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HOLLOW REVETMENT ELEMENTS

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ABSTRACT

A proposal is made for a design of the cover layers of nonvertical coastal structures (such as seawalls, revetments, groins, jetties and breakwaters) by applying hollow structural elements. The respective cavity is oriented parallel to the slope face and permits the inside washing movement of the swash produced by breakers. The purpose of the new designed structure is to influence interaction processes between the near surface water particle kinematics of incomplete standing waves in front of the structure and the swash movement on the slope face. The effectiveness of such a working principle is traced back to a selective reflection effect, realised by model investigations. Applying this new type of elements, slopes can be designed steeper and/or crown heights lower.

1. INTRODUCTION

Transfer mechanisms of wave induced loadings on sloping structures represent one of the most important topics of coastal and harbour engineering research activities since many years. There are several phenomena known to be responsible for failures of revetment structures: periodically differing pressure fields on both sides of revetment elements, impact forces due to breaking waves, wave run-up and overtopping, up- and downrush velocities etc.. All of them are dominated by the breaker height. There is, however, a phenomenon affecting the breaker height, which has not been considered sufficiently in the past:

The interaction processes between the washing movement on the slope face and the wave induced particle movement in front of it.

To the author's knowledge up to now no structure has been designed so far with the objective to influence the above mentioned effect in such a way that wave induced forces and/or wave run-up heights on the structure will be minimised.

2. PHYSICAL PHENOMENON

The assumption is made that the movement of the mass of water in front of a sloping structure (such as seawalls, revetments, groins, jetties and breakwaters) can be regarded as an oscillating continuum, characterised by different natural frequencies according to the actual geometric boundaries (water depth, slope an-

gles). In this arrangement the source of excitation is realised in the waves coming from sea, and the different degrees of freedom are represented - on the one hand - by the deflections associated with a set of individual partial standing waves (partial clapotis) (Büsching, 1992)[5] and - on the other hand - by the washing movement due to run-up and run-down of broken waves on the slope face. The total oscillating system is being assumed to be equivalent to an elastic chain consisting of several oscillators with different natural frequencies.

3. PROPOSAL

In any coupled oscillating system the influence on one degree of freedom has an effect on the remaining degrees of freedom. Hence, the author has proposed to separate the washing movement from the remaining flow field in order to avoid interaction processes between them (Büsching, 1991)[1]. As a matter of principle this can be achieved by double sheathing structures, consisting of an inner and an outside coverlayer with a cavity between them. Fig.1 shows the axionometrical view of the principle arrangement of a hollow structure, forming an *integrant structural element* of a sloping structure per unit meter shoreline.

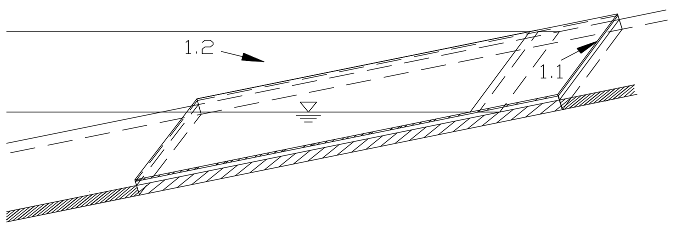

Fig.1: Cavity per Unit Meter as an Integrant Part of a Sloping Structure

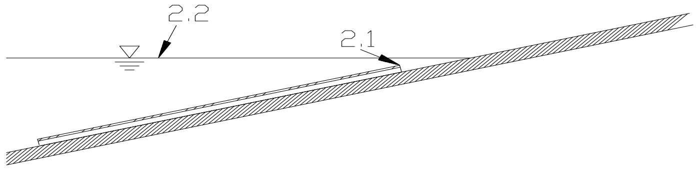

Fig.2: Sheathing above Existing Cover Layer

In Fig.2 a vertical cross section of a coverlayer configuration is shown completed by a sheathing structure and Fig.3 contains the principle arrangement of hollow structural elements with openings at their upper sides. Accordingly the respective cavities consist of hollow structural elements, which are at least partly closed on their circumference and thus permit the inside passage of the downrush water of breakers. In particular such arrangements allow the water, after wave breaking being present above the edges (1.1), (2.1) or (3.1), to be led back below reference water levels (1.2), (2.2) or (3.2) respectively.

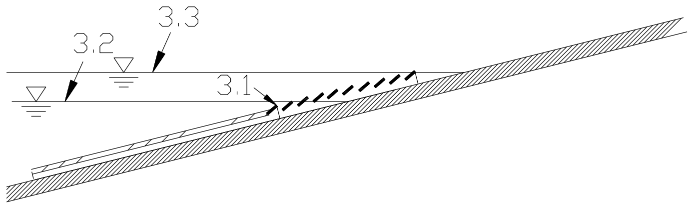

Fig.3: Partly Permeable Sheathing above Existing Cover Layer

As has been proved by model investigations, such a device is suitable not only to reduce breaker heights and run-up heights but also to influence the breaker type and its position on the slope face, see further below.

4. STRUCTURAL PERFORMANCE

New designs of sloping coastal or harbour structures can be based on the integrant arrangement of cavities to be oriented more or less parallel to the slope face. On the other hand prefabricated cavity structures, to be fixed to existing supporting structures, can often provide a more economical solution. In both cases it is, however, easy to meet the coincident requirements of permeable or impermeable revetments (perpendicular to the slope face). Hollow revetment elements - whether partly open at their upper and/or bottom sides or closed at any side - can be made of concrete, steel or compound materials, even by the use of synthetic materials. Hollow concrete elements preferably can be used for the cover layers of revetment structures. In the case of breakwaters or similar structures bigger size hollow armour units can be designed, simultaneously forming the basic supporting system. From the large variety of proposals contained in the respective patent documents (Büsching,1989[2], 1990[3], 1991)[4] two examples only are outlined briefly below.

4.1 Hollow Concrete Revetment Element

The use of structural elements, made of concrete, in general should be restricted to highly loaded partitions of dike or sloping harbour structures only. This objective can easily be met in using hollow revetment elements, as they are required in the vicinity of the design water level only. With respect to the working function, however, the moulding of the inlet openings and of the cross-sectional area of the tubular members are essential. In order to prevent possible blockages the cross-sectional area has to be adapted to the hydraulic requirements.
In this context it has to be pointed out that the system disposes of a *mechanism acting against blockages*: If a partial blockage occurs this will result in a malfunction of the system. In this case the system responds with increasing amplitudes in its pronounced degrees of freedom - say increasing wave heights and increasing washing movements on the slope face. This effect contributes to the instationary process counteracting sedimentation and consolidation anyhow. Moreover there is an influence resulting from the altitude level of the lower edge of the hollow structure relative to a limiting level, up to which wave run-up can act in the sense

of a flushing movement. The later effect can be intensified by an appropriate moulding of the lower edge of the hollow structure.

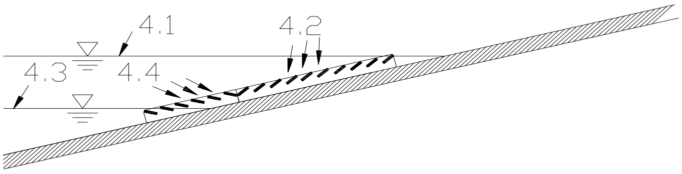

Fig.4: Swash Openings in the Upper and the Lower Part of a Hollow Revetment Structure

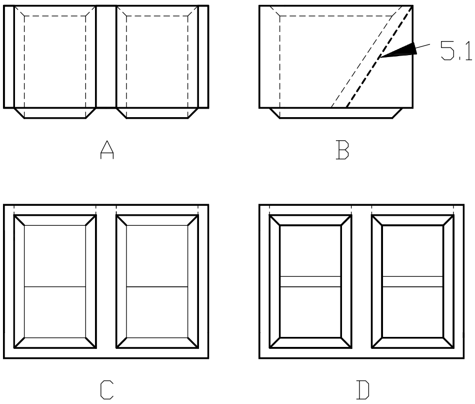

Fig.5: Hollow Concrete Revetment Element; Plan View (A), Side View (B), Upstream View (C), Downstream View (D)

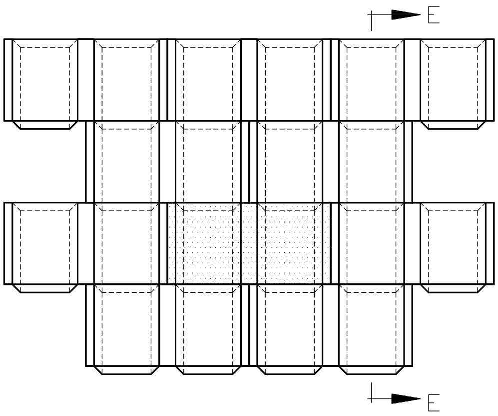

Fig.6: Plan View of Interlocking Hollow Concrete Revetment Elements

An adequate moulding can bee seen from Fig.04.: Near water levels (4.1) (design level) the openings (4.2) support the inlet of backrush water, whereas during periods of lower (tide-)water levels (4.3), near the lower edge of the hollow structure, the openings (4.4) support the inlet of the uprush water.

Fig.5 shows a hollow concrete revetment element with corresponding mouldings at its upstream and downstream ends. As to be seen from Fig.6 the mouldings are of such a kind that interconnections exist between every 5 concrete elements. In order to support the inflow of water, the top sides (5.1) of the elements are inclined. Fig.7 shows an arrangement of such elements placed on a slope homologously. The same elements can be used for a configuration similar to that described in Fig.4. However, an additional element has to be used to fit in the joint area.

In Fig.8 a single prototype hollow concrete element is shown which is being used for tests on a natural scale at the breakwater site of the harbour entrance of Baltrum Island/North Sea. The main purpose of this prototype test is to prove the system's ability to act against blockages as described above. For this reason the whole slope face was constructed in using the same elements, which do not appear to support predominately the inflow or outflow, see Fig. 12.

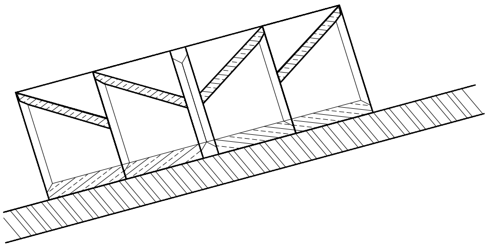

Abb.7: Sectional View of Interlocking Hollow Concrete Revetment Elements

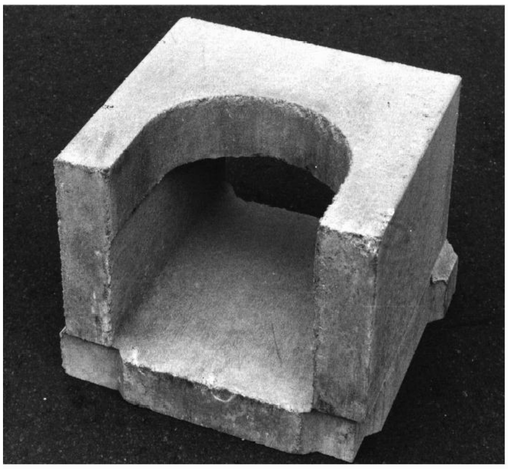

Fig.8: Prototype Scale Model of a Hollow Concrete Element

Since 1992 *no blockages* have occurred, although sandy beaches exist very close to the breakwater. In addition, the positive side effect of an increased air entrainment can be studied here. It can be supposed that this effect on the one hand will diminish the probability of shock pressures, and on another can improve the near slope water quality.

4.2 Hollow Armour Units

It is well known that reflection from sloping breakwaters becomes less when the permeability of cover layers (consisting of Tetrapods, Dolosse, Accropodes, Seabees or similar armour units) has been increased. There is evidence that this effect is *not only* due to corresponding rates of transmitted energy through the breakwater and energy dissipation processes taking place in the different parts of the breakwater. Hence it can be concluded that the positive effect of such structures also can be traced back to the reduced interaction processes, described above: After wave breaking a considerable part of the water masses, present on the breakwater, is at first transferred *into the structure*. As the outflow from the structure takes place below the water level and moreover the phase lag has changed, the respective interaction with the near surface particle kinematics of the following wave often is reduced.

It can, however, be supposed that the total loading conditions will be improved further *more by a more efficient (uniform) drainage system*. This can not be achieved by bigger spaces between (known) armour units, because this would result in a loss of stability of the structure. But *hollow armour units* can be constructed in such a way that they dispose of efficient hydraulic cross sections.

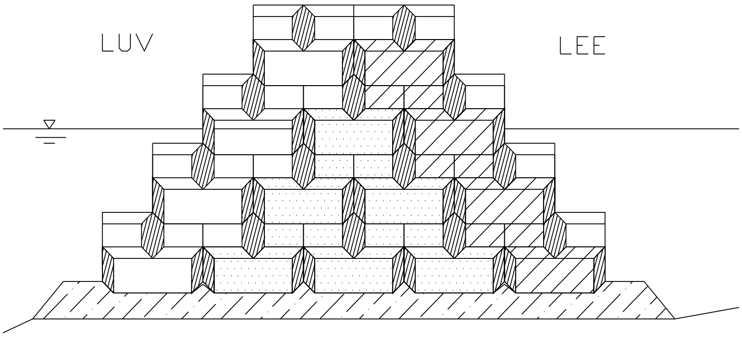

Fig.9: Breakwater Constructed by Hollow Armour Units

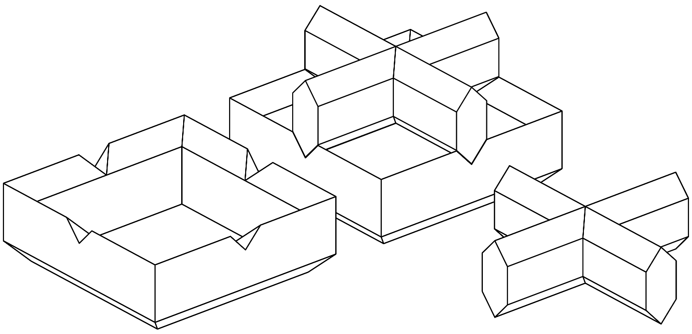

Fig.10: Hollow Concrete Armour Unit Composed of two Components

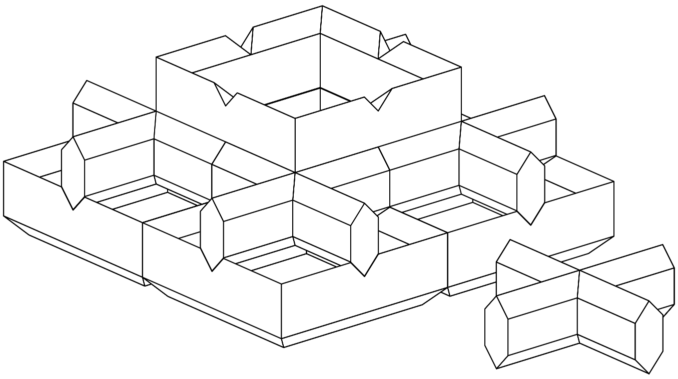

Fig.11: Binding Effect of Hollow Concrete Armour Units

Fig.9 shows the cross section of a breakwater structure composed of hollow armour units. In order to prevent wave induced currents through the structure, the armour units are filled up with a suitable material in the core section. Similar material can also be filled into the units of the harbour side slope, whereas the armour units at the seaward side remain empty in order to permit the favoured inside passage of the downrush water.

The structural element of the breakwater contained in Fig.9 is to be seen in the middle part of Fig.10. This can be moulded on the whole by reinforced concrete; preferably it is composed, however, from the components placed on its left and on its right hand sides.

Apparently the execution of such a construction will require a higher degree of accuracy than random placing of known armour units. On the other hand there are advantages resulting from the fact that wave absorption is more effective, slopes can be performed steeper, crown heights lower and the demand for weight of the individual armour unit is reduced. In particular the binding effect between the units appears to be improved; the pulling out of single units - as known from Tetrapods - seems not to be a relevant matter of attention, see Fig.11.

5. MODEL INVESTIGATIONS

In order to demonstrate the advantages of a hollow revetment structure versus a conventional smooth structure, model investigations (scale 1:5; slopes 1:0 ≥ 1:n ≥ 1:3) have been performed in the Hydraulic Laboratory of Bielefeld Polytechnic University (FH Bielefeld) since 1990. First results on irregular water level deflections in front of sloping structures 1:3 had been published previously by the author in 1992 [5]. The most important outcome from that work consisted in the finding that reflection from a sloping structure - whether smooth or hollow - strongly depends on the frequencies contained in the spectrum of gravity waves. The longer the frequency components the more downslope they are reflected. Due to such a response from the sloping structure a *set of partial clapotis* could be detected to be present coincidentally in front of the sloping structure. The partial clapotis - each composed from a number of bound frequency components of the same wave length and by this reason possessing of an anomalous dispersion [6] - being the more pronounced the lower its mean frequency. The reflection coefficients $C_{R,i}$ belonging to such individual partial standing waves in this case were approximated in applying

$$C_{R,i} = \frac{\sqrt{E\max,i} - \sqrt{E\min,i}}{\sqrt{E\max,i} + \sqrt{E\min,i}}\,.$$

Where :

Emax = maximum energy of contributing components at clapotis antinode,
Emin = minimum energy of contributing components at clapotis node,
i = number of clapotis.

Reflection coefficients based on response spectra taken nearest to the sloping structures are to be seen from Fig.12.
The present paper on the one hand incorporates a supplement to the previous measurements and on another consists in an extension to reflection phenomena of *monochromatic waves* acting on *different* slopes:

1:n = 1:0 (90°),
1:n = 1:0.1 (84.25°),
1:n = 1:0.5 (63.43°),
1:n = 1:1 (45°),
1:n = 1:2 (26.56°),
1:n = 1:3 (18.43°).

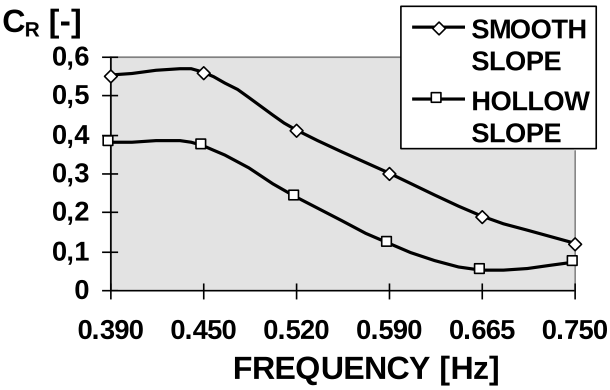

Fig.12: Reflection Coefficients of Component Waves on Slopes 1:3

The set of monochromatic waves was selected such to correspond roughly to the frequency range of the response spectra measured previously.

5.1 Model Setup

The particular model arrangement is oriented at the prototype conditions corresponding to the harbour entrance of Baltrum Island/North Sea. Here an 8 m high breakwater was built in 1992 in a water depth of about 4.5 m (MHW). The objective of the breakwater is to prevent waves from the harbour entrance and further more to reduce reflections in the harbour. Therefore it was decided to carry out rather comprehensive investigations comprising impermeable smooth slopes and such equipped with the hollow revetment structure to be seen from Fig.8 and Fig.13.

Fig.13: Hollow Slope Structure 1:3 at Harbour Entrance of Baltrum Island, North Sea

As far as irregular waves on slopes 1:3 are concerned, the measurements had been carried out by Kruse (1994)[7] and the measurements on monochromatic waves (with reference to the total set of slopes) were performed by Meyer (1995)[8] and Thienelt (1995)[8].
Because of the water depth conditions to be considered in the model, the input wave spectrum used was similar to those measured near the breaker zone of Sylt Island/North Sea (Büsching, 1976)[9]. Hence, in the model input and response spectra (scale 1:5) the energy densities are concentrated around two peaks at frequencies $f_1 = 0.50$ Hz and $f_2 = 0.67$ Hz corresponding to a wave group short enough to not be rereflected from the wavemaker. Although the shape of the input spectrum used for the previous investigations was different, it will be shown that the respective results can nevertheless be compared to the results already available from the previous investigations as well as to the actual results of the set of monochromatic waves comprising frequencies $0.45 \leq f \leq 0.85$ Hz and wave steepnesses $1{:}30 \leq H/L \leq 1{:}20$, see further below.
The most important change with reference to the previous investigations consisted, however, in concentrating measurements on the very vicinity of the sloping structure. This area previously could not be investigated because of the water depth being to small for the operation of wave gauges. For the actual measurements 16 pressure devices were placed on the slope face in addition to the wave gauges still used at stations further away from the slope. In order to get more detailed information, the spacing of the pressure devices on the slope in all cases was less than 10 cm and the spacing of wave gauges was 18 cm in front of the structure foot.

5.2 Results

In the following the contents of a few graphs only will be explained briefly. The total results will be contained in an additional publication. Values shown refer to the model 1:5.

5.2.1 Irregular Waves on Slopes 1:3

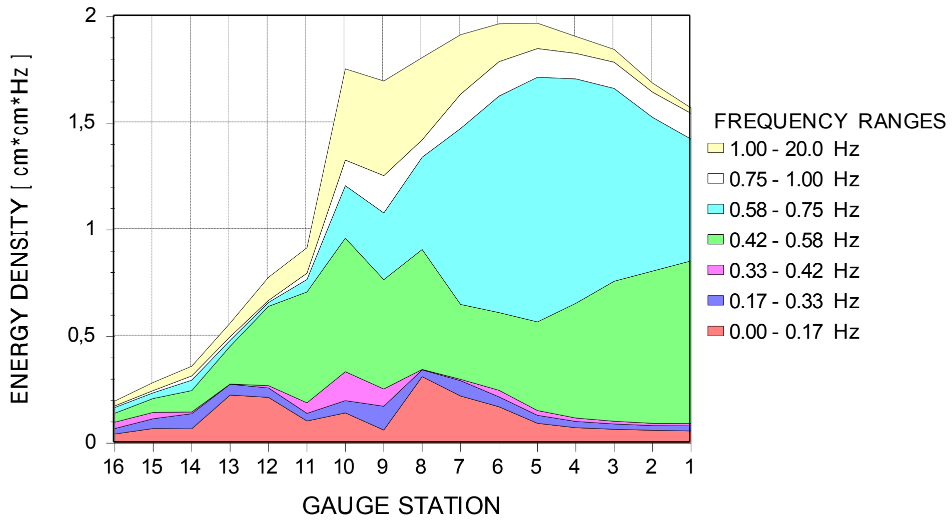

Fig. 14: Upper Curve: Total Spectrum Energy on a Smooth Slope; Curves below: Energy Content of Different Frequency Bands

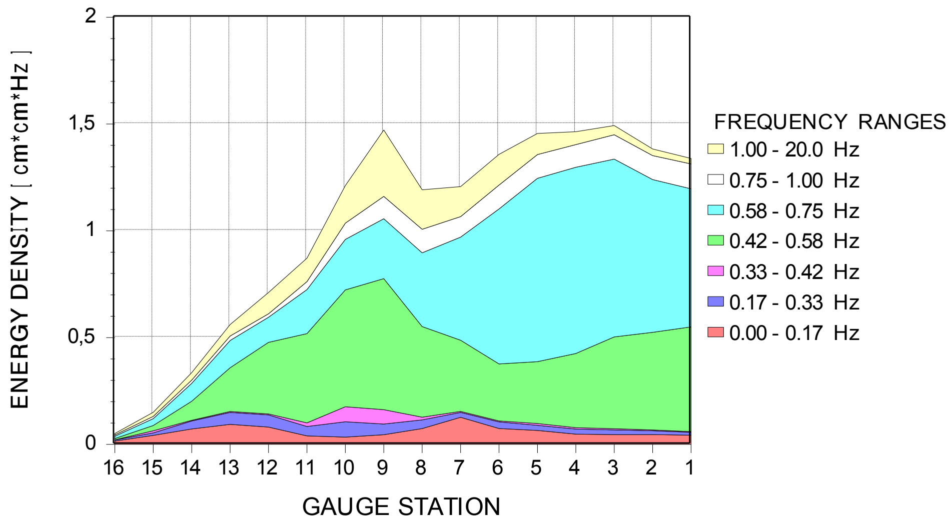

Fig.15: Upper Curve: Total Spectrum Energy on a Hollow Slope; Curves below: Energy Content of Different Frequency Bands

The signals from the 16 pressure transducers were measured synchronously and were processed by spectrum analyses confined to a frequency range of 0.03 to 20 Hz. The plane of the stillwater level intersects the slope face between gauge station numbers 10 and 11.
On Fig. 14 and Fig. 15 the values of the respective integrated spectrum areas representing the total variances of the signals are plotted with reference to the gauge stations. Hence, a kind of en-

ergy distribution is represented by Fig. 14 for the smooth slope and by Fig. 15 for the hollow slope structure. Comparing the two graphs the efficiency of the hollow structure is obvious especially because of the 25% reduction in the range about maximum pressure energy at gauge station numbers 1 through 8. From Fig.14 it can be seen that maximum breaker height on the smooth slope on an average can be located near gauge station 5, whereas there is a second maximum due to the jets of plunging breakers hitting the slope face at pressure transducer number 10.
On the hollow slope (Fig.15) also two maxima are to be seen, however, at gauge stations 3 and 9 respectively. The change in the shape of the energy distribution is due to a different breaker type on the hollow slope structure. It has to be mentioned here that pressure devices were located corresponding to the centres of the openings in the hollow structure.
With respect to the energy content of confined frequency ranges (as specified in the graph) it is confirmed, that on both slopes the energy is dominating in the two adjacing frequency ranges 0.42 to 0.58 Hz and 0.58 to 0.75 Hz. Moreover from the distribution of the energy of those frequency ranges along with the slope face the coincident presence of partial standing waves - as known from the previous investigations - can also be detected with a node near station 6 for the frequency range 0.42 to 0.58 Hz and an antinode near station 5 respectively 4 for the frequency range 0.58 to 0.75 Hz. From the reduction of the energy content in the frequency range 1.0 to 20.0 Hz (hollow versus smooth slope) it can be concluded that also *wave impact pressures* are less on a hollow structure. Finally it can be concluded from the lack of energy at station 16 on Fig.15 versus Fig.14 that washing movement is less on the hollow slope.

5.2.2 Monochromatic Waves on Different Slopes

In order to investigate changes of reflection phenomena in front of steeper slopes than 1:3 also, water level deflections were measured - on distances of about one wave length - at wave gauge stations equally spaced 18 cm starting near the line of intersection of the stillwater level with the slope face. Hence, for instance, for a monochromatic wave of 0.45 Hz measurements were taken synchronously at about 25 gauge stations. With the measurements plotted reflection coefficients for monochromatic waves were calculated applying

$$C_R = \frac{H_{\max} - H_{\min}}{H_{\max} + H_{\min}}$$

Where H_{max}= maximum wave height at clapotis antinode,
H_{min}= minimum wave height at clapotis node.

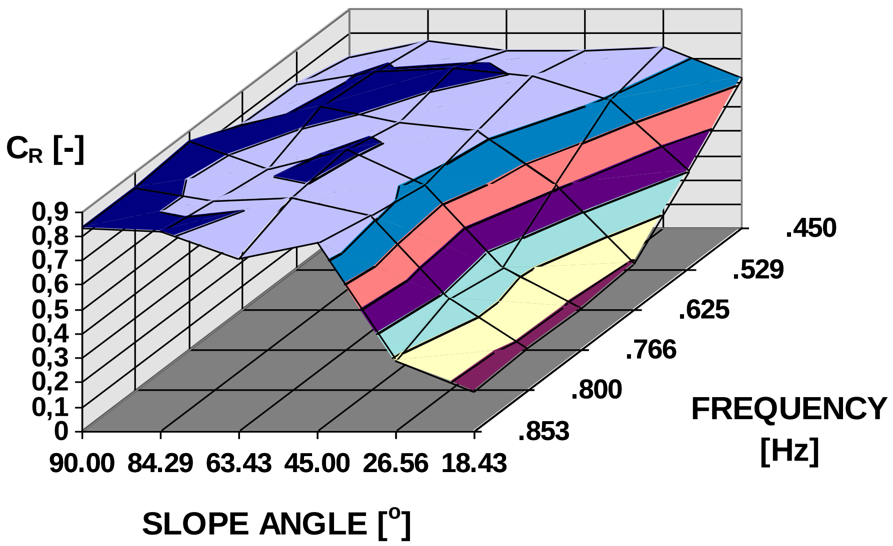

Fig.16: Reflection Coefficients at Smooth Slope Structures Depending on Slope Angle and Frequency.

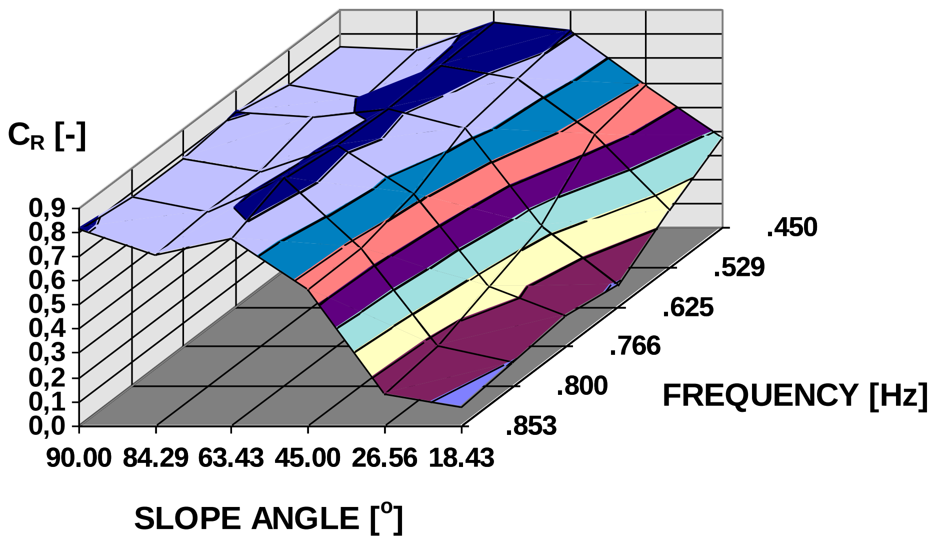

Fig.17: Reflection Coefficients at Hollow Slope Structures Depending on Slope Angle and Frequency.

As 6 waves were investigated on 6 different slopes, totally 36 reflection coefficients were extracted from the measurements each for the smooth and the hollow revetment structure. They are to be seen altogether in Fig.16 and Fig.17 respectively.

On the steeper *smooth* slopes inclined 1:0 (90°) ≥ 1:n ≥ 1:1 (45°) reflection coefficients found are in the order of $C_R \approx 0.8$ slightly with the tendency of decreasing values with decreasing frequencies. On slopes 1:2 (26.56°) and 1:3 (18.43°), however, reflection coefficients for the higher frequencies are much smaller and the *inverse* tendency with decreasing frequency can be seen. Especially the values on the slope inclined 1:3 can very well be compared to those of Fig.12.

On the hollow slope structure in general the reflection coefficients are smaller except for the slope 1:0.5 (63.43°) and the lower frequencies on slope 1:1 (45°). But contrary to Fig. 16 already on this slope the tendency of increasing reflection coefficients with decreasing frequencies is found and from that on reflection coefficients decrease steadily with the slope angle decreasing and with the frequency increasing. The values on the hollow slope 1:3 also can very well be compared to those of Fig.12.

In addition to the reduction of reflection coefficients on slopes ≤ 1:1 (45°) another property of the hollow slope structure consists in its ability of changing the breaker type. This feature can be correlated to the reflection coefficient, see below. But probably there is also a correlation between the breaker type and the node position of the partial clapotis nearest to the slope face. On Fig.18 and Fig.19 the relative values a/L (a = distance of the node position from the line of intersection stillwater level with the slope face; L = wave length) are plotted for the smooth slope structure and the hollow slope structure respectively. It has to be mentioned here that only for the steeper slopes 1:0, 1:0.1 and 1:0.5 the position of *every* node nearest to the slope could be measured *directly*. On the more gentle slopes partly those positions are somewhat theoretic and have been derived from nodes, which were measured further away from the slope faces. In general it is found that the node position has shifted in the upslope direction with the slope angle decreasing and with the frequency increasing.

In the following tables it is tried to attach visual observations of water level deflections (partial standing waves or breakers) to values a/L. On the smooth slope limits *roughly* can be determined:

0.25 ≥ a/L ≥ 0.20	nearly perfect standing waves,
0.20 ≥ a/L ≥ 0.15	transition to surging breakers,
0.15 ≥ a/L ≥ 0.10	surging breakers,
0.10 ≥ a/L ≥ 0.025	collapsing breakers,
0.025 ≥ a/L ≥ -0.1	plunging breakers.

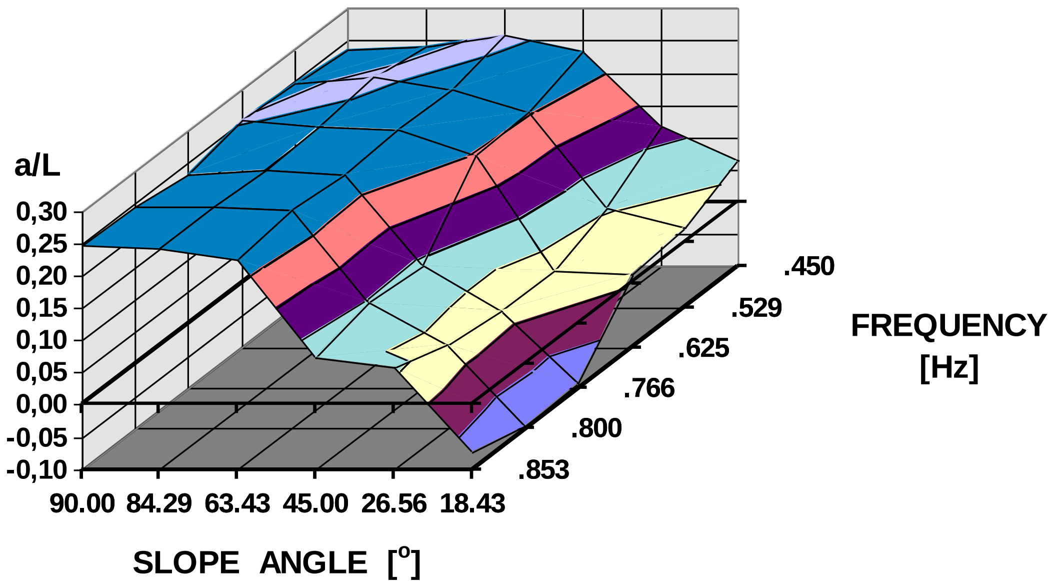

Fig.18: Relative Node Distances a/L from Smooth Slopes Depending on Slope Angle and Frequency.

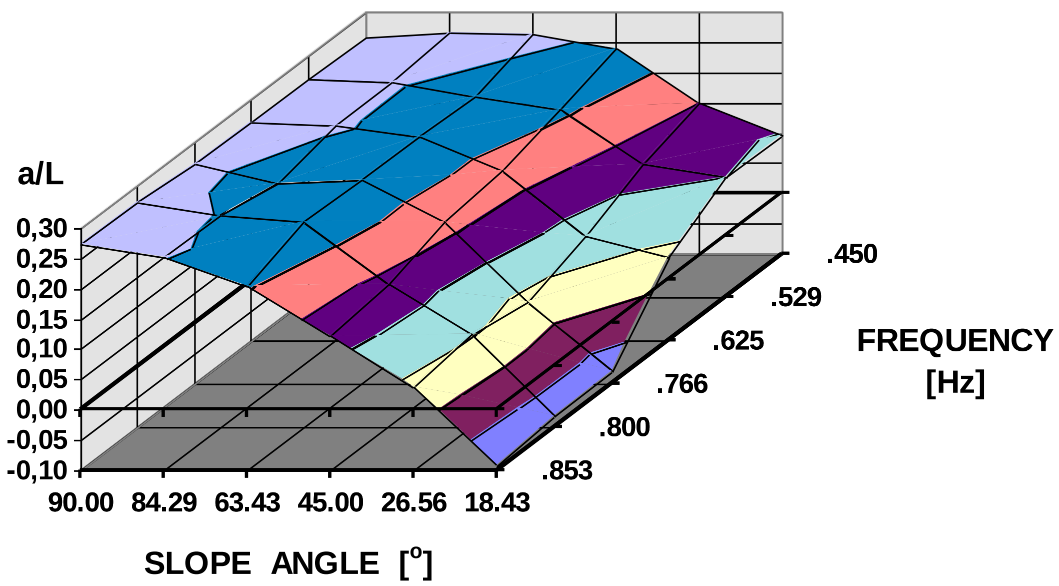

Fig.19: Relative Node Distances a/L from Hollow Slopes Depending on Slope Angle and Frequency.

On the hollow slope structure the limits are somewhat different:

$0.27 \geq a/L \geq 0.15$ nearly perfect standing waves,

$0.15 \geq a/L \geq 0.10$ transition to surging breakers,

$0.10 \geq a/L \geq 0.05$ surging breakers,
$0.05 \geq a/L \geq -0.10$ collapsing breakers.

With respect to the hollow structure it has to be mentioned that distances a also refer to the line of intersection between stillwater level and the *smooth* slope face. Accordingly the values a/L are bigger, because reflection occurs from the hollow elements placed *in front* of the smooth slope. It can be seen from Fig.19 that this fact at least is true to the vertical structure (slope 1:0),as $a/L > 0.25$.
It should be emphasised that *plunging breakers* exist on the smooth slope 1:3 at *all* frequencies, but actually could *not at all* be observed on the hollow slope structure.

6. CONCLUSIONS:

6.1 Irregular Waves on Slopes 1:3

Comparing the upper curve of Fig.14 to that of Fig.15 the different shapes of the *pressure variance distributions* can be attributed to the different breaker types observed: *plunging breakers* on the smooth slope versus *collapsing breakers* on the hollow slope structure. Moreover it can be stated, that the reduction of the total pressure variance by some 25% is quite remarkable. But it is less than the reduction of 35% with reference to the total *variance of the water level deflections* (breakers) in front of the structure measured in the previous investigations [5]. In this respect it is supposed that the smaller percentage rate is due to an entrapping effect of water in the hollow structure, because the water particle movement in the moment of collapsing on the whole is oriented vertical to the slope face but the vertical movement in a plunging breaker is confined to the breaker jet only.
Discussing the relative phases of the *partial clapotis* detected, the response of the pressure transducers 9 to 16 should be disregarded, because breaking kinematics is dominating at those stations. The findings can also be compared to that of the previous investigations: For instance on the smooth slope the antinode of the first clapotis (composed from component frequencies 0.58 to 0.75 Hz)is found at station 5 whereas the antinode of the second (lower frequency) clapotis (made up from component frequencies 0.42 to 0.58 Hz) can be supposed to be located at a position further downslope, which is not included in the Fig.14 and Fig.15. Thus a *selective reflection effect* governed by the water depth is confirmed in such a way that longer frequency components are reflected from a sloping structure further downslope, as the boundary of the slope becomes effective to longer frequency components earlier than to shorter ones.

6.2 Monochromatic Waves on Different Slopes

From the overall result of decreasing reflection coefficients with slope angles decreasing and frequencies increasing on slopes ≤ 1:1 (Fig. 16) it can be extrapolated inversely that longer waves even on gentle smooth slopes dispose of quite remarkable reflection coefficients. Such a tendency is preserved on the hollow slope structure (Fig.17) although reflection coefficients are remarkably less. There is no doubt that the hollow structure offers an economic solution for slopes inclined 1:3 and 1:2. The *maxima* of reduction rates are ΔC_R = -0.24 (-39%,) for the longest wave (0.45 Hz) on slope 1:3, but for the shortest wave (0.853 Hz) ΔC_R = -0.22 (-28%) even on slope 1:1. Thus hollow elements can also be used on a slope 1:1, if waves are short. At steeper slopes, however, this kind of structure is of no use. This was expected, as the working principle is not adapted to the particle movement of nearly standing waves.

With respect to the phase relation of partial clapotis on the individual slopes it is confirmed also for monochromatic waves that they are reflected at a position the more downslope the longer they are. As a general impression it can be inferred that the phenomenon of *partial reflection from a sloping structure* essentially is governed by a phase difference between oncoming and reflected waves. Comparing Fig.18 and Fig.19 it is found that this difference is predominantly depending on the slope angle but not so much on the surface configuration of the sloping structure.

As to the *most impressive* change of breaker types combined with a remarkable change in the runup movement (both correlated to decreasing reflection coefficients on the hollow slope versus smooth slopes), it can be stated that it is *not* predominantly due to energy dissipation induced by the hollow structure. It is, however, caused by successfully influencing the coupling mechanism between the washing movement and the particle movement at the breaker toe in sense of a prevented feed-back. The particle movement in front of the breaker is no longer supported by the backwash movement (moreover with the consequence of a reduction of the breaker height). Especially this can be deduced from the change of breaker type on slopes 1:3. As dissipation by plunging breakers is said to be more intense than by collapsing breakers, the reflection coefficient associated with plunging breakers should be less than that of collapsing breakers. But quite the contrary was found for irregular waves as well as for monochromatic waves breaking by plunging on the smooth slope or by collapsing on the hollow slope structure respectively.

Thus summarising also the results of the present investigations support the idea, the author started from: The washing movement on the slope face together with the individual partial standing waves can be considered to form a coupled oscillating system. This system, assigned by different degrees of freedom, can be affected by influencing the washing movement on the slope face.

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