EROSION OF SEDIMENT THROUGH CELLULAR REVETMENT BLOCKS APPLIED AS SLOPE PROTECTION ALONG COASTS AND INLAND WATERWAYS

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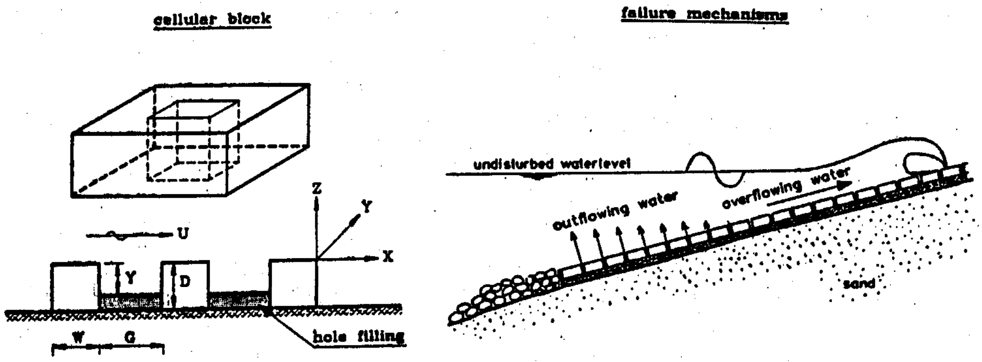
ABSTRACT: Erosion of banks and dikes subjected to water motion can be prevented, for instance, by application of cellular concrete revetment blocks. This type of revetment combines the merits of a closed block revetment and a slope revetment consisting of loose materials. Advantages are high permeability, high stability against wave attack and low block weight. On top of this, cellular blocks are appealing because they allow the growth of vegetation. It is of vital importance that the granular material in the holes does not erode completely. Therefore physical model tests were carried out in order to investigate the stability of the fillings in the holes when attacked by waves and currents. Based on the results relationships might be derived between, on the one hand, water motion and on the other hand, hole dimensions and characteristics of the materials in the holes. This paper describes the tests and the results obtained so far.

1 INTRODUCTION

Unprotected dikes and banks subjected to water motion can erode severely. Erosion can be prevented, for instance, by application of a closed concrete block revetment. Uplift pressures under this almost impermeable covering layer can lead to the failure of the structure. Very permeable loosely packed materials such as riprap, on the other hand, cannot always withstand the forces due to wave attack, since individual elements hardly support each other.
A protective structure consisting of cellular concrete revetment blocks, that is to say blocks with holes running entirely through the blocks (see Figure 1), combines the merits of a closed revetment and a revetment of loosely packed materials.
Individual blocks are permeable enough to prevent the occurrence of high uplift pressures and support each other against wave attack. Furthermore, the holes in the blocks reduce block weight which not only makes handling easier, but allow as well growth of vegetation on banks and dikes. This aspect makes this type of revetment particularly attractive, because of the increasing interest for protective systems with a high environmental appreciation.
However, to establish a vegetation, it is of vital importance that granular material in the holes, such as sand and black earth, does not erode completely. At dikes coarser fillings are used. Erosion of these fillings should not lead to undermining of the blocks. This paper describes research into erosion and stability of granular material in the holes of concrete blocks.
Erosion of sediment in holes of cellular


cellular block

failure mechanisms

Fig. 1 Cellular concrete block revetment

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concrete revetment blocks depends on the water motion just above and in the whole structure, hole dimensions and characteristics of the sediment. Research on this subject has been carried out by Brown (1984), Parsons and Apmann (1965) and Markle (1983). A review of the relevant literature will be given.
Furthermore, attention will be paid to the velocity profile above the blocks and the hydraulic roughness of cellular revetment blocks, because these phenomena influence the occurrence of eddies in the holes and consequently the erosion of sediment. With respect to the hydraulic roughness a link has been made with artificial roughness elements.

However, because of the scarce information reported in literature, physical model tests at a lenght scale of 1 were necessary to derive design criteria for the allowable erosion of sediment in holes of cellular block revetments. The differences in hydraulic loads on slope protections along coasts and inland waterways, were the reason to carry out separate tests. Bank protections along inland waterways, for instance, are mainly attacked by ship-induced water motion, such as return current, water-level depression, transversal stern wave and ship waves, of which the latter are very simular to wind waves. In the case of dikes along coasts, however, the loads are initiated by wind waves, with important aspects such as run-up, run-down and outflowing water during run-down. Based on these differences separate investigations were carried out for blocks attacked by return current and transversal stern wave, and blocks attacked by waves (wind and ship waves). An analysis has been made using the test results, making it possible to draw conclusions concerning the possibility to apply cellular concrete revetment blocks as slope protection along coasts and inland waterways, depending on the actual water motion, hole dimensions and characteristics of sediment in the holes. The design criteria to be obtained in the end, will make it possible to determine whether or not unacceptable erosion will occur.
To conclude, it should be noted that this research project started in 1987 and continues in 1988. This implies that the presented results are just provisional.

2 THEORETICAL CONSIDERATIONS

A desk study was performed, to draw up an inventory of existing knowledge related to cellular block revetments. In the case of bank protections the study dealed with the influence of the hydraulic roughness of the covering layer on the velocity profile just above the blocks, a literature review of the velocities in holes and the prediction of the erosion depth in holes filled with sediment, at the initial stage. In the case of dikes the phenomena that play a role were investigated, making a distinction between relatively small and relatively large holes.

2.1 Velocity profile

The velocity profile of a current above a bank protection determines the resulting shear stress and consequently the shear stress parameter ψ. For the critical condition at the initiation of motion of granular material, the critical shear stress parameter is defined as :

$$\psi_{cr} = \frac{u_{*cr}^{2}}{g\Delta\ D_n} \qquad (1)$$

u_{*cr} = critical shear velocity, (m/s)
u_{*cr} = $(\tau_{cr}/\rho)^{0.5}$
τ_{cr} = critical shear stress (N/m^2)
ψ_{cr} = critical shear stress parameter (-)
ρ = density of water (kg/m^3)
ρ_s = density of granular material (kg/m^3)
g = acceleration due to gravity (m/s^2)
Δ = relative density (-)
Δ = $(\rho_s - \rho)/\rho$ (-)
D_n = characteristic size of granular material (m)

In case of a uniform turbulent flow with a hydraulic rough wall, the value of u_* can be related to the average velocity u, according to :

$$\frac{\bar{u}}{u_*} = \frac{C}{\sqrt{g}} = \frac{2.3}{\kappa}\log\frac{12\ R}{k_s} \qquad (2)$$

$\bar{u}$ = mean current velocity [m/s]
C = Chezy coefficient [m$^{1/2}$/s]
R = hydraulic radius (m)
k_s = equivalent roughness, granular material $k_s = 2\ D_n$ (m)
κ = constant of Von Karman $\kappa \approx 0.4$ [-]

For a cellular concrete block revetment values of k_s are unknown, as well as the velocity profile just above the blocks. Therefore, this type of revetment has been compared with artificial roughness elements. Two extremes can then be considered: a bed with roughness elements placed with a large spacing and a bed with roughness elements placed close to each other. In both cases the hydraulic roughness is small. For intermediate situations the hydraulic roughness is higher because of the energy losses in the spacing between the roughness elements (see Figure 2).

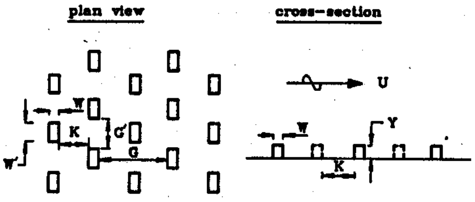

Fig. 2 Definition sketch artificial roughness

Using the results of the studies to the velocity profile and the hydraulic roughness of artificial roughness elements (see, for instance, Knight/MacDonald (1979), Ryabov (1967), Adachi (1964)), it can be concluded that for Y equals about W equals about G (Y = actual depth of the hole, W = block width , G = hole width), the hydraulic roughness can be predicted with:

a)

$$\frac{k_s}{Y} = 0.08 \left(\frac{W + G}{Y}\right)^{2.685} \text{ for } \frac{W + G}{Y} < 5 \qquad (3)$$

b)

$$\frac{k_s}{Y} = 400 \left(\frac{W + G}{Y}\right)^{-1.295} \text{ for } \frac{W + G}{Y} > 15 \qquad (4)$$

c)

the transition zone of Figure 3 can be used for values of $5 < \frac{W + G}{Y} < 15$ (5)

Furthermore, a logarithmic velocity profile as given by equation (2) was affirmed by Knight/McDonald (1979), Ryabov (1967) and Adachi (1964).

Cellular blocks can be considered as a structure with roughness elements placed very close to each other. Tests, carried out with a commercial block-mattress, proved the correctness of equation (3) for hydraulic roughness and of the logarithmic velocity profile.

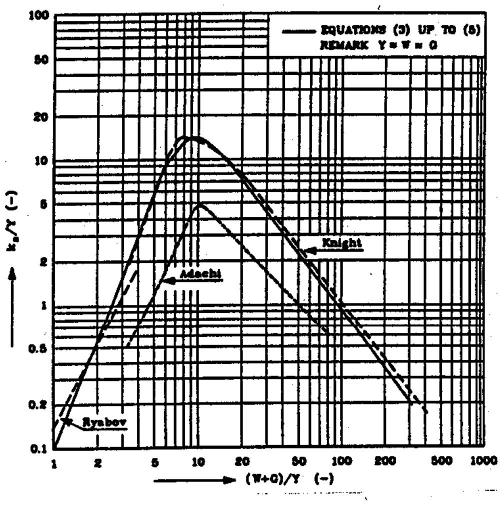

Fig. 3 Relationship between k_s/Y and W + G/Y for artificial roughness elements

2.2 Prediction of erosion depth

Important for erosion of sediment in holes is the velocity in the eddy in the hole. With respect to this velocity research has been carried out, amongst others by Fuhrböter (1979), Rockwell and Knisely (1979), Ethembabaoglu (1978). From their results it can be concluded that the ratio between maximum velocity in the eddy and the velocity just above the blocks varies between 0.25 and 0.60. Theoretically, a value of 0.3 to 0.4 can be deduced. Furthermore, the mentioned studies seem to demonstate that the value is independent of Y/G in the range 0.25 < Y/G < 2.0

Erosion of sediment in holes has been investigated by Parsons and Apmann (1965) and Brown (1984). According to the results of Parsons and Apmann the equilibrium erosion depth Y_e in the case of sand, will be about :

$$\frac{Y_e}{G} = 0.8 \text{ to } 1.0 \qquad (6)$$

On the other hand, Brown mentions erosion for depths larger than the hole width.

Comparing the results of both studies it has to be concluded that Brown predicts erosion depths 1.5 times larger than Parsons and Apmann (1965). Perhaps the influence of the slope plays a role. Brown studied a current on a slope, while Parsons and Apmann studied a horizontal bottom. Brown presents also an equation for the prediction of erosion:

$$\frac{Y}{G} = 0.00115\ (u^{2.2}/D_{50}{}^{0.95}) \qquad (7)$$

Summerising, it had to be concluded that the literature does not give enough information to predict erosion of sediment in holes of cellular blocks.

2.3 Wave-induced erosion

Wave attack on slopes along coasts protected by a cellular block revetment, may result in sediment losses of underlayers. Two mechanisms are possible (see Figure 1): erosion due to outflowing water during maximum withdrawal of a wave and erosion due to water flowing over the slope during run-up and run-down just before and after wave impacts. Of course both mechanisms can also occur simultaneously.

The first mechanism occurs in the case of relatively small holes compared to the block thickness (D/G >3). It could be demonstrated that the gradient over the blocks initiate local fluidisation, being responsible for the loss of sediment, instead of the velocities of the flow over the slope. It also means that wave impacts do not influence the erosion. An equation for the critical velocity in the hole could be deduced based on the forces on a sphere in a conduit :

$$u_{cr} = 1.14\ (1 - \frac{A}{A_g})^{1.2}\ (g\Delta D_n \cdot \cos\alpha)^{0.5} \qquad (8)$$

A_g = hole area [m^2]
A = block area [m^2]
α = slope [°]

Unfortunately it was not possible to check equation (8) with literature results, because relevant literature was not available.

The second mechanism occurs for blocks with holes with relatively large dimensions, compared to the block thickness (G/D > 1). In this situation the outflowing water can be ignored and the erosion process can be predicted in the same manner as described in section 2.2. Using Battjes and Roos (1975) a reliable estimate can be made of the velocities in the run-up and run-down and consequently also of the velocities in the holes.

For intermediate situations with hole dimensions between both described extremes, the simultaneous influence of both overflowing water and outflowing water effects the erosion process. Starting from relatively small holes, the influence of the velocities of the overflowing water then increases with increasing hole dimensions. Consequently, the influence of the outflowing water decreases. Research carried out within the framework of the Eastern Scheldt Storm Surge Barrier (1982) showed the relative influence on hole erosion of water flowing over the slope, compared to outflowing water (D/G equaled about 2). Based on present knowledge, however, a prediction of water velocities in the holes as a result of both water flows, cannot yet be made, and consequently the erosion cannot be predicted.

For special purposes a black-box approach can be applied. Critical wave heigth and period with respect to erosion are then related to the hole dimensions directly. Markle (1983) describes such tests for waves on a slope and derived the following relation :

$$\frac{D}{G} > 1.33 \tan\alpha \qquad (9)$$

Summerising, it had to be concluded that also in the case of cellular concrete block revetments applied along coasts, scarce information is available to predict erosion of sediment. Therefore, model investigations were performed, which are described in the next chapter.

3 EXPERIMENTAL SET-UP AND RESULTS

The physical tests to determine erosion of sediment in holes of cellular concrete revetment blocks applied under current and wave attack, will be treated separately in the following. Both tests were carried out at prototype scale.

3.1 Bank protection along inland waterways

The tests with respect to revetments attacked by return currents and transversal stern waves, have been performed in an

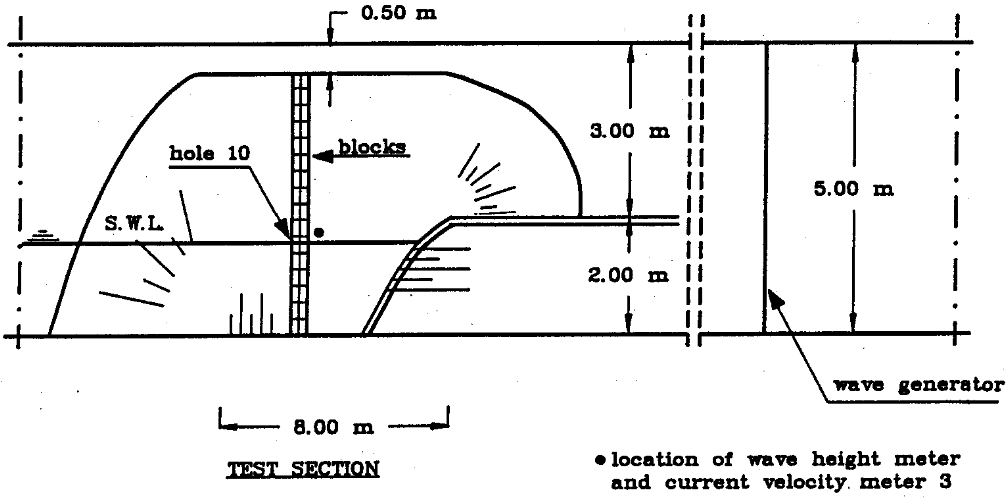

Fig. 4 General view of model lay-out

ordinary wave flume at Delft Hydraulics (maximum wave height H = 0.40 m). The model slope was not built, as is usually the case, at the end of the flume, but along the left side (see Figure 4). It was assumed that the generated waves propagating along the slope, will simulate an equal erosion as the return current and the transversal stern wave. More in particular, during the passage of a wave through the return current is simulated and during the passage of the wave crest the transversal stern wave is simulated. Thus, each wave simulates the passage of a ship. It should be noted that return current and transversal stern wave are decisive components for the erosion at respectively the lower and higher areas at the slope.
A general view of the model is presented in Figure 4. The test section with a lenght of 36 m and a slope of 1:3 was made in concrete on a subsoil of sand (D50=165µm). The cellular revetment blocks (0.30m x 0.30m x 0.15m, see Figure 4) were placed in two rows. The width of the holes in the blocks was varied (G =0.08m, 0.12m and 0.15m). The holes were filled with sand (D50 = 165µm) or black earth (characterised as a loamy fine sand with reduced clay content, D50 = 115µm).

During the tests water-level variations, orbital velocities and wave heights were measured. The water depth was held on 1.00 m with generated wave heights of 0.06 m, 0.13m and 0.17 m (wave period 2.75 s.) The number of waves for each tested situation varied in the range of 7 to 1600 which may be considered to be representative for the number of ships passing by.

Two test series were executed : a series with sand and a series with black earth. The following table gives a summary.

Table 1. Test series

hole size (m)	material	wave height at location 3 (m)	number of waves (variable)
0.15x0.15	sand	0.06, 0.13 , 0.16	7...1600
0.12x0.12	sand	0.06, 0.13 , 0.16	7...1600
0.08x0.08	sand	0.06, 0.13 , 0.16	7...1600
0.15x0.15	black earth	0.06, 0.13 , 0.16	7...1600
0.12x0.12	black earth	0.06, 0.13 , 0.16	7...1600
0.08x0.08	black earth	0.06, 0.13 , 0.16	7...1600

From the measured water velocities it was concluded that the various wave heights result in velocities which are comparable to the velocities in the transversal stern wave and the return current induced by conventional inland motor vessels.

Each test consists of a number of waves which were increased step by step. At several moments during the test the bed level in the holes was sounded. The erosion could be derived from the difference between two successive soundings. After a complete test with a certain wave height, the holes were refilled and the procedure was repeated for a different wave height.

Typical test results for sand and black earth under the same conditions are presented in Figure 5. (For hole number, see Figure 4).

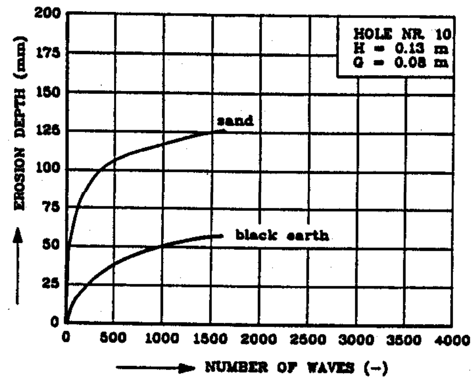

Fig. 5 Erosion depth of vs. number of waves

Based on the test results it can be concluded that:

- The attacks by the ship-induced return current and transversal stern wave were very well simulated in this test set-up.
- The maximum erosion occurred near the still water level.
- Hardly any erosion occurred in the lower areas at the slope.
- Holes with a width of 0.08 m for both sand and black earth can be applied safely without reaching a critical erosion depth equal to the block thickness.
- Holes filled with black earth will erode less than holes filled with sand.

3.2 Dike protection along coasts

An extensive series of model investigations have been performed in the Delta flume of Delft Hydraulics. The test facility is equipped to reproduce waves up to 2 m, both regular and irregular. For the present investigation only regular waves have been used, mainly because it is expected that the relationship between wave characteristics and erosion depth is most evident for regular waves.

All tests were performed on prototype scale on a slope with steepness of 1:3 (vert.:hor.). At several locations along the slope, blocks with specified widths of the holes were installed. These were also equipped with pressure gauges and a water velocity meter. The pressure difference across the block and water velocity on the slope were recorded by a computer during each test. The erosion depth in the holes was measured only after each test run, consisting of approximately 100 waves. Since the bed of the holes did not remain parallel to the slope, both maximum and minimum erosion depth were measured.

The tests were preformed with blocks of 0.5 m x 0.5 m and 0.15 m thick. If the hole diameter was less than 100mm, then each block had six holes. In other cases only one hole per block was present. The test program and some of the results are summarised in Table 2.

Table 2 Wave height to reach an erosion depth of 120 mm

	6 holes/block			1 hole / block		
G [mm]	51	70	91	125	170	225
D_n [mm]						
0.2	-	-	-	-	<0.2	-
5	<0.2	<0.2	0.35	0.48	0.32	0.24
6	-	-	-	0.32	-	0.28
11	-	-	-	0.56	-	-
24	-	-	-	-	0.41	0.36

The table shows the hole diameter G and the characteristic grain size of the filling D_n of the performed test series. Each series consisted of a number of tests with step by step increasing incident wave height H. If the wave steepness became unrealistically high, the wave period was increased, as is shown in Table 3.

Table 3 Planned tests in a test series.

testnr.	T[s]	H[m]	H/L[-]	ξ [–]
1	2.25	0.2	0.025	2.09
2	2.25	0.3	0.038	1.70
3	2.25	0.4	0.051	1.48
4	3	0.4	0.028	1.97
5	3	0.55	0.039	1.68
6	3	0.7	0.050	1.49
7	4	0.7	0.028	1.98
8	4	0.9	0.036	1.75
9	4	1.1	0.044	1.58
10	5	0.3	0.008	3.79
11	5	0.5	0.013	2.94
12	5	0.7	0.018	2.48

Test 9 could not always be performed because of potential instability of the slope revetment. Test 10, 11 and 12 were added to the programme to investigate the influence of the wave period. The holes were not refilled after each test, but after the change of wave period (after test 3, 6 and 9). Refilling after each test was not considered necessary, because the equilibrium erosion depth increases with increasing wave height.

4 ANALYSIS OF THE RESULTS

4.1 Bank protection

The erosion depth depends on wave height (or current velocity), sediment characteristics, hole dimensions and number of waves. In order to determine whether or not cellular blocks can be applied as revetment, it is important to know the equilibrium erosion depth. This depth should be less than the block thickness. The present investigations were carried out with blocks of 0.15 m thickness. Results of some tests related to the equilibrium erosion depth Ye are presented in Figure 6.

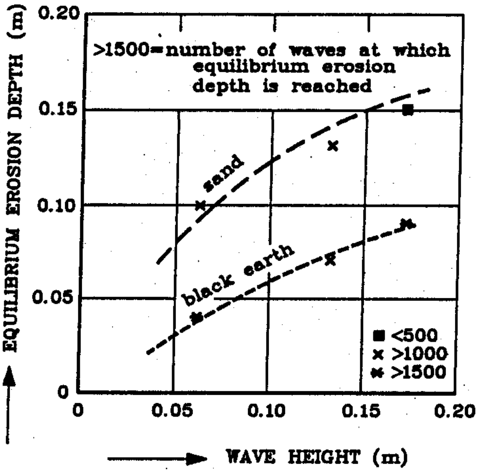

Fig. 6 Equilibrium erosion depth related to wave height and number of waves

Based on the test results for the investigated situations, it is concluded that the equilibrium erosion depth increases with increasing hole dimensions. Also, the equilibrium erosion depth is reached earlier (that is, for a lesser number of waves) with increasing hole dimensions. Besides, under the same conditions the equilibrium erosion depth for holes filled with black earth are less than those filled with sand.

In addition to the equilibrium erosion depth, the relationship between erosion depth E and the number of waves N should be analysed as well. The results presented in Figure 5 suggest a relationship which can be described with the following equation :

$$E = c \log \left(\frac{N}{N_o}\right) \qquad (10)$$

The coefficients c and N_o are functions of wave height, hole dimensions and sediment characteristics.

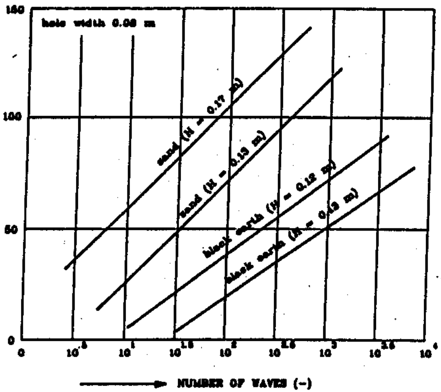

Fig. 7 Semi-logarithmic relationship between erosion depth and number of waves

Examples of equation (10) with test results are presented in Figure 7. A preliminary analysis for blocks with holes of 0.08m indicate the following values for N_o and c for sand and black earth.

Table 4. Preliminary results for the coefficients c and N_o

hole filling	c	N_o		
		H=0.06m	0.13m	0.17m
sand	50	20	3	0.5
black earth	35	100	30	8

A further analysis will be carried out in the near future.

A comparison can be made with the results obtained by Brown (see equation 7) and Parsons and Apmann (equation 6). Parsons

and Apmann predict an equilibrium erosion depth less than the hole width. For the investigated holes filled with black earth, this prediction seems correct. However, for holes filled with sand the erosion depth is larger in nearly all situations.
Applying equation (7) according to Brown (1984), the erosion depths are calculated for all situations. The results of these calculations are that the predicted erosion depth of holes filled with sand, is smaller than the erosion depth in holes filled with black earth. This is the opposite of the test results. Probably the loamy character of the black earth influences the results.

Summarising, the preliminary analysis does not confirm prediction equations mentioned in literature. Erosion depths seem predictable with an equation as equation (10).

4.2 Dike protection

The recordings of the water velocity on the slope and the pressure difference over the blocks have not yet been analysed, and therefore the present paper focusses on the measured erosion depth in relation to the wave characteristics. The erosion depth as a function of wave height is shown for some of the tests in Figure 8 up to 11. The given erosion depth is the maximum value measured along the slope. Usually the maximum was found at the still water level or just below.
Figure 8 shows a smaller erosion depth for the tests 9, 10 and 11, which are performed with relatively long waves (T = 5 s). On the other hand, Figure 9 shows an opposite trend. From this result the preliminary conclusion is drawn that the influence of the wave period T does not have to be considered separately. The influence of T only contributes to the variance of the relationship between erosion depth and wave height. This conclusion will be evaluated when the measured velocities and pressures have become available.

From Figure 10 it is clear that the erosion depth at a certain wave height decreases if the hole diameter decreases from 225 mm up to 125 mm. This could be expected because of the results of Brown (1984). The erosion mechanism is apparently activated by the flow over the slope. Figure 11 shows an opposite trend: increasing erosion with decreasing hole diameter.
From these results it is concluded that the pressure difference across the blocks is decisive for holes smaller than approximately 100 mm under the given conditions. If the holes are larger, then the flow over the slope is decisive.

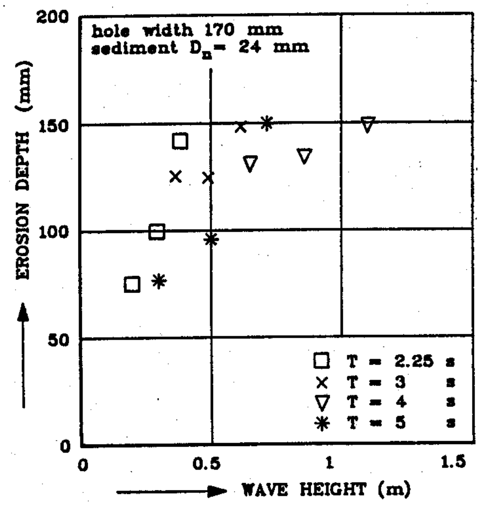

Fig. 8 Erosion vs. wave height

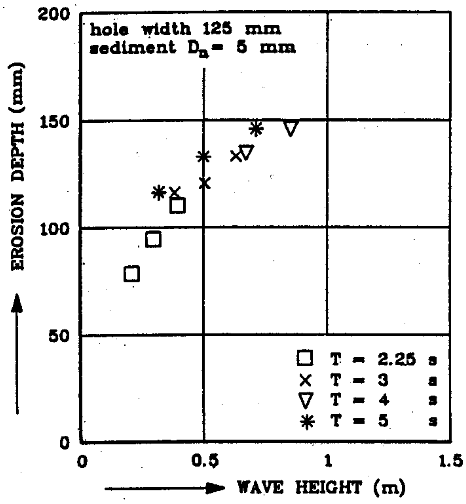

Fig. 9 Erosion vs. wave height

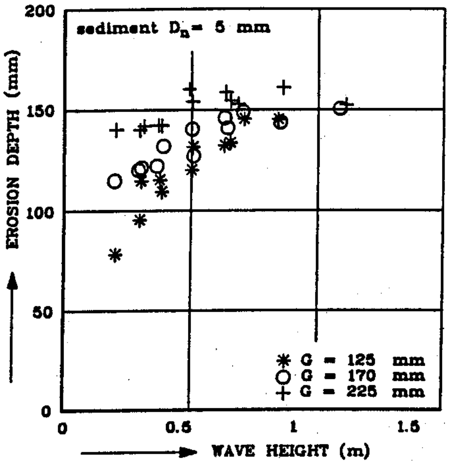

Fig 10 Erosion vs. wave height

The test results are summarised in Table 2. It gives the wave height which caused an erosion of 120 mm. This is considered to be the maximum tolerable erosion for the used blocks with thickness of 150 mm. From the table it can be concluded that the acceptable wave height is at maximum if G = 125 mm. For G = 225 mm the acceptable wave height is much smaller, even if the grain size is increased from 5 mm to 24 mm.

General conclusions could not yet be given, since not all measurements have been analysed at present.

5 CONCLUSIONS AND RECOMMENDATIONS

A literature review and physical model tests with respect to the erosion of sediment in holes of cellular concrete revetment blocks, applied on slopes along coasts and inland waterways, has lead to preliminary results. The main conclusions obtained so far are :

- Application of cellular concrete block revetments seems possible.
- The erosion of material in the holes of the blocks depends mainly on the size of the holes.
- Prediction equations for the erosion might be derived for both revetments along coasts and inland waterways.

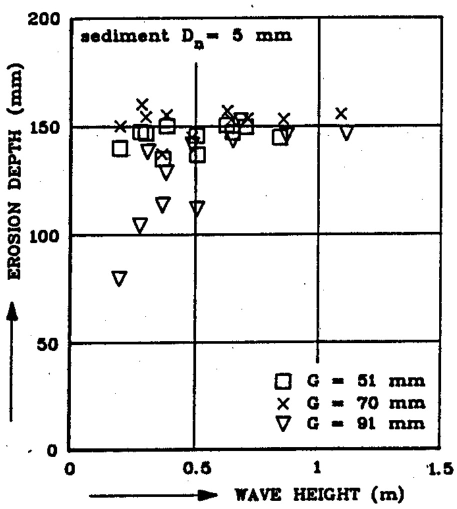

Fig. 11 Erosion vs. wave height

Based on the results obtained up to now, it is recommended to increase the number of data by carrying out tests with other geometries and dimensions. This will result in an application of cellular concrete block revetments under different conditions concerning wave and current attack. For specific conditions, however, it is possible to make a reliable design, based on the results obtained so far.

6 ACKNOWLEDGEMENT

The presented results of a literature review and model tests, are based on a long term general research project on the stability of revetments along coasts and inland fairways. This research is carried out partly by Delft Hydraulics by order of the Dutch Public Works Department. The authors wish to thank the Dutch Public Works Department for their permission to publish these results.

NOTATION

A	=	block area	m^2
Ag	=	hole area	m^2
C	=	Chezy coefficient	$m^{1/2}/s$
c	=	coefficient	-
D	=	block thickness	m
D_n	=	characteristic size of granular material	m
D_{50}	=	diameter of granular material exceeded by 50% of the material	m
E	=	erosion depth	m
G	=	hole width	m

g = accelaration due to gravity m/s^2
H = wave height m
k_s = equivalent roughness m
L = wave length m
N = number of waves -
N_o = coefficient -
R = hydraulic radius m
T = wave period s
u = current velocity m/s
$\bar{u}$ = mean current velocity m/s
u_{cr} = critical current velocity m/s
u_* = shear velocity m/s
u_{*cr} = critical shear velocity m/s
W = block width m
Y = actual hole depth m
Y_e = equilibrium hole depth m
α = slope °
Δ = relative density -
κ = constant of Von Karman -
ρ = density of water kg/m^3
ρ_s = density of granular material kg/m^3
τ = shear stress N/m^2
τ_{cr} = critical shear stress $N/m2$
ψ = shear stress parameter -
ψ_{cr} = critical shear stress parameter -

REFERENCES

Adachi, S. 1964. On the artificial strip roughness. Disaster prevention research institute, Kyoto University Bulletin 60.

Battjes, J.A. and Roos, A, Characteristics of flow in run-up of periodic waves. Communications on Hydraulic, 75-3 Department of Civil Engineering, Delft University of Technology.

Brown, C.T. 1984. Flexible revetments, theory and practice. International Conference on Flexible armoured revetments incorporating geotextiles. London.

Delft Hydraulics and Delft Geotechnics. 1982. Full-scale investigations with respect to closure works (in Dutch). Report M 1795 part VI. Delft.

Ethembabaoglu, S. 1978. Some characteristics of unstable flow past slots. Journal of the Hydraulics Division, ASCE, Vol. 104, HY5.

Führböter, A.and Macke, E. 1979. Modellversuche für die Sohlsicherung des Eider-Sperrwerkes. Leichtweiss Institut für Wasserbau der Technischen Universitat Braunschweig, Bericht nr. 440.

Knight, D.W. and MacDonald, J.A. 1979. Hydraulic Resistance of Artificial Strip Roughness. Journal of the Hydraulic Division, ASCE, Vol. 105, HY6.

Markle, D.G. 1983. Wave stability study of riprap filled holes. US Army Engineer Waterways Experiment Station, Vicksburg.

Parsons, D.A. and Apmann, A.M. 1965. Cellular concrete block revetment. Journal of the Waterways and Harbours Division, ASCE, Vol. 91, WW2.

Rockwell, D. and Knisely, C. 1979. Unsteady features of flow past a cavity. Journal of the Hydraulics Division, ASCE, Vol. 105, HY8.

Ryabov, A.K. 1967. Hydraulic design of channels with artificial roughness. Hydrotechnical Construction, no. 9.