (**) succeeded in manufacturing stretched PP foam strands with the unusually low density of 0.2 g/cm^3. In a laboratory set-up is was shown that, if used with care, this material is more effective for bottom stabilisation than unfoamed or lightly foamed products, thanks to its much better buoyancy. Tank trials carried out by the Hydraulics Laboratory "De Voorst" confirmed that the Shell material could be very effective as artificial seaweed. At that stage (mid 1967) contacts were established between Sheel, Nicolon and Rijkswaterstaat.

During the development work on a suitable system to use the foamed strands as artificial seaweed, a number of factors had to be taken into account.

(*) Throughout the publication the words "Shell" and "Group" are used collectively in relation to companies associated together under the name of the Royal Dutch/Shell Group of companies.

(**) Koninklijke Shell Plastics Laboratorium Delft.

Firstly, the tank trials at the Hydraulics Laboratory "De Voorst" had shown that the strands should be arranged side by side, thus forming a kind of "screen". Such an arrangement is much more effective than, for instance, tufts of strands spaced at intervals, between which turbulence can occur, which may have an adverse effect.

Secondly, once installed under water, the strands in the screen must be able to move freely and independently to ensure that not too much buoyancy-reducing foreign material is caught by the curtain.

Thirdly, the strands must be attached to an effective anchoring means. Taking into account that in coastal-protection projects one is dealing with huge quantities of material, it is clear that the side-by-side arrangement of the weed threads and the attachment to the anchoring device must be simple and economic. In the Shell/Nicolon system these problems have been solved by processing the Stretched Foam Strands (S.F.S.) on a loom into a kind of fabric, thus automatically obtaining the desired arrangement of the strands. Effective anchoring of the screen is obtained by providing the fabric at one end with a hollow seam and filling this "anchoring tube" with a weighting material such as sand, or small pebbles. Figure 1 shows the fabric with the unfilled anchoring tube.

The method of weaving is schematically shown in Figure 2 and comprises the use of an S.F.S. weft yarn forming the actual weed threads and a beam with two types of warp yarn. At one end of the fabric an S.F.S. warp yarn is used to obtain a seam to which the anchoring tube can be attached while over the remainder of the width of the fabric thin warp yarns of alginate are woven in at regular intervals. These alginate yarns facilitate fabric manufacture on the loom and moreover prevent problems such as knotting during transport, handling and laying of the weed. The alginate yarn dissolves quickly in salt water so that a short while after installation the weed threads can move independently.

For applications in fresh water so far no entirely satisfactory warp yam has been found but a solution for this problem can be expected in the very near future. One of the possibilities which are being investigated is the use of paper as the warp material.

The anchoring tubes so far used are made from a strong 90-120 g/m^2 nylon fabric, sewn to the seam of the foam strand screen. Typical dimensions and further characteristics of the weed screens with anchoring tube are given in Table 2.

In conjunction with Shell and Nicolon, Rijkswaterstaat initiated a number of experiments with lightweight foam tape at locations along the Dutch coast. This article is primarily intented to publish the results of the various trials and to make available the present knowledge about the laying of weed fields and the anchoring methods used.

Apart from the use of artificial seaweed for coastal protection, trials with artificial seaweed have also been done to protect submarine pipelines. Furthermore, qualitative theoretical considerations are given about the hydrodynamic aspects of the use of artificial seaweed. These theoretical considerations are compared with recent model trials carried out by the Hydaulics Laboratory "De Voorst" (at the instigation of Nicolon) and the resulting experimental data.

2 — Description of the Shell/Nicolon artificial seaweed system

The system is based on stretched PP foam made via an extruder-gassing system. Stretched PP foam strands can best be characterised as white, shiny ribbons of small width; these consist of an open, three-dimensional network of interconnected fibrous elements surrounded by a thin (predominantly closed) skin. Some typical properties of this products are given in Table 1. Particularly the following properties render the material eminently suitable for artificial seaweed:

- Low density giving high buoyancy;
- High yarn strength, resulting in a long lifetime under water and troublefree handling and further processing of the yarn;
- In spite of the open structure, there is hardly any penetration of water into the material due to its hydrophobic nature, the scaling by the surrounding closed skin and the very low diffusion rate of water through this skin;
- Resistance to the influence of bacteria, fungi and most chemicals.

Table 1

Typical properties of stretched PP foam strands

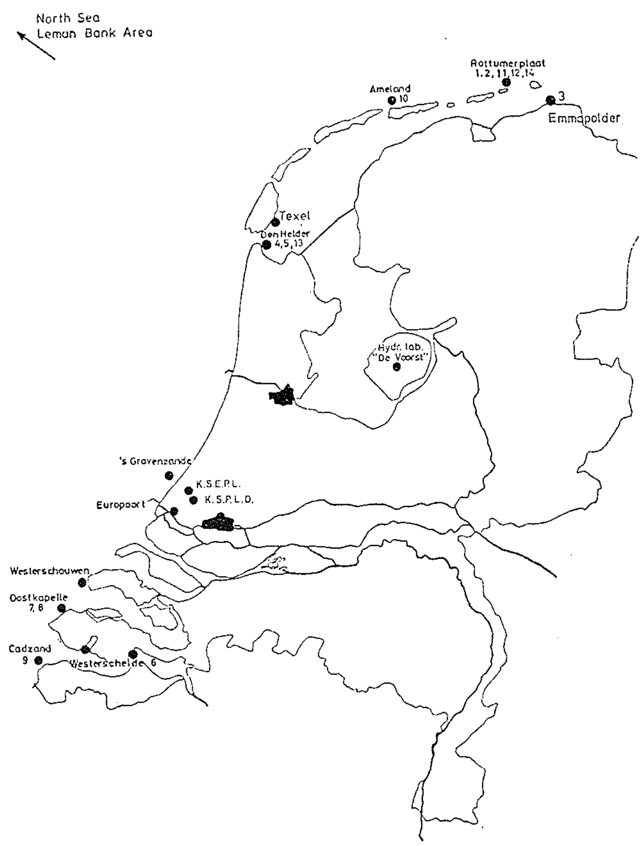
Density .... (kg/l)	0.125 - 0.250
Denier .... (g/9,000 m)	1,000 - 14,000
Tensile strength .... (g/denier)	2.0 - 3.0
Structure	open
Width of strands .... (mm)	2.5 - 3.0

Table 2

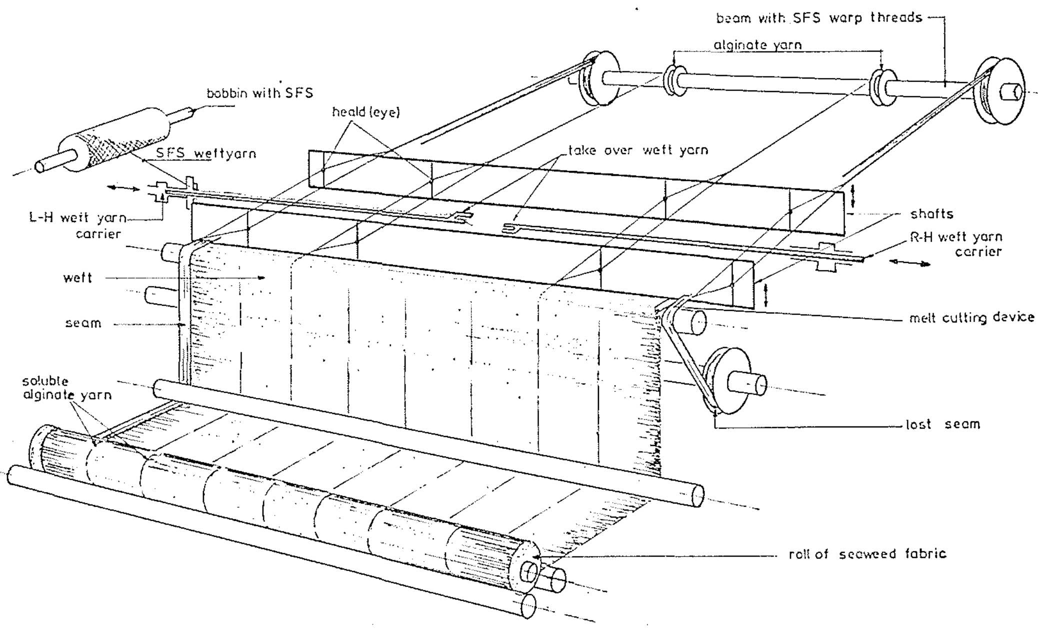
Typical dimensions and further characteristics of artificial seaweed screens with anchoring tube

Length of weed strands .... (m)	1 - 2 max. 4 m in view of loom width
Width of seam for attaching the anchoring tube .... (cm)	5
Width of screen .... (m)	1 - several hundreds of m
Number of weed strands per cm	ca. 4
Basic weight of screen .... (g/m^2)	70
Diameter of anchoring tube ...... (cm)	15
Volume of anchoring tube when cylindrical .... (l/m)	ca. 18

1/ Nylon fabric hollow anchoring tube sewer onto the S.F.S. fabric.



3/ Locations of trials in Holland.



2/ Shuttleless loom for weaving artificial seaweed.

3 — Experimental

Since mid 1966 Rijkswaterstaat have carried out a number of experiments with artificial seaweed along the Dutch coast (Fig. 3).

The experiment fall into three categories:

a) Preliminary trials (Table 3, experiments 1 to 4, 6 and 9) with as main objectives the development of suitable anchoring methods and to gain a first impression about the stabilising and sand catching ability of artifical seaweed.

b) Small-scale trials (experiments 5, 7, 8 and 11) in which the artificial seaweed was employed to combat real erosion problems. In this work usually channels in beaches, in tidal shallows or in the sea-bottom were dammed up with rows of seaweed with the aim of rendering the troughs inactive and to establish whether sand-accumulation took place.

c) Large-scale trials in which the weed was employed to protect certain sections of the coast line which were particularly threatened by the sea, and to protect submarine-pipelines against underwashing. These experiments will be described in more detail in chapter 4.

4 — Experience in practice

In considering the effect of artificial seaweed, the following questions should be answered:

1) How was the weed installed?

2) How did the weed perform during the trials?

3) How was the topography of the bottom changed as a result or the presence of this seaweed?

An answer to these questions will be given in sections 4.1/4.4 incl.

4.1 - Laying methods.

The method of weed laying depends entirely on the kind and size of the field and the location where it has to be installed. The experience in the laying of artificial seaweed is still limited but some general points can be noted.

Two basically different situations must be distinguished:

— laying of weed in an area accessible over land and dry at low tide;

— laying of weed outside the tidal zone.

For the first situation, good results were obtained in laying a weed field using the method described below:

A simple hopper was mounted on the side of a truck. The lower part of the hopper was connected to a 3 m long plastic tube placed at an angle of about 20° with the horizontal. The truck was loaded with sand and the anchoring tubes of the 20 m wide weed screens were slipped over the pipe. Subsequently sand was shovelled into the hopper and washed into the anchoring tube with water pumped out of the sea (Fig. 4 and 5). Meanwhile the truck slowly drove in the laying direction.

The impression is that this combined method of filling the anchoring tube and weed laying could also be suitable for operations on a very large scale, although a more automated system would then be desirable. Anyhow, in such situations it should be avoided that long lengths of heavy weed screen have to be handled or shifted, considering the enormous weight of the filled anchoring tubes.

For weed laying in deeper water, other methods are required. In trials at Den Helder and in the North Sea use was made of the so-called "random" method, in which short lengths of weighted weed screen were dumped. Although this method seems somewhat rough and inaccurate, the results show that, nevertheless, a good performance of the weed fields is obtained. The method has the important advantage that weather conditions are not very critical. Experts have estimated that in the Northsea area, where bad weather is the rule rather than the exception, the random method can still be carried out on some 200 days/year.

Only when the water depth is larger and the current strong, should it be borne in mind that with at random dumping, the weed screens can drift away over a considerable distance on their way down to the bottom.

A small experiment was carried out near the New Waterway at a location where the depth was 15 m and at a measured flow rate of 1.5 m/s on the water surface, 1.10 m/s at a depth of 7 m and 0.7 m/s near the bottom. The weighting per m screen width was 20-30 kg at this average flow rate of 1 m/s, the lighter sections descended at an angle of 45° with the vertical and the heavier sections at an angle of 30° (sinking rate 1.2-1.5 m/s). Hence, considerable floating away from the location of dumping can be expected, as was the case in the trials carried out in the North Sea at a depth of 35 m. At small water depths, however, which are more common in coastal protection projects, the floating-away deviations are negligible.

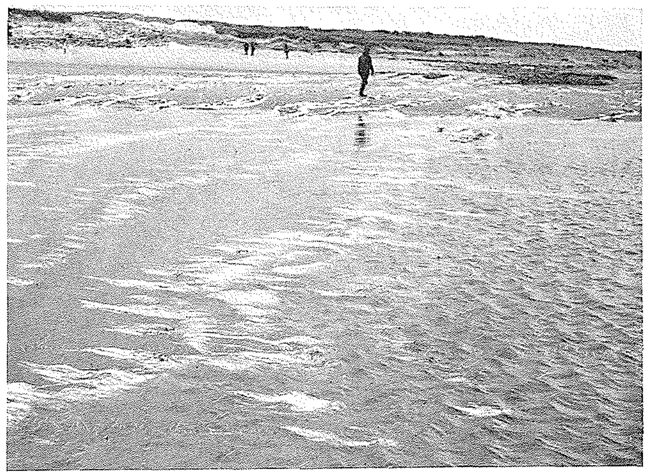
Other, more accurate, laying methods that have been considered have, next to the advantage of precision, the disadvantage that the number of days suitable for laying is much smaller. An example of an accurate laying methode is the beam method which has been applied in trial 15 near Texel (see section 4.4.2).

Finally the question arises how much weed has to be laid in a given situation. A fair amount of data was obtained from recent tank trials at the Hydraulics Laboratory "De Voorst", where variables such as water level, weed length and interval were considered. These trials suggest that the maximum effectiveness of series of parallel weed screens is achieved when the screens, when bent down by the current, overlap each other slightly. In this way the reduction in flow rate near the bottom is optimum. In most practical trials this starting point was used and one screen having a width of 1 m and with 2 m long threads was installed per m^2 of bottom. If the length of the threads is different, the distance between the screens can be adjusted accordingly.

4.2 - Durability of the seaweed field.

Apart from anchoring, the results about the durability of the seaweed were not always the same; in many cases the weed was sanded up and could not be traced again. Trials carried out in the tidal and surf zones showed that the weed threads become entangled fairly easily, which resulted in reduced effectiveness. Furthermore, in the long

4/ Laying method of seaweed in tidal zones.



5/ Seaweed field at Rottumerplaat after 5 months' exposure.

term deterioration of material can be observed as a result of UV radiation [a], although this does not occur as long as the weed stays under water. Under water, all kinds of organisms may hang on, as a result of which buoyancy and effectiveness will decrease in the long run. Hence, this material with a density of 0.2 is of course better than seaweed with a higher density. It should be emphasized that trials carried out so far have been too short to enable us to form a definite opinion on the durability of the weed.

The durability of the seawed field is not only determined by the seaweed itself, but, to a great extent, also by the anchoring method.

From the experiments it can be concluded that rigid anchoring methods, such as mats of reinforcing rods, concrete blocks, etc. all give rise to practical difficulties. In the first place attachment of the weed to such an anchoring system is complicated and labour-intensive; furthermore, the weed can chafe on the eye bolt (trial No. 4) and be torn away (trial No. 7). In addition rigid anchoring systems can easily be underwashed; in other words, it is important that the anchoring system can follow the bottom profile.

The system of a flexible nylon anchoring tube filled with sand or another weighting material has been found to offer a practical solution to these problems; it has been shown to be adequate under all kinds of conditions. Only under extremely severe conditions, such as those encountered in the surf zone, is additoinal anchorage likely to be required. In this case one could think of an anchoring tube filled with pebbles or sand, while the tube is attached, in a number of places, to piles driven into the sand or to anchoring saucers buried in the soil.

A plastic saucer of 14 cm diameter, which has been injected to a depth of 0.5 to 1 m by means of a water jet, can have an anchoring strength of about 150 kgf. The anchoring tube must be placed slightly zig-zag or undulating between the fixed anchoring points to prevent underwashing. The trials (in particular trial No. 12) indicate that a flow rate of 1 m/s, an anchoring weight of 7-15 kg/m^2 of screen gives sufficient anchoring.

[a] This can be prevented by stabilising against UV radiation.

4.3 - The effect of seaweed on bottom topography.

Despite an intensive support of the experiments by measuring the bottom topography before and after the trials, it is not simple to establish the effect of the artificial seaweed. An attempt has been made in Table 3, which shows the results obtained. In small-scale trials it is not easy to differentiate between the effect of the seaweed and that of natural variations of the bottom in the coastal area; the latter could be greater. A clear indication is obtained if at the seaweed field there are discontinuities in an otherwise gradual course of the bottom topography. At Oostkapelle, for instance (trial No. 8) it was found that a kind of small dam had formed in a beach trough; it is very unlikely that this was mere coincidence.

In trial 10 at Borndiep the width of the gully clearly decreased at the site of the seaweed. It is therefore evident that the favourable results are due to the effect of the synthetic seaweed, the more so as unsatisfactory results are often clearly the results of insufficient anchoring (2, 3, 4, 6) or of a faulty method of laying seaweed (1, 10). The unsatisfactory result of trial 14 at Rottumerplaat (Fig. 5) should perhaps be attributed to the natural changes on the spot, which are considerable, as compared with the effect of the seaweed.

Of the four larger-scale trials, three were satisfactory (trial 13, 15 and 16). The effect of the fourth trial (in the surf zone at Rottumerplaat, trial 14) was not clear owing to the enormous changes in the bottom profile in this area. Probably this weed has not been laid in an optimum way: the long rolls were placed at an angle of 60° to the beach line, after which erosion troughs were formed adjacent to them. Before the anchoring tubes had been

Table 3

Survey of main features of trials carried out with artificial seawed

Trial No.	Place	Purpose of weed	Size and nature of trials	Conditions	Weed	Results
1.	Rottumerplaat		Preliminary, small trial	Tidal flat	0.7 density tapes attached to stones	Sand between stones was washed away
2	Rottumerplaat	To catch sand and to stabilise bottom	Preliminary, small trial	Tidal flat	0.7 density tapes attached to a steel mat of reinforcing rods	Sand build-up of 1 m.at favourable locations anchoring too rigid or too light
3	Emma polder (land reclamation)		ditto	Calm, muddy water tidal zone	0.7 density tapes woven into screen with anchoring tube. Weighting with iron rods.	Weed was polluted and laid flat; weaving method to be changed..
4	Den Helder	ditto	ditto	4 - 5 m deep water	0.7 density tapes attached to concrete blocks	Weed chafed on eye-bolts and was torn away
5	Den Helder		"Dam" of 3.5 x150 m^2	4 - 5 m deep water current of 0.6 m/sec	0.7 density tapes attached in tufts along nylon rope	Sand build-up of 0.9 m in 4 weeks. Weed subsequently lost its effectiveness
6	Westerschelde	-	Preliminary, small trial	Sand bank, shallow water	0.7 density tapes attached to steel mat of reinforcing rods	Weed and anchoring disappeared within a fortnight
7	Oostkapelle	Damming up of swash channel.	Small-scale trial	Foreshore (Surf zone during high tide)	0.2 density Shell/Nicolon screens anchored with steel cables	Channel filled up with sand, weed had been effective for 2 years, followed by undesirable growth of acorn shells
8	Oostkapelle and Westerschouwen	Protection of groynes suppression of erosion between groynes	Small-scale trial	Foreshore (Surf zone)	0.2 density Shell/Nicolon screens anchored with steel cables	Bottom properly stabilised, weed now effective for 2 years
9	Cadzand	Prevention of dune underwashing near creek	Small-scale trial	Weed placed in a trough	Few parallel rows of screens of 0.2 density material	Underwashing was stopped, trough moved to another, harmless location
10	Bornrif, Ameland	Prevention of dune underwashing in a tidal channel	"First aid" action; weed dam of 4x75 m	Weeddam placed in a 0.75 m deep channel in the seabottom	6 parallel Shell/Nicolon, 0.2 density screens of 75 m long	Trough became deeper and less wide; dam was underwashed
11	Rottumeroog	Damming up of an underwater trough	Size of "dam" 7 x 150 m	Trough in tidal area, depth 3 - 4 m	7 Shell/Nicolon 0.2 density screens placed parallel	Trough sanded up quickly; weed dam got lost owing to enormous natural sand movement
12	Rottumerplaat	-	Trial to establish weighting required for proper anchoring	Tidal area, surf zone at high tide	Short lengths of Shell/Nicolon screens ballast 7 - 15 kg/m^2	All weightings used gave proper anchoring
13	Den Helder	Stabilisation of seabottom close to sea-wall to prevent underwashing of the latter	Larger-scale trial, field of 30 x 150 m	Water depth 4 - 5m current 1 m/s	2 m long Shell/Nicolon weed screens laid at random	Bottom perfectly stable since 3 years (contrary to continuous erosion previously)
14	Rottumerplaat	Protection of beach and dunes	Larger-scale trial; field of 40 x 150 m	Area is dry at low tide	Parallel rows of Shell/Nicolon 0.2 density weed screens	Anchoring functions properly; bottom stabilisation effect cannot yet be judged owing to natural changes taking place
15	Texel	Stabilisation of seabottom close to seawall to prevent underwashing of the latter	Large-scale trial field 80 x 100 m; beam method	Slope with water depth of 5 - 20m current up to 1.2 m/s	Parallel rows of Shell/Nicolon 0.2 density weed screens 1.5 m long	Beam method guarantees accurate laying of weed screens.Within two months a layer of sand of 30-40 cm was caught over the whole area
16	Drilling platforms in Northsea at Leman Bank area	Submarine pipeline protection against underwashing	Large-scale trial; two fields of 90 x 150 m	Water depth 30 - 40 m current up to 2 m/s	2 m long Shell/Nicolon weed screens laid at random	Underwashing was stopped, pipe line almost covered with sand at the located area

embedded, they caused more or less increased erosion; to prevent this, it is advisable to interrupt the long rows at regular intervals with rolls parallel to the coast so that a system of square blocks is obtained.

4.4 - Detailed description of some practical trials.

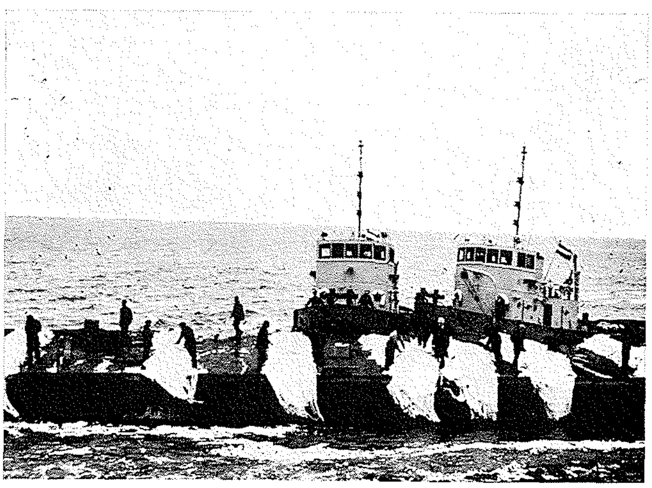
4.4.1 - Experiments at Den Helder

One of the trial fields of a more considerable size was laid by Rijkswaterstaat at Den Helder in 1969. The location of this trial field (Fig. 3) concerned the northern part of the dike protecting the eastern tongue of land along the naval port of Den Helder, where erosion regularly occurred. Regular soundings over a long period of time indicated a very great mobility of the bottom. It was decided to combat this erosion with artificial seaweed.

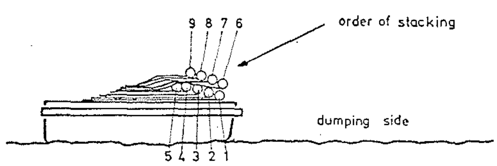
The water depth in this area varies from 4 to 6 m, while the maximum flow rate is 1 m/s, with a daily average of about 0.6 m/s. The bottom is sandy.

For the trial, screens were used of 1.5 m width and with weed threads of 2 m length, provided with anchoring tubes of 15 cm diameter. For weighting, small pebbles were used in an amount of 18 kg/m of screen. In total, 1540 pieces of screen were used for covering an area of 4,500 m^2 (30 $\times$ 150 m). Filling of the anchoring tubes with pebbles was done on shore, after which the sections were stacked on deck of a pontoon.

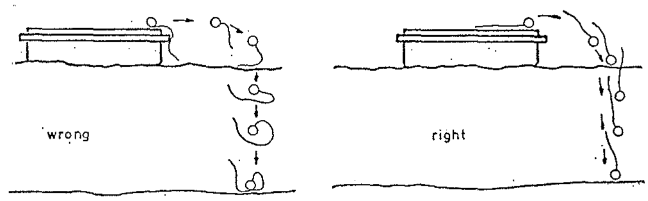
In principle, laying was done by towing the pontoon over the area to be protected and dumping the stacked sections more or less at random (Fig. 6). To this end the area was first marked with buoys and flags were placed on shore for positioning purposes. The screens were stacked in 7 rows of 220 screens on a pontoon of 30 m width. In stacking the screens it was found to be of importance that the seaweed sections were stacked in such a way that entanglement of the threads during dumping overboard was prevented (Fig. 7).



6/ Random dumping of seaweed sections into deep water.



7/ Stacking of the seaweed sections.



8/ Dumping seaweed sections.

Further, we learned that the screens should never be stacked in such a way that the screens hang alongside the pontoon just before dumping because in that case it is difficult to prevent the weed screen from getting underneath the anchoring tube (Fig. 8).

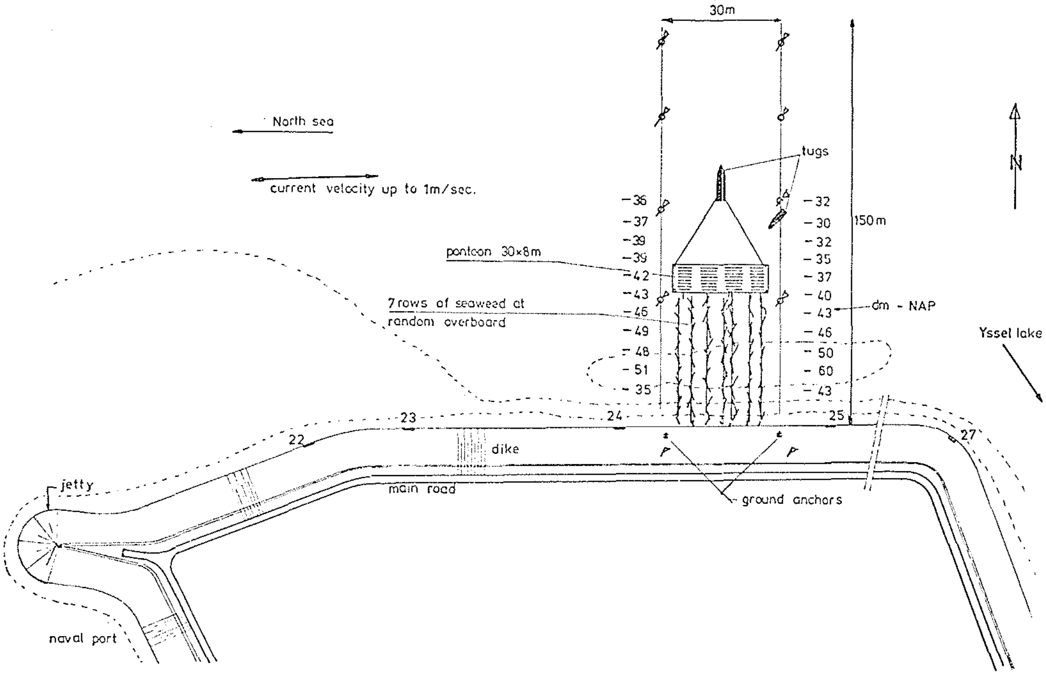
The pontoon was towed to the location of laying and connected to ground anchors and heavy ropes ashore (Fig. 9). A tug pulled the pontoon slowly seaward in a direction perpendicular to the dike. Meanwhile two men at each row dumped the screens into the sea at such a rate that one screen was laid per 3 m^2 bottom area. During dumping, attempts were made to turn each screen over 90° in order to have the weed properly positioned perpendicular to the direction of the current, which was parallel to the dike (Fig. 10).

In total, the laying operation requires the following manpower and vessels:

14 men for dumping;
2 men at the bollards on the pontoon for paying out the ropes anchored to the dike;
2 men co-ordinating the dumping;
6 men in two tugs (one reserve);
1 man in a flatboat;
1 man on shore for checking anchoring and ropes.

The whole launching operation took two hours but can be done faster with more experience and more favourable weather conditions (during laying wind force 7 to 8 was measured).

Since the laying of the weed, the area has been regularly and carefully surveyed by echo-sounding. These measurements revealed that the bottom has since become stable in and close to the weed field. From time to time sand accumulations of the order of 30-50 cm were measured but this sand usually disappeared again during heavy weather. Erosion, however, no longer takes place; therefore, this trial can be considered successful.



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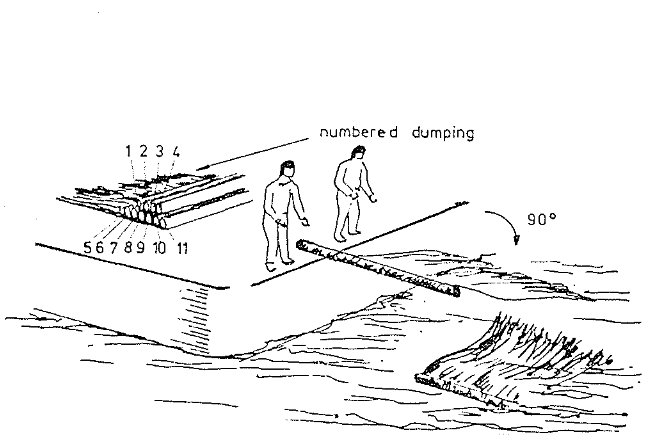
9/ Trials 5 and 13 in Marsdiep near den Helder.

10/ Dumping seaweed perpendicularly to the tidal current.

11/ Trial near 't Horntje (Texel); beam method.



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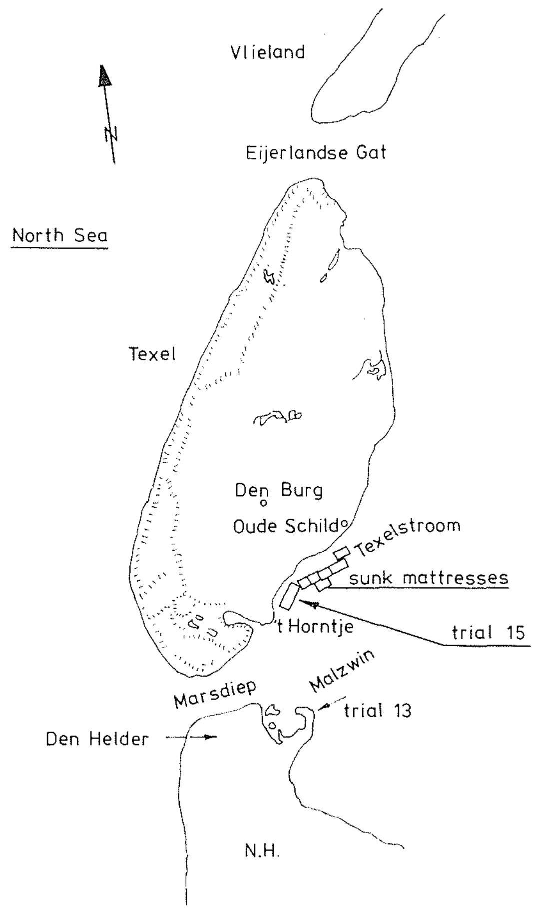

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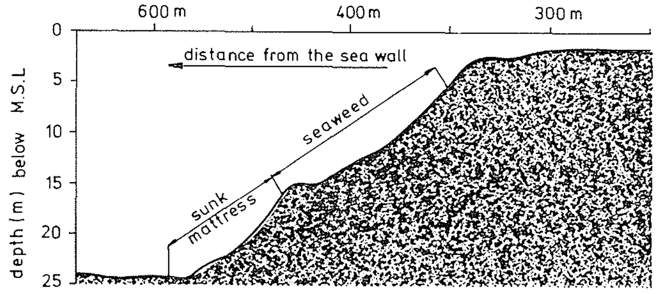
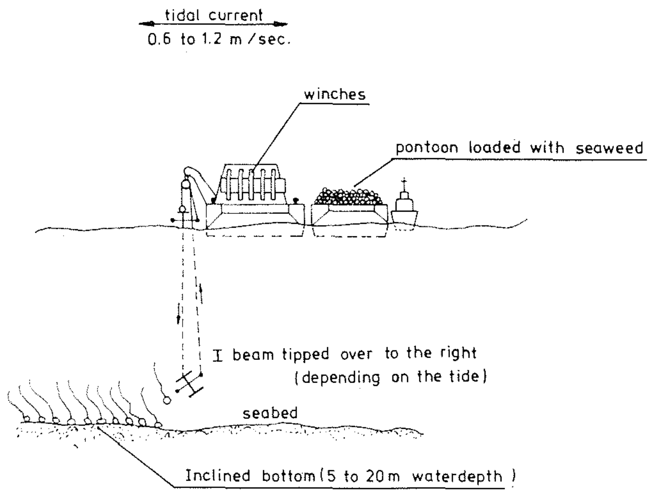
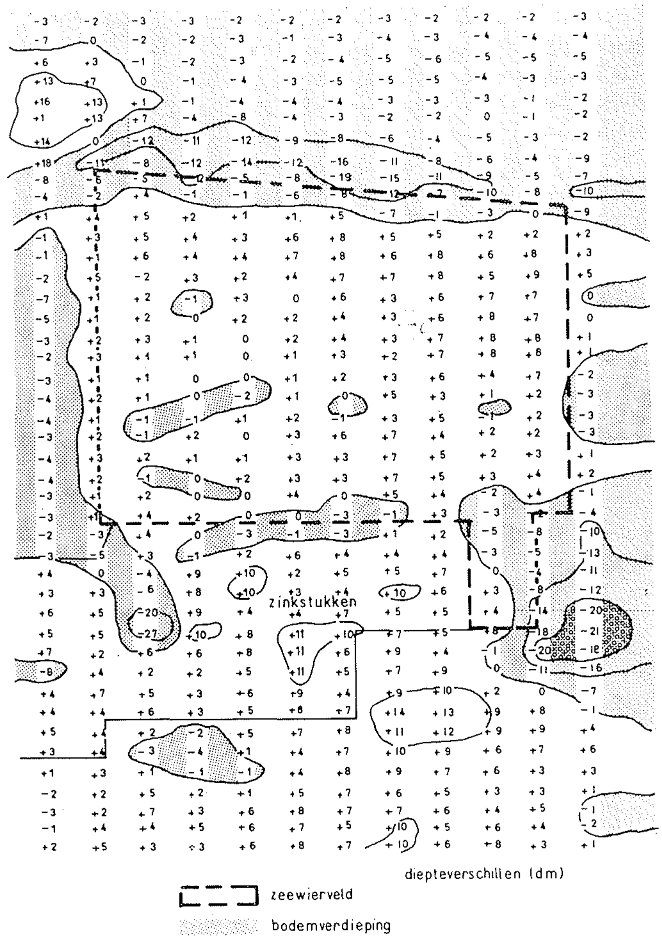


12/ Cross-section perpendicular to the shore.



13/ Laying method.



14/ Map showing differences in bottom depth covering the period 7 December 1971-30 June 1972.

At low tide and when the water is clear, the weed is visible at several places and appears still to stand upright, indicating that the buoyancy has hardly or not suffered from algae growth or dirt pick-up. In addition, recent measurements (three years after laying) showed that the increase in density due to diffusion of water through the skin into the foam, is negligible.

4.4.2 - Field trial at 't Horntje (Texel).

To obtain a clearer picture of the properties of the seaweed, it was decided that the field trials, carried out at 't Horntje with a row of willow mattresses be extended by laying an 80 × 120 m field of artifical seaweed (fig. 11).

The field is located at the bank of a deep tidal channel in the most southern inlet to the "Wadden shallows," tidal flats in the North of the Netherlands. The channel erodes this bank, which is a part of Texel the most southern of the "Wadden Islands" at the border of these flats. The area, fed by this inlet has a tidal prism of 10^9 m^3; the velocity of the ebb stream at the location of the seaweed reaches values of more than 1 m/s. The average tidal difference on the spot is 1.34 m; the location is fairly well protected from the North Sea heave. The wind waves generated on the Wadden Shallows (H = 0.5-1 m, T = 3-5 s) prevail.

The seaweed was laid on the inclined bottom, the water depth increasing from 5 to 15 m. The maximum gradient was about 1:5 (Fig. 12).

Artificial seaweed screens of 1.5 m height were attached to anchoring tubes of 1.5 m length and 15 cm diameter. For weighting small pebbles were used in an amount of 20 kg/m screen. The distance between the screens was 1 m.

Based on experiments in the Hydraulics Laboratory "De Voorst", during which it was found that regularly laid seaweed screens are more effective than those which have been laid randomly, efforts were made in this case to lay the seaweed as carefully as possible in a pattern perpendicular to the tidal current (unlike the other experiments).

In order to avoid the scattering of the material over a large area, as a result of the great depth and the strong current, an adapted laying method was required. For accurate laying, the anchoring tubes were laid, over a length of about 30 m, on a 24 ton I-shaped steel beam, which, by means of wire ropes, was hung in davits which were attached to a properly anchored pontoon (fig. 13).

With the aid of a winch, the horizontal I-beam was lowered until approx. 1 m above the seabottom. Then the beam was tipped over, the anchoring tubes with seaweed slipped from the beam and dropped onto the sea floor. Subsequently the beam was hoisted and the pontoon shifted one metre after which the cycle was restarted. Depending on the water depth, this cycle took 3-7 minutes. Owing to the tide, seaweed can only be laid once a four-hour period per day, in which period approx. 1 000 m^2 of seabottom can be covered.

Figure 14 shows the differences in height (in dm) between 7 December, 1971 and 30 June, 1972 the area considered, the seaweed was laid between 16 December, 1971 and 16 February. It is clear that in this area an average sand accumulation of the order of about 0.35 m has built up, whereas the area at the same height in the neighbourhood keeps deepening. This is also clear from Figures 15 and 16, which show the average depth of the seaweed field and of the adjacent area to the west. The bottom changes seawards of the seaweed field are a result of natural changes in the channel in question.

4.4.3 - Submarine pipeline protection

In May 1971 a seaweed trial was carried out in the North Sea near two Shell/Esso drilling platforms situated in the Leman Bank area, 80 km off the English coast. The purpose of this trial was to establish whether artificial seaweed could help to protect submarine pipelines from underwashing.

Divers had observed that near one of the platforms (platform CD in Fig. 17 a) a 200 mm dia pipeline, interconnecting the two platforms, showed scouring to a depth of 15 cm over a length of 30 m, while below the riser heel of the pipeline a crater of approximately 1.5 m depth was observed. As heavy underwashing over long distances can lead to breakage of the pipelines (since they are not designed to withstand high bending stresses and repairs are extremely expensive both with regard to execution and as a result of the fact that the line will be out of service), it was deemed useful to find out in how far artifial seaweed could form a proper protection.

Two trial fields, each having a surface area of 150 × 30 m, were allocated near the platform for seaweed trials. As it was of vital importance that no damage should be done to submarine pipelines and their corrosion-protective layer, accurate laying methods requiring the use of iron anchors, chains, sledges, etc. were considered unacceptable. It was therefore decided to use the method according to which the weed screens are dumped overboard at random. From previous experiments (see section 4.3) it was estimated how much the sections would drift away so that this could be taken into account (fig. 17 b). The seaweed sections were dumped overboard from a supply boat which moved forwards and backwards over the allocated area.

At each field 1,300 weed sections with a width of 2 m and a curtain height of 2.2 m were used. The anchoring tubes were filled with 40 kg of pebbles. Prior to these trials, the seaweed sections were filled and stacked on pallets, each pallet accommodating 40 sections. The water depth near the drilling platforms is 35 m. During the trial the tide caused a water current of 1 m/s; a wind force of 7 was measured and the waves were 2-3 m high.

A month after the dumping, divers went down for inspection of the weed fields near drilling platform CD. They found a seaweed field of approx. 170 m long and a fair latitudinal spread with almost equal quantities on either side of the pipeline. The underwashed pipeline was almost completely buried by sand caught by the weed, of which a length of 60-90 cm protruded above the newly formed sand layer. In the crater at the riser heel a sand accumulation of 60 cm was measured (Fig. 17 c).

It certainly looks as if the artificial seaweed performs well, while the simple system of dumping the sections overboard has, under the prevailing weather conditions, proved to be a suitable method at this water depth and provides a quick solution when there is a risk of breakage of a submarine pipeline by underwashing.

5 — Hydraulic considerations

The performance of artificial seaweed can, apart from experiments in nature, also be studied in the laboratory by means of trials under controlled conditions and from theoretical calculations.

In the Hydraulic Research Station in Wallingford model-scale trials have been carried out; these have been reported on in [1] and [2]; these trials concerned the effect of seaweed on beaches under the influence of waves. The results were not well-defined but they gave the indication that the transport of sand by the seaweed was checked [2]. At a wave height of 75 cm and a period of 1.33 s, there was a wave attenuation of 4 % within a seaweed field of 4.5 m length, the material (polypropylene with a s.g. of 0.9) was arranged in tufts.

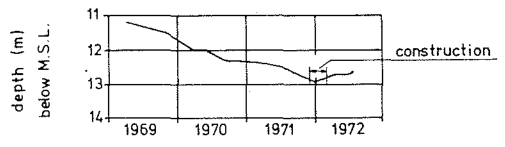
In addition, trials were carried out by the Hydraulics Laboratory at "De Voorst", on behalf of Koninklijke/Shell Plastics Laboratorium Delft and Nicolon, concerning the effect of artificial seaweed in currents. These trials have previously been referred to by Van Dixhoorn et al [4]; we shall revert to this point below.

Ertel [3] developed a theory for the attenuation of the waves in (natural) seaweed. In a numerical example he comes to the conclusion that a wave with a height of 2 m and a period of 5 s in a seaweed field with bundles spaced 25 cm apart (over the full height) would be attenuated within one wave lenght ($\cong$ 40 m) to 12 % and within two wave lengths to 1.4 %. His schematic representations are very rough and somewhat arbitrary.

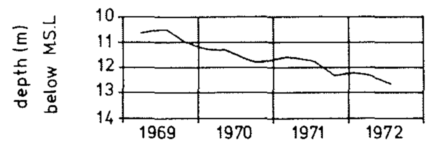
A theory about the effect of artificial seaweed in currents has not been developed so far, but the current pattern of the wind in and over a vegetation has been studied fairly thoroughly both theoretically and experimentally (see e.g. Guyot [5]). A rough qualitative consideration regarding this current pattern is given below; subsequently the trials carried out by the Hydraulics Laboratory "De Voorst" will be described more closely.

In a current without seaweed a shear force acts on the bottom as a result of the turbulent water rushing over; in a current with seaweed the following changes, as compared with a current without seaweed, can be distinguished.

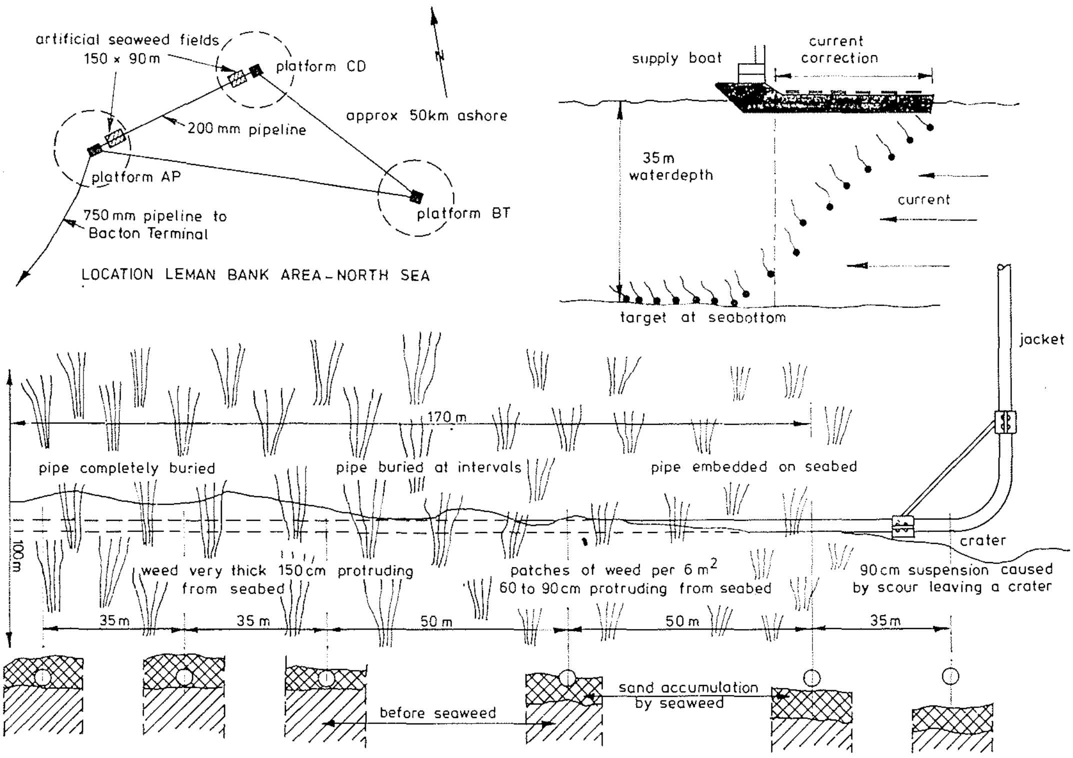
Upstream from the seaweed a certain pressure head results; it depends on the situation what will be the re-



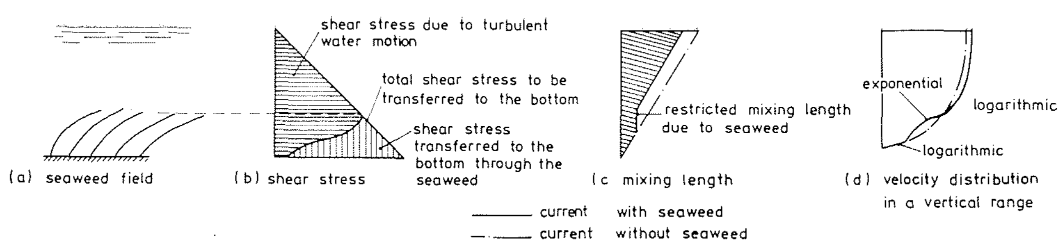
15/ Average bottom changes in test area.



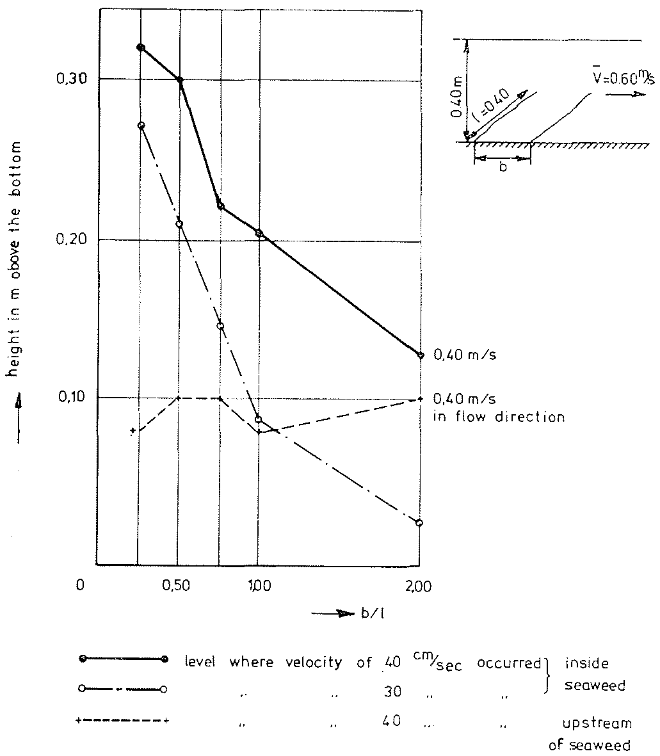
16/ Average bottom changes in the adjacent area west of the test area.



17/ Protection of a 200 mm ∅ submarine pipeline.



18/ Schematic representation of the seaweed effects.



19/ Influence of geometry of the weed screen on the velocities over the bottom in the weed field.

sult. In a gully or in a channel the gradient of the water-level above the seaweed will increase, as a result of which the above-mentioned shear force will also increase. If, however, the water can flow away laterally, then the most important effect will be an increased velocity round the seaweed field and a decreased velocity inside the seaweed field.

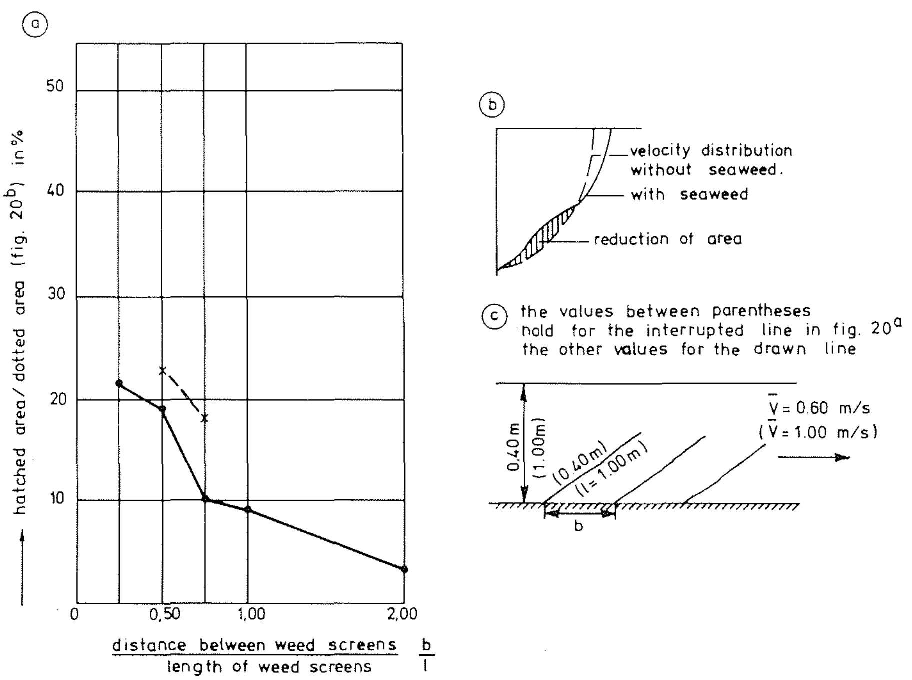
As a result of the dynamic pressure, the seaweed is pushed downwards; the ratio between the dynamic pressure and the buoyancy determines in how far this will be the case.

The dynamic pressure can be divided into an "external dynamic pressure" on the seaweed field (which is proportional to the difference of the square of the water velocity inside and outside the seaweed) and an "internal dynamic pressure", which is the result of the water velocity through the seaweed field.

The external dynamic pressure acts particularly on the luff-side of the seaweed field; it pushes the formost seaweed threads more downwards than the others. As a consequence of the external dynamic pressure, there is a transition from the velocity distribution over the vertical range outside the seaweed field to the velocity distribution inside the seaweed field.

The internal dynamic pressure is exerted on the entire seaweed field; the result is that, even far from the luff-side, the seaweed does not stand upright. Furthermore, this pressure results in the transfer of the turbulent shear stress of the overlying water to the seaweed. The latter statement can be elucidated as follows.

In a current *without* seaweed the turbulent shear stress



20/ Effect of mutual distance of weed screens (expressed in screen length) on the reduction of the velocity near the bottom.

at a certain height above the bottom is proportional to the gradient and the weight of the overlying water; the shear stress is therefore zero at the surface, but increases linearly with depth to a maximum at the bottom (Figs. 18 a and b). This shear stress is transmitted by transfer of horizontal impulses due to turbulent vertical velocity variations: if water particles from layers near the bottom, which are in slow motion, are exchanged with particles from higher layers, which move faster, then the current in the higher layers will be slackened, where the current in the lower layers is accelerated. From this it follows that the shear stress will increase with the vertical distance over which the water exchanges (the mixing length) and with the velocity gradient in vertical direction.

In a current *with* seaweed, the shear stress in the water layers above the seaweed will likewise increase linearly with the distance to the water surface; in the seaweed field itself, however, this shear stress will not only be transferred to the bottom by turbulent exchange but also by the tensile stress in the seaweed threads. The transfer of the shear stress in the water to the tensile stress in the seaweed threads is effected by the said internal dynamic pressure on the seaweed field (fig. 18 b).

A good calculation of the velocity distribution of a current *without* seaweed is obtained by assuming the mixing length to increase linearly with distance (Fig. 18 c), after which a logarithmic velocity distribution is found.

In the case of a current *with* seaweed, the mixing length in the seaweed field is limited to a maximum (Fig. 18 c) of the order of the perpendicular distance between two successive seaweed screens; over the seaweed the mixing path can increase again. Now three layers are formed, whereby in the intermediate layer the mixing path through the seaweed is restricted, while this is not yet the case in the lower layer and no longer the case in the upper layer.

If the water layer with seaweed is thin in comparison with the water layer above, the velocity distribution can be approximated [5]; it is logarithmic in the lower layer (fig. 18 d), subsequently it is exponential in the intermediate layer and then again logarithmic in the upper layer (Fig. 18 d).

It is beyond the framework of this article to give a calculation method, which is, however, being developed by Rijkswaterstaat.

What does this current pattern mean for the sand movements in the seaweed field? In general, sand transport is divided into bottom transport and suspended transport.

The *bottom transport* depends on the ratio between the turbulent shear stress on the bottom and the allowable shear stress; the latter is of the order of the weight of one layer of grains times a friction coefficient. As the seaweed absorbs a large portion of the shear stress, the bottom transport will decrease strongly.

The distribution of the *suspended* transport over the vertical is caused by the equilibrium between upward sand transport as a result of the turbulent mixing (which transports water from the lower layers with high sand concentration to the upper layers with low concentration), on the one hand, and the inherent vertical movement of the sediment as a consequence of gravity, on the other. Owing to the seaweed, there is less mixing; the sand will then swirl up less. As a result, starting from a given bottom concentration (following from the bottom transport) lower sand concentration will occur in the vertical range, hence, there will be reduced suspended transport.

If, however, a current along the sides of the seaweed field is possible, this will result in increased current velocities and hence, scouring. Furthermore, although a sand saturated current on the luff-side of the field will deposit its sand in the seaweed field, on the lee-side the sand-transport capacity will be greater than the amount of sand present in the current, as a result of which erosion will occur [(b)]. These edge effects need not *a priori* be detrimental; this will depend on the situation. Probably this edge effect will be less if the distance between the screens is increased at the edges of the seaweed field.

With regard to the distance between the screens, the following can be stated: if the distance between the screens is large, the "intermediate layer", where the seaweed reduces the mixing length, will disappear (Fig. 18 c). It is clear that, as a result, the effectiveness of the seaweed also diminishes; this can be expected if the distance between the screens is more than 1-2 times the length of the weed.

Only a rough picture is given here; the influence of entanglement of threads or the difference between tufts or seaweed screens cannot be directly derived from it. This is much more evident from model trials; it is important to know how far these correspond with the above picture.

The experiments at the Hydraulics Laboratory were carried out at water depths between 0.5 and 2 m and at an average current velocity, mostly 0.6 m/s; in these trials no waves were applied. The first trials showed a significant difference between the results with screens perpendicular to the current and tufts, the specific density of the seaweed tapes being the same. In the case of the screens, a reduction of the current at the bed and even a considerable decrease in current erosion was obtained, but the tufts did not reduce the current velocity at all, probably because more turbulence occurred between the tufts.

The results of the first trials led to more systematic research into the method of laying the seaweed; it was found that the parameter b/l ($b =$ distance between the screns, $l =$ lenght of the weed screens) is of much importance in limiting the current velocities at the bottom (Figs. 19 and 20). In figure 19 is indicated the height at which current velocities of 30 cm/s and 40 cm/s occurred as a function of b/l. This height has been found to be greater at low values of b/l, which means that in this case lower velocities occur at the bottom.

In Figure 20 b the velocity distribution of the current upstream of the seaweed area and the simultaneous distribution inside the area have been plotted in the same figure. Both distributions together enclose the hatched area in Figure 20 b, which is a certain percentage of the total area, enclosed by one of the velocity distributions and the horizontal and vertical axis (dotted area). This percentage has been plotted against the distance/lenght ratio b/l (in Fig. 20 a). When b/l is small (which means a large overlap of the successive screens) a large reduction is found.

Attention is drawn to the fact that these graphs are only valid for foamed polypropylene, since only this material was used in these new trials. Furthermore, these trials showed that the relative reduction of the current

(b) The Dutch call this "sand hunger" of a stream, which is an illustrative expression.

does not depend on the magnitude of the current itself. Within the variation of the waterdepths used, no significant effect of water depth was found.

The velocity distribution found in the laboratory corresponds not satisfactorily with the theoretical one; the theoretically predicted decrease in sand transport after seaweed installation was also confirmed in trials (Fig. 21). Figure 21 shows that the amount of sediment transport, which occurs in a current without seaweed only occurs in currents with seaweed, when the mean current velocity is much higher. An indication of erosion along the edges of a seaweed field is shown by the landward edge of the seaweed field on Texel (Fig. 14).

6 — Cost aspects

6.1 - Installation cost of Shell/Nicolon weed screens.

In chapter 4, at the end of section 4.1 it has been indicated that in many cases one meter of weed screens having threads of 2 m length per m^2 of bottom is considered to give adequate protection against erosion. An accurate estimate of the costs for the weed screens, including weighting and installation, cannot be given, owing to the fact that the conditions under which artificial seaweed is used vary widely, depending on the location and the laying method applied.

A reasonable guess seems that on average these costs will be approx. Nfl. 15-20 per m^2 of sea floor. So—when compared with traditional coastal protection methods—the artificial seaweed approach will be about 4-6 times cheaper.

6.2 - 0.2 g/cm^3 versus 0.7 g/cm^3 material.

The question has often come up, whether stretched foam strands with a low density of about 0.2 g/cm^3 can compete pricewise with the high-density chemically blown tapes (about 0.7 g/cm^3), for artificial seaweed applications, since the manufacturing costs for the latter material is 30 % lower.

The answer to this is affirmative: for a screen made of stretched polypropylene strands, 70 g of yarn is required per m^2 of screen, while for a screen made of chemically blown tapes, 210 g of yarn is required per m^2 of screen. The stretched polypropylene tape has the additional advantage of having an appreciably greater buoyancy: it can be calculated that with a certain amount of base polymer a buoyancy of at least 5 times higher is obtained when stretched polypropylene foam strands are used instead of the high density chemically blown tapes.

7 — Other applications

Apart from coastal protection and submarine-pipeline protection, artificial weed might also be used for other interesting applications.

7.1 - Biological purification of effluent.

As micro-organisms easily stick to artificial weed, the Agricultural University at Wageningen, The Netherlands, is investigating whether biological water purification can be enhanced by placing artificial weed in polluted water or in tanks of water-purification plants.

7.2 - Artificial fishing reefs and related applications.

It has been found that artificial seaweed attracts all kinds of fish in areas where natural hiding- and nesting places are lacking. Small-scale trials carried out by Koninklijke/Shell Plastics Laboratorium Delft confirmed this point. Hence, installation of weed fields in places, with less favourable fishing and spawning conditions due to current conditions might be considered.

7.3 - Stabilisation of fairways.

In shallower waters huge channels are often dregded in the sea bottom to create fairways for large ships, e.g. mammoth tankers. Stabilisation of the sides of these channels with artificial weed could greatly reduce dredging coasts.

8 — Conclusions

8.1 - Shell/Nicolon screens of stretched polypropylene foam strands can be an effective means under favourable conditions in combating coastal erosion. Although the product can only be assessed after many years and after frequent usage, it is probably well suitable for stabilisation of the sea bottom, for building up a dam in swash- or tidal channels and suppressing underwashing of pipelines.

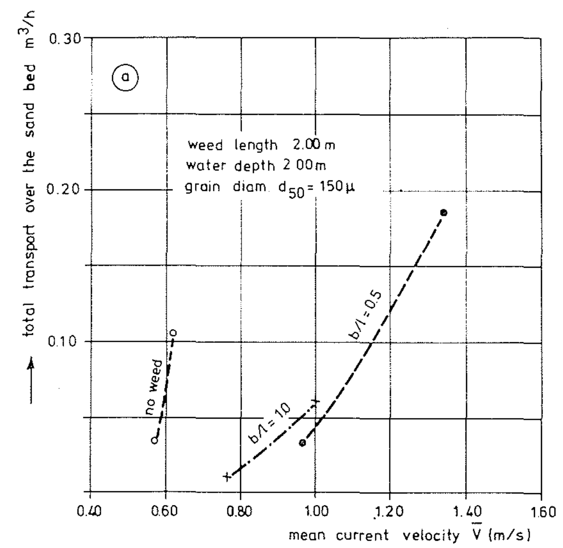
8.2 - In areas that are dry at low tide, knotting of weed threads may reduce the period over which the weed remains active. Furthermore, when used in such a zone, the weed must be stabilised against ultraviolet radiation.

8.3 - In the surf zone, a large seaweed field, consisting of long parallel rolls only should be avoided. At regular intervals, seaweed screens must be installed, perpendicular to the long rolls, so that the current is reduced in all directions. The effectiveness of seaweed in the surf zone has not yet been demonstrated in all cases.

8.4 - For weed anchoring, rigid constructions must be avoided in view of underwashing of the anchoring device. If properly installed, the system with the flexible anchoring tube filled with sand or another weighting material, has been found to work satisfactorily in practice.

8.5 - An amount of 10-15 kg of weighting material per m^2 of screen usually gives adequate anchoring. In a surf zone or in a very strong current, however, it is recommended that additional, fixed anchoring points be attached; however, in such a way that no underwashing can occur.

8.6 - As random dumping is also possible under favourable conditions, this method is recommended for areas



21/ Influence of the weed on the sand transport.

with an unfavourable wave climate. At water depths of up to 10-15 m, this method has been found to be sufficiently accurate; at greater depths and (or) very strong currents, a method such as applied at Texel can be recommended.

8.7 - Allowance should be made for edge effects, which can, however, be minimised by deliberate placement of the seaweed.

8.8 - Under the prevailing conditions, it was found that 1-2 m^2 seaweed per m^2 sea bottom is sufficient, and this was confirmed in trials and theoretical considerations. Under the present conditions, the costs, including weighting and laying, will amount to about Nfl. 15-20 per m^2 sea bottom.

8.9 - In connection with its considerably higher buoyancy, light-weight foamed strands (0.2 g/cm^3) are preferable to the usually heavier unfoamed or chemically blown material for seaweed applications.

8.10 - The increase in weight of the foamed material due to diffusion of water has been found to be negligible after many years of service.

8.11 - Apart from protection against coastal erosion, artificial seaweed can possibly also be used for other purposes, such as the protection of pipelines, breeding places for fish, wave attenuation, etc.; this point is being investigated.

8.12 - If seaweed is used on beaches, the possibility of swimmers becoming entangled in the weed and being drowned, has to be taken into consideration. Hence, application in such shallow areas should be done with due care.

Acknowledgement

We are much indebted to Nicolon N.V. for their permission to publish the results of the laboratory trials, which were carried out on their behalf at the Hydraulics Laboratory.

We also gratefully acknowledge the collaboration of the staff of the said laboratory.

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Voir le résumé en français à la page suivante

Résumé

Etude de la protection des conduites immergées dans les zones côtières ou au large au moyen de brins de mousse de polypropylène étirés

Un nouveau dispositif de lutte contre l'érosion des côtes, constitué d'algues marines artificielles, a été mis au point par la Société Shell, en collaboration avec l'entreprise néerlandaise Nicolon (*). Ce matériau a fait l'objet d'essais en mer en différentes zones situées au voisinage de la côte néerlandaise, effectués en consultation avec les Ponts et Chaussées de ce pays (Rijkswaterstaat). L'élément de base du dispositif est constitué de brins de mousse de polypropylène étirés (masse volumique = 0,2 g/cm^3), réalisés à l'aide de la technique de refoulement au gaz mise au point par la Société Shell. La « flottabilité » élevée (800 g/l) de ce matériau en assure, tant la très grande efficacité en remplissant les rôles pour lesquels il a été conçu, qu'une excellente durée utile, du fait que l'influence des différents phénomènes susceptibles de réduire la flottabilité du matériau (tel que le développement des micro-organismes, etc.) reste relativement minime tant que les algues artificielles se trouvent entièrement immergées. Par ailleurs, il a été constaté que l'augmentation de la densité du matériau due à la diffusion de l'eau à l'intérieur de celui-ci est négligeable, et ce même après une durée d'emploi prolongée.

Les brins sont tissés selon une trame à brins juxtaposés, de manière à constituer une toile formant écran. L'expérience a montré que cette disposition est préférable à celle en mèches. Le dispositif d'ancrage prend la forme d'un tube en nylon rempli d'un matériau pondéreux (tel que sable ou gravier), fixé à l'écran.

Les essais en mer ont consisté en la fermeture de chenaux existant dans les hauts-fonds de marée et les plages, ainsi qu'en la stabilisation des fonds marins dans les zones d'érosion et d'affouillement côtier intensifs. Les résultats de ces essais ont été concluants : les chenaux se sont ensablés très rapidement, et la mise en œuvre de véritables « champs » d'algues artificielles a conduit à un arrêt total de l'érosion. La présence de dispositifs de défense de ce type, à différents endroits le long de la côte néerlandaise, s'est révélée d'une excellente efficacité depuis la première mise en œuvre il y a trois ans. L'ancrage correct des algues artificielles présente une importance primordiale : à ce sujet, l'expérience acquise en mer a montré que le tube d'ancrage souple, figurant dans le système Shell/Nicolon, est à préférer aux systèmes rigides, étant donné que ces derniers se sont souvent révélés être susceptibles d'affouillement. En effet, il est indispensable que le dispositif d'ancrage puisse « suivre » toute évolution des fonds.

L'administration du Rijkswaterstaat possède une solide expérience en matière de l'implantation des « champs » d'algues artificielles. La méthode d'implantation que l'on préférera sera fonction des conditions des lieux, mais l'expérience a montré que, en ce qui concerne les profondeurs d'eau inférieures ou égales à 10 m, la mise en place « au hasard » d'écrans d'algues d'une longueur de 1-2 m donne de bons résultats, du fait, entre autres, de l'importance relativement secondaire des conditions météorologiques. Ce procédé peut convenir également en eaux plus profondes, mais dans ce cas, il faut alors bien tenir compte de l'éventualité d'un déplacement (en dérivant) des écrans de leur lieu d'implantation.

Les calculs d'ordre économique effectués ont montré que le prix estimatif des écrans réalisés selon le système Shell/Nicolon revient à environ 15-20 florins par mètre carré recouvert, compte tenu des prix du ballastage et de la mise en place. Il ressort de ce résultat que le dispositif à algues artificielles est susceptible d'être sensiblement plus économique que les procédés classiques de défense côtière et de stabilisation des fonds. Cependant, il serait prématuré d'en déduire que ce dispositif puisse se substituer à l'ensemble des procédés de protection des fonds marins, mais toujours est-il que sa mise en œuvre possible mérite une considération sérieuse dans tous les cas.

La comparaison entre les flottabilités des bandes en polypropylène réalisées par soufflage chimique (qui avaient fait l'objet d'essais antérieurs), et des brins réalisés à partir de mousse de ce même matériau, montre que celle des bandes est très inférieure à celle des brins; il semblerait donc que, à flottabilité égale, le prix de revient de ce dernier matériau soit inférieur à celui du premier d'un facteur d'au moins 5.

Compte tenu de l'efficacité des brins de mousse de polypropylène étirés en tant que moyen de défense contre l'érosion, ainsi que des avantages économiques manifestes de ce matériau, la Société Nicolon s'est assurée une licence d'exploitation du procédé mis au point par la Société Shell, et elle a déjà lancé la production commerciale des brins et des écrans en algues artificielles.

(*) Société produisant des tissus ou toiles spéciales pour emploi dans les domaines de l'hydraulique, ou en découlant. Siège à Enschede (Pays-Bas).