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DESIGN OF CONCRETE BLOCK REVETMENTS SUBJECT TO WAVE ACTION

A literature review

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ABSTRACT

A literature review has been conducted into the design guidelines for concrete block revetments in a coastal environment. Both permeable and relatively impermeable structures have been considered, but no account has been taken of cabling or interlocking of the blocks. The various hydraulic loading mechanisma have been outlined.

Expressions intended to allow the calculation of wave pressures and forces are presented. However, many of these are in a form unsuitable for design work, based as they are on empirical coefficients with little firm justification.

The report lists a number of stability criteria for both the protective outer layer and the filter layers of coastal revetments. The hydraulic performance is also discussed. Recommendations are made for further work, in the form of model studies, to improve both the quantity and quality of the available design guidelines.

NOTATION

A	Area of concrete revetment block
b	Thickness of filter layer
c	Velocity of sound in water
C	Empirical coefficient relating to revetment stability
C_1	Shape coefficient specific to block type
d_b	Nominal sub-base soil particle diameter
d_f	Nominal filter particle diameter
D	Thickness of concrete blocks
D_a	Representative thickness of included air content of breaking waves
E	Elasticity of water
$\bar{E}_L$	Mean elasticity of air
g	Acceleration due to gravity
H	Nominal wave height
H_b	Breaking wave height
H_s	Significant wave height
Ir	Iribarren number
k	Permeability of filter layers
k'	Permeability of block layer
K	Empirical stability coefficient
K_1	Empirical stability coefficient
K_D	Empirical stability number in Hudson equation
K_g	Permeability of geotextile filter layer
K_r	Coefficient of wave reflection
K_s	Permeability of sub-soil
L_o	Deepwater wave length
n	Revetment slope inclination (= $\tan\alpha$)
O	Nominal geotextile pore size
P_{max}	Maximum shock pressure due to wave impacts
q	Empirical slope coefficient
R	Hydraulic radius of wave impact area
U	Coefficient of uniformity of soil
v	Wave breaker velocity acting normal to revetment slope
W	Weight of individual armour block
y_b	Distance from breaker crest to bed
α	Angle of revetment slope to horizontal
Δ	Relative density of block (= $\frac{\rho_s - \rho}{\rho}$)

∂	Shock pressure number
λ	Seepage length
ρ	Density of water
ρ_s	Density of armour block

CONTENTS

1 INTRODUCTION

1.1 General

A revetment may be considered as the facing layers or armouring systems used to protect an embankment, or slope, against erosion by current and wave action. The protective surface layer is usually laid on to the suitably prepared face of an existing embankment or natural slope in order to stabilise its seaward face. It must also be supported at the toe and, unless laid on an impervious material, provided with adequate drainage.

A variety of different materials, including concrete, stone, timber and asphaltic cements, may be used for the protective surface layer, and the final structure may be either smooth, rough or stepped. Moreover the revetment may be of either rigid (continuous) or flexible construction, the latter consisting of discreet elements often interlocked or jointed. A rigid structure, though of potentially greater stability than its flexible counterpart, will be prone to 'spanning' should the underlayers settle, or be eroded, beneath it. If this occurs the revetment will be seriously weakened under the external loading of wave impacts and may fail without warning. Flexible revetments, on the other hand, should ideally maintain contact with the underlayers as they settle in use, though they should not be viewed as a solution to poor embankment construction. They are, however, inherently less stable than rigid revetments by virtue of their consisting of a number of smaller discrete elements rather than one continuous slab. The cabling together of individual revetment blocks into mats is but one method of providing extra stability while maintaining a degree of flexibility, and several such proprietary systems have been introduced in recent years. Examples of these are the Dytap[1], Dycel[1], Sebloc[1], Armorflex[2,3] and Petraflex[4,5] systems.

Although there are obviously many types of revetment, they may, in general, all be classed as either,

a) Permeable, or

b) Impermeable structures

A permeable revetment has an 'open' protective facing which allows water to flow into and out of the structure. Because of this permeability, filter layers are incorporated to prevent fines being washed out from the subsoil and to help relieve hydrostatic pressures from within the embankment. The filter layers typically consist of one or more granular layers and/or a geotextile fabric. Correct design of the filter layers is as important to the long term stability of the revetment as is the design of the protective surface layers.

Impermeable revetment facings generally prevent the flow of water through the structure. They are, therefore, unsuitable for use on permeable soils unless drainage outlets and filter underlayers are provided to relieve the internal hydrostatic pressures, which would otherwise severely stress the structure. The success of any impermeable revetment facing must depend on its ability to prevent erosion of the subsoil due to the fines being washed out. On exposed coastal sites with a wide variation in water levels and on dam faces subject to rapid drawdown it may well prove impossible to reconcile the need for adequate drainage with the impermeability of the structure. Therefore revetment facings impermeable to wave action are not considered further in this review.

1.2 Extent of review

This review aims to draw together and summarise the available knowledge on the design of concrete block coastal revetments with regard to their stability and hydraulic performance. Although the theoretical considerations are limited to 'loose' block revetments without either interlock or cabling, the influence of these factors on the stability of the revetment is quantified where possible. No mention is made of the design of toe beams or of anchorages for the revetment structure; it is however anticipated that this topic will be covered in a further report. As previously stated, strictly impermeable revetment facings have not been considered; relatively low permeability structures comprising of tightly fitted concrete blocks are, however, included. Distinctions are drawn between revetments sited on permeable and impermeable subsoils, and the design criteria for filter layers are also reviewed, but only to the extent to which they apply to coastal revetments.

During the course of this review it quickly became apparent that a variety of different measures of wave height (ie a maximum and significant height for random waves and a regular wave height) had been used throughout the relevant literature. However, in many cases, the particular measure of wave height used was not explicitly declared. Thus, in this report, where a wave height was clearly defined it is so used, however where there is uncertainty about a particular measure of wave height it is defined in this report as H, a nominal design wave height.

1.3 Outline of report

The hydraulic loading mechanisms for revetments under wave action are reviewed in Chapter 2. Particular reference is made to quasi-static pressure differences and to wave impact loads on sloped revetments. Chapter 3 presents current design formulae for both the protective armour layer and the filter underlayers of concrete block revetments. Methods of improving the stability are briefly reviewed, and, where possible, an estimate of the potential stability gain is given. The hydraulic performance of concrete block coastal revetments is considered in Chapter 4. The limited number of references concerning the wave run-up, overtopping and reflection characteristics of these structures are reviewed and the available data compared to that for impermeable revetments. Tentative correction factors for concrete block revetments are suggested. Chapter 5 draws together the conclusions arising from this review. Recommendations are made for further research following which detailed design guidelines may be formulated.

2 HYDRAULIC LOADING CONDITIONS

2.1 General

The principal forces on coastal revetments are those due to the action of waves. These waves may be broadly classified into two categories, that is locally generated wind waves and distantly generated swell waves. The height of locally generated waves depends principally upon,

a) the wind speed

b) the duration for which it has been blowing

c) the effective fetch length over which it acts

d) the average depth of water over that fetch

e) the pre-existing sea state.

The height of swell waves also depends on these parameters but measured at the distant location at which the waves were generated, and at all intermediate points on their route to the coast. Over long distances swell waves are subjected to two gradual changes, that is a loss of height and an increase in wave period. This increase in period is of particular importance for concrete block revetments, where the stability is strongly dependent on wave period.

As waves propagate from deep to shallower water they are subject to a number of effects which result in the waves both steepening and swinging round to approach the coast more normally. This steepening of the waves increases up to a critical limit at which the waves break. For waves breaking on a slope several different breaker types can be distinguished depending upon the wave steepness and the gradient of the slope. These are spilling, plunging, collapsing and surging breakers. These breaker types will differ both in their energy dissipation characteristics and in the forces they exert upon the slope. The behaviour of such breaker types is discussed by many authors. For further details the interested reader is referred to Peregrine[26].

2.2 External loading

The stability of a concrete block revetment is dependent upon both the characteristics of the revetment and upon the loads applied to it. Since the revetment may fail by erosion of its filter layers under medium but frequently occurring loads, as well as by direct excessive loading, particular importance should be attached to the frequency of occurrence of specific loads at specific locations on the structure. These loads are, however, difficult to quantify and for hydraulic loading, at least, are subject to a number of variables:

- wave heights and periods
- angle of wave attack
- type and location of breaking wave
- grouping of waves
- wave run-up
- tidal levels
- currents

Stephan[6] considers that there are two main categories of wave loading on revetments:

a) shear forces tangential to the slope produced by wave run-up/run-down

b) compressive forces normal to the slope produced by wave impact loadings and quasi-static pressure effects

Pilarczyk[7] goes further than this and identifies eight separate loading mechanisms for concrete blocks under wave action. These mechanisms are shown schematically in Figure 1 and outlined below.

Mechanism 1:- After the wave has broken and the wave run-up has reached its maximum level, the water on the slope starts to flow back under the influence of gravity. During this phase the pressures on the revetment are reduced. If, however, the revetment is hydraulically rough this return flow may result in secondary drag, inertia and lift forces.

Mechanism 2:- During the return flow stage water may penetrate between the blocks into the filter layers. Since the wave run-up is generally greater than the wave draw-down, relative to the still water level, seepage into the revetment can take place over a larger area than seepage out of the revetment. Consequently, there is an increase in the phreatic level within the filter layers, and through this an increase in the uplift pressures on the revetment. This effect is, however, dependent upon the relative permeability of the concrete block layer and the filter layers, and upon the geometry of the revetment. It is also cumulative for a number of waves.

Mechanism 3:- As the following wave approaches the slope a general increase in the pressures on the slope occurs. These pressures may then be transmitted through the filter layer immediately in front of the wave resulting in an increase in uplift pressures beneath the revetment. These uplift pressures will, however, only occur over a limited area immediately adjoining the wave front.

Mechanism 4:- Prior to the wave breaking there are also considerable changes occurring in the waves' internal velocity field as the streamlines start to curve upwards. These changes can result in a reduction of pressures above the revetment which, in turn, will lead to an increase in the pressure gradient across the structure.

Mechanism 5:- If the wave breaks on the slope it will cause an impact loading, which will result in a severe, but short-lived increase in pressure. This increase in pressure can be transmitted through the filter layers leading to the occurrence of near-instantaneous uplift pressures beneath the revetment.

Mechanism 6:- After this short lived phenomenon there is a sudden, large increase in pressure as a result of the mass of the wave falling back onto the slope. This pressure may propagate through the filter layers, just in front of the point where the wave broke, again leading to the occurrence of uplift pressures on the revetment.

Mechanism 7:- Subsequent to the mass of the wave striking the revetment there may be a large reduction in pressures on the slope, even to the extent of negative pressures (ie, below atmospheric) occurring. This phenomenon can be ascribed to the oscillations of the air pocket enclosed within the breaking wave. The extremely low pressures generated may in themselves be responsible for the failure of the revetment as a result of the greatly increased pressure gradient across it.

Mechanism 8:- After the wave has broken run-up again takes place. During this last stage pressures on the revetment increase. There are, however, no critical conditions provided that the slope is smooth and blocks have not been partly raised as a result of previous pressure effects.

The Dutch "Guide to Concrete Dyke Revetments"(8), (CUR-VB) concludes that loading mechanisms 2 and 3 (quasi-static pressure differences, and pressures due to the approaching wave front) are of particular importance to the stability of loose block revetments. CUR-VB also emphasises that the loading mechanisms listed above cannot be considered separately, and combinations of these mechanisms will occur and may be responsible for failure of the revetment.

2.3 Quasi-static pressure differences

The Delft Hydraulics and Soil Mechanics laboratories have jointly developed a mathematical model for revetment stability under quasi-static pressure differences. This model is briefly reported by den Boer, Kenter and Pilarczyk(9) and by CUR-VB(8). The model, although claimed to be able to cope with all the quasi-static phenomena described in Section 2.2, has so far only proved reasonably successful in predicting pore pressures for mechanisms 2 and 3. It has, however, demonstrated that the relative permeability between the protective surface layer and the underlying filter layers is of great importance to the overall stability of the revetment. It is suggested that this relative permeability may best be expressed in terms of a notional seepage length, λ, as

$$\lambda = \sin\alpha \left(bD \frac{k}{k'}\right)^{\frac{1}{2}} \qquad (2.1)$$

where α is the angle of the revetment slope

b is the thickness of the filter layer

D is the thickness of the concrete blocks

k is the permeability of the filter layer

k' is the permeability of the block layer

This may however be an oversimplification.

The model has also allowed the following conclusions to be drawn:

a) the risk of damage to the revetment decreases as the permeability of the surface layer increases and the permeability, or thickness, of the filter layer decreases

b) the elevation of the mean phreatic surface above its original level increases the more permeable the revetment, however, the pore pressures are then reduced

Although the mathematical model is of obvious use in aiding our understanding of revetment failures there has been insufficient information published to allow a more detailed assessment of it to be made. Thus at present it would seem to be of only limited application to the design of such structures. Indeed, CUR-VB[8] concludes that "for the time being one will have to rely mainly upon the results from scale model tests" for the design of concrete block revetments. To this end Pilarczyk[10] has carried out a simplistic equilibrium analysis of concrete block stability on a permeable underlayer and obtained the formula,

$$\frac{H}{\Delta D} = \frac{\cos \alpha}{C \, (Ir)^{1/2}} \qquad (2.2)$$

where H is a nominal wave height

Δ is the relative density of a block

D is the thickness of a block

α is the angle of the revetment slope

C is an empirical coefficient

Ir is the Iribarren number = $\tan \alpha \, (H/L_0)^{-\frac{1}{2}}$

CUR-VB[8] ascribes a value of 0.25 to the coefficient C, and, with the assumption that $\cos \alpha \approx 1$, suggests that the formula now represents a somewhat conservative design approach. However, in the derivation of the formula no account was taken of the effects of friction, relative surface layer/filter layer permeabilities or of the filter layer thickness. Furthermore the formula is only applicable to quasi-static pressure loadings and does not include loadings due to wave impact pressures.

Blaauw et al[11] present a very similar formula for the design of revetments on inland waterways:-

$$\frac{H}{\Delta D} = \frac{\cos \alpha}{K_1} \qquad (2.3)$$

where K_1 is an empirical coefficient depending upon friction/interlock between blocks and upon the porosity of the revetment

For ship waves suggested values of K are 0.2 for free blocks and 0.15 for blocks with the joints infilled with gravel. Although the formula supposedly includes the wide ranging permutations of friction and permeability within a single coefficient, it does not, being developed for ship waves, include the effects of wave period. Indeed, comparison of this formula with that developed by Pilarczyk[10] indicate that Blaauw's formula is valid only for one particular value of the Iribarren number (Ir = 1.25), and cannot, therefore, be considered applicable to revetments subject to wind and/or swell waves.

2.4 Wave impact loading

Research in West Germany by Stephan[6], and Boelke and Relotius[13] has tended to concentrate on the wave impact loading of revetments rather than on quasi-static pressure differences. Stephan, in a series of model tests, qualitatively considered the distribution of pressures, resulting from wave impacts, for a variety of different revetment constructions. These pressure distributions are given in Figure 2. In the case of closed (solid) revetments, pressures generated by the impact shock loading can be transmitted through the protective surface layer via existing cracks. These pressures may then result in uplift forces on the revetment itself (Fig 2a). Concrete block revetments are loaded in a similar way, however in this case, the adjacent joints will have a relieving effect, (Fig 2b), the extent of which depends on the interblock bonding. If the blocks are vertically bonded (Fig 2c) there will be an initial dampening of the shock pressures as they penetrate the revetment. Adjacent joints will not, however, be able to relieve the pressures to the extent that would occur with blocks without interlock and the pressures, although less, would be distributed over a larger area (i.e., to more blocks). For any block revetment the distribution of shock pressures is largely dependent upon the size of the blocks, the width of the joints and the pattern of the applied pressure field produced by the wave action. If the spacing between the joints is too small, additional shock pressures may be transmitted through adjacent joints resulting in a superimposition of the determinative uplift forces (Fig 2g). Filter layers are also particularly important to the transmission of shock pressures, and pressure distributions will be different for homogeneous sub-soils without filter layers (Fig 2d), for sub-soils with fabric filters (Fig 2e), and for granular filters (Fig 2f).

The degree of shock pressure loading from wave impacts appears to be particularly dependent upon the slope of the revetment, which together with the wave steepness determines the breaker type. Boelke and Relotius(13) carried out a series of model tests on slopes of different inclination and concluded that a 1:3 slope experienced the highest and most frequent shock pressures from wave impact loading. They also found that for slopes lying between 1:4 and 1:6, the shock pressures occurred in an area from $0.6H_s$ below still water level to $0.3H_s$ above still water level, where H_s is the significant wave height. On these slopes the maximum frequency occurred $0.5H_s$ below still water level. On slopes flatter than 1:3 the shock pressures were found to be reduced by the dampening effect of the returning water from the previous wave.

A similar trend, for shallow slopes, was observed by Greslou and Montaz(14) and Whillock(15), the latter also observing that the maximum uplift pressure due to wave impacts occurs just below the impact area. Boelke and Relotius(13) also carried out field tests to confirm their model results. From those tests they concluded that the random phenomenon of shock pressure impacts was best described by a Gaussian log-normal distribution.

For slopes steeper than 1:1, Fuhrboter(17) developed the following equation for the maximum shock pressure, P_{max}, due to wave impacts:

$$P_{max} = \rho v c \left(\frac{c}{v} - \partial\right)^{1/3} \qquad (2.4)$$

where v is velocity acting normal to the slope, defined as:

$$v = (g.y_b)^{\frac{1}{2}} . \left(\frac{1 + 2n^2}{1 + n^2}\right)^{\frac{1}{2}} \qquad (2.5)$$

and y_b is distance from breaker crest to bed n is slope inclination

c is velocity of sound in water

∂ is shock pressure number, $= \left(\frac{\bar{E}_L}{E} \cdot \frac{R}{D_a}\right)^{2/3}$

$\bar{E}_L$ is mean elasticity of air

E is elasticity of water

R is hydraulic radius of impact area

D_a is a representative thickness of the included air content

ρ is density of water

By making several simplifying assumptions and using data obtained from a study of jet impacts on slopes, Fuhrboter then reduced equations 2.4 and 2.5 to:

$$P_{max} \approx 3g \ \rho \ H_B \left(\frac{1 + 2n^2}{1 + n^2}\right)^{1/3} \qquad (2.6)$$

where H_B is the breaking wave height.

A similar equation is presented in the Dutch publication "The use of asphalt in hydraulic engineering",[18]

$$P_{max} = \rho g H . q \qquad (2.7)$$

where H is a nominal wave height

g is acceleration due to gravity

q is an empirical factor relating to slope

This equation has a much simpler derivation than those of Fuhrboter. However, the effect of the slope is accounted for purely by an empirical factor which may be partly dependent upon the test conditions under which it was obtained. Typical values for q are given below:

Slope	q
1:2	2.3
1:3	2.7
1:4	2.3
1:6	2.0

In general the values given by the Dutch tend to cover the slopes most commonly used in coastal revetments. However, it may be possible to derive a single slope function applicable to both steep and shallow slopes by comparing equations 2.6 and 2.7. This yields,

$$q \cong 3 \left(\frac{1 + 2n^2}{1 + n^2}\right)^{1/3} \tag{2.8}$$

Values for these two slope coefficients are plotted against slope, tan α, in Figure 3. Although a possible line-of-best-fit is shown, many more values are needed, particularly for slopes shallower than 1:1, before this trend can be confirmed.

It should be emphasised that both equations 2.6 and 2.7 are relatively unproven; they cannot therefore be recommended for design purposes. Indeed, substantially more research is required before the shock pressures resulting from wave impact can be estimated with any confidence.

2.5 Internal stability of revetment

The internal stability of a revetment, that is the stability of its filter or under layers, is vitally important to the overall performance of the structure. Indeed Stephan(6) concludes that damage to revetments repeatedly occurs because of the inadequate design of filter layers, none more so than in the case of concrete block structures lying on fabric filters.

The manner in which waves constitute a direct external load on a revetment, as well as an indirect internal load, via wave induced pore pressures, has already been discussed. However, this internal loading can also act directly on the filter layers and, if severe enough, can lead to erosion of the filter layers and hence to the failure of the revetment itself. The mechanism for this failure lies with the excess pore pressures, within the filter layers, resulting from the phreatic surface being unable to immediately follow any sudden lowering of the external water level (wave run-up/run-down). These excess pressures will result in the generation of hydraulic gradients in three separate directions:

a) along the revetment

b) up and down the revetment slope

c) perpendicular to the slope

Of these, the hydraulic gradient along the revetment is primarily due to oblique wave attack and is of minor importance to the stability of the structure. The remaining gradients, however, if they exceed critical values, can cause slumping and erosion of the filter layers. These critical values are discussed further in Section 3.3.

Blaauw et al[11] attempted to establish a relationship between the internal filter loads and the external wave loading, by using both numerical and physical models, and prototype measurements. The most satisfactory practical measure for the internal hydraulic gradients was thus found to be the product of the wave run-down (from maximum run-up to maximum draw-down) and the rate of that run-down. A variety of revetment sections were tested, both with and without underlayers. The results of these tests indicated that:

a) the down slope hydraulic gradient, beneath the geotextile, on a concrete block/geotextile revetment can be reduced by approximately 30% if a granular filter is incorporated into the system

b) perpendicular hydraulic gradients are little affected by the presence, or absence, of filter underlayers

c) the perpendicular hydraulic gradient, by reducing the effective grain weight during periods of upward flow, is the principal factor contributing to the loss of underlayer stability

Prototype measurements[11] generally confirmed these observations. However, they also indicated that for a concrete block revetment with a joint width of less than 0.5mm, the uplift pressures, with a granular filter, were approximately 60% greater than those occurring on the same revetment without a granular filter. Thus, there is a conflict between internal and external stability. The presence of a granular filter beneath a concrete block revetment may increase uplift pressures but, at the same time, it reduces the transverse (down slope) hydraulic gradient. It would seem therefore, that the design of any revetment may ultimately need to be a compromise between the differing requirements for internal and external stability.

3 STABILITY DESIGN CRITERIA

3.1 General

As has already been mentioned, the stability of a concrete block revetment depends upon the performance of both its outer protective layer, and filter layer. Among the factors that will influence this stability are:-

a) the hydraulic loads

b) the weight and/or dimensions of the blocks

c) friction between blocks and filter layer, and between adjacent blocks

d) compressive forces in the plane of the revetment

e) the relative permeability of the protective surface layer and underlayers

f) the revetment slope

g) the soil tightness and erosion resistance of the filter layers

h) the thickness of the filter layers

i) any interlock or cabling or anchoraging of the system

With all these variables, it is perhaps not surprising that the theoretical development of concrete block revetment design is still in its infancy. Indeed, nearly all the available design equations are based on the results of specific model tests under particular conditions and are not, therefore, strictly applicable for general use. However, faced with such a dearth of reliable information, the engineer has little choice but either to base his design on readily available empirical equations, or to carry out scaled physical model tests. These tests are themselves only approximate, however, due to the difficulties involved in correctly modelling the geotechnical aspects of revetments.

3.2 Concrete block stability criteria

For many years the design of concrete block revetments has been closely linked to the Hudson[19] equation; an equation which was originally derived from physical model tests of rock armoured breakwaters under regular wave attack. Hudson's equation gives:

$$W = \rho_s H^3/(K_D.\Delta^3.\cot\alpha) \qquad (3.1)$$

where W is the weight of an individual armour unit

K_D is an empirical stability number

Δ is relative block density = $\frac{\rho_s - \rho}{\rho}$

ρ_s is the density of an armour unit

ρ is the density of water

H is a nominal wave height

Indeed, many of the design curves[3,4] presented by manufacturers of the various proprietory systems are based on this equation, with the system weights related directly to wave height. However, Hudson's equation has a basic failing in that it totally neglects the effect of wave period. Furthermore, its use implies that for a particular revetment there is just one stability number. This is not strictly valid and it has been increasingly recognised that because of the influence of wave period, the stability of an armour unit is best described by a function rather than a single number.

Pilarczyk[20] considers that for block revetments it is better to express the Hudson equation as a function of block thickness:

$$\frac{H}{\Delta D} = (K_D \cdot \cot \alpha)^{1/3} \qquad (3.2)$$

or,

$$K_D = (H/\Delta D)^3 . \tan \alpha \qquad (3.3)$$

where D is the block thickness

A comparison of the relative stabilities of two different revetments using equations 3.1 and 3.3 is cited by Pilarczyk as proof that equation 3.3 gives a more realistic representation of block stability. However, this equation still does not include the influence of wave period nor many of the other variables and therefore needs to be applied with caution.

Although it is generally accepted that wave period can influence the stability of concrete block revetments, the manner in which it does so is somewhat confused. Whillock[15], Dorr et al[21] and Weckmann and Scales[2], all agree that increasing the wave period reduces the wave height at which damage to the revetment begins to occur. Lindenberg[22] however, concluded from the results of a study on the stability of Armorflex blocks, that the revetment was more stable at longer wave periods. Pilarczyk[7] tries to reconcile these opposing views by considering the stability to be a non-linear function of wave period. He reports the results of a series of large scale tests, with regular waves and 1:3 slope, which revealed that the stability function for block revetments, in terms of $H/\Delta D$ and the Iribarren number is a gentle 'U-shaped' curve. A similar function had previously been observed for rip-rap; although in the case of rip-rap the minimum stability occurs at a higher value of the Iribarren number.

Based on these observations Pilarczyk obtained minimum stability numbers for a variety of different revetment constructions. He concluded that:

a) for loose block revetments on permeable underlayers, minimum stability occurs at:

$$\frac{H}{\Delta D} = 2.5 \quad \text{for slopes} > 1:2 \qquad (3.4)$$

b) for loose block revetments on impermeable underlayers, minimum stability occurs at:

$$\frac{H}{\Delta D} = 7 \quad \text{for slopes} > 1:3 \qquad (3.5)$$

Furthermore, infilling of the joints between blocks with gravel can increase this stability by between 25% and 100%. It should also be noted that these minimum stability numbers may be partly dependent upon the block type (see Section 3.4).

Whillock[15] carried out a series of model tests using square blocks supported at differing heights above an impermeable base. Again regular waves were used. From the results of these tests he concluded that for revetment blocks on an impermeable underlayer the block thickness should not be less than one-sixth of the wave height. This results in a stricter criterion than that given previously by Pilarczyk. It is, however, very similar to that suggested by CUR-VB[8] which recommends a lower stability limit of,

$$\frac{H}{\Delta D} \cong 3 \qquad (3.6)$$

for loose blocks with filter layers, and

$$\frac{H}{\Delta D} \cong 5 \quad \left(\text{ie, } \frac{D}{H} \cong \frac{1}{6.5}\right) \qquad (3.7)$$

for loose blocks on a relatively impermeable clay. However, CUR-VB then goes on to state that the parameters $H/\Delta D$ and the Iribarren number only very partially represent the failure mechanisms, and that great care is therefore required in the application of these criteria.

A further restriction upon these minimum stability numbers is that they cannot necessarily be extended to slopes outside those for which they were derived. Indeed, where a range of slopes has been given for a particular stability number, those should be strictly adhered to. It is generally agreed that the revetment slope influences the stability of the structure. However, the actual effect is the subject of some contention. Amongst others Whillock[15], Tuxford[4] and the Dytap revetment design handbook[1] all suggest that loose concrete blocks are more stable on flatter slopes. However, Pilarczyk[10] argues that the reverse is true and that increasing the slope reduces the uplift forces and hence increases stability. Moreover, the support due to end-loading by blocks lying further up the slope also increases as the slope steepens. It seems reasonable to assume that while gravity effects are less at steeper slopes, the interlock/interblock friction is considerably increased. Thus a steep slope revetment may have a slightly greater stability than a shallow slope revetment but, conversely, its failure is likely to be more abrupt. In practise revetments are generally constructed at slopes of around 1:3, steeper slopes are rarely used. It is however clear that the problem of the revetment slope effect will only be resolved by further research.

Although this section has mainly been devoted to the effects of wave period and revetment slope upon the stability of concrete block revetments, it has to be emphasised that it is the relative permeability of the armour layer and under layers that is the over-riding factor in determining the ultimate strength of the structure[11,15]. So far, however, no readily available design methodology has been developed which takes into account this relative permeability.

3.3 Filter layer stability criteria

The design of geotextile filters in slope protection works has been well documented by Ingold[23], Faure et al[24] and Charlton[25], all of whom presented design criteria. This review will therefore concentrate mainly on the criteria required for granular filters in a coastal environment, although a brief summary of the geotextile criteria will be included.

The most important requirement of a filter in slope protection works is that it should protect the underlying soil against erosion by waves or currents. Furthermore, the filter should prevent migration of the soil particles. If the internal flow is perpendicular to the interface between filter and sub-soil, the filter will always be soil tight provided that the hydraulic gradient is less than a critical value. For cohesionless soils this critical value is about one. Without cohesive forces between the soil particles, or other additional pressures due to surcharges, the equilibrium will be disturbed by gradients in excess of this critical value, and movement of the soil particles is possible. In the case of uni-direction flow, the soil particles may 'arch' at the entrance to the filter pores, thus improving the soil tightness of the filter. Under such circumstances, a natural filter can be formed so that for soil tightness it would be sufficient to exclude only the largest particles from migrating through the filter. However, in practise, coastal revetments are usually subjected to cyclic loading, and under these conditions a natural filter would be unlikely to form.

If the internal flow is parallel to the interface between filter and sub-soil, the items of major importance to soil tightness are the hydraulic gradient, and through that the flow velocity, within the filter. When a critical value of the gradient is exceeded the flow velocity in the filter becomes so great that the base material begins to move and the soil tightness is lost.

CUR-VB[8] gives the following requirements for filters subjected to strong cyclic flows:

a) for granular filters with nearly uniform filter and base materials,

$$d_{50f} < 4 \text{ to } 5\ d_{50b} \qquad (3.8)$$

where subscript 'f' refers to filter and subscript 'b' to base, and d is a nominal soil particle diameter

b) for granular filters with non-uniform particles,

$$d_{15f} < 4 \text{ to } 5\ d_{85b} \qquad (3.9)$$

To ensure the internal stability of granular filters the following general rule should be applied:

$$d_{60f} < 10\ d_{10f} \qquad (3.10)$$

This rule assumes that no internal migration will occur irrespective of the steepness of the gradient. However, for small hydraulic gradients this criterion can be eased. It should perhaps be mentioned, though, that at present no accurate values for the critical hydraulic gradients relating to internal revetment stability are available.

CUR-VB[8] also reports that in order to prevent blockage of a granular filter the following criterion should be observed:

$$d_{5f} > 75\ \mu m \qquad (3.11)$$

In order to prevent fine particles from the sub-soil being washed into the filter layer and eventually causing internal erosion of the sub-soil, the Dytap design handbook[1] suggests a filter criterion very similar to that given by CUR-VB:

$$d_{15f} < 5d_{85b} \qquad (3.12)$$

While Faure et al[24] present the expression,

$$d_{15f} < 4d_{85b} \qquad (3.13)$$

De Graauw et al[42] present results and conclusions of fundamental work on flow along and across core/filter interfaces under both steady and cyclic flow. Tests with coarse sands under cyclic flows at periods around 10 seconds (close to many prototype situations), revealed that the critical hydraulic gradients for the onset of sand transport through the filter under cyclic conditions are substantially lower than for the steady flow situation. For a safe design, it is recommended that in the case of strong cyclic flow,

$$d_{50f} < 2 \text{ to } 3d_{50b} \qquad (3.14)$$

Perhaps the most efficient means of draining a coastal revetment is to include both granular and fabric filters. Although, as previously mentioned, the design of geotexile fabrics has been well documented, a brief summary of the criteria is included for completeness:

Ingold[23] presents various filter criteria in terms of the geotextile pore size, O_{90}, and the coefficient of uniformity of the soil, U, where U increases as the soil becomes more well graded.

a) For $1 < U < 50$;

$$O_{90} < 2U\left[1 - (2/U)^{\frac{1}{2}}\right] d_{50b} \qquad (3.15)$$

but, $O_{90} < 45d_{50b}$

b) For $U < 5$, a uniform soil;

$$O_{90} < d_{90b}$$

c) For $U > 5$, a well graded soil;

$$O_{90} < 2U\left[0.2 - (2/U)^{\frac{1}{2}}\right] d_{90b} \qquad (3.16)$$

but $O_{90} < 2d_{90b}$

d) For non cohesive soils containing more than 50% by weight of silt:

$$O_{90} < 200\ \mu m \qquad (3.17)$$

Tuxford[4] suggests similar criteria to these, but includes some additional expressions for cohesive soils:

$$O_{90} < 10 d_{50b} \qquad (3.18)$$

and $$O_{90} < d_{90b} \qquad (3.19)$$

He concludes that those criteria, if met, will prevent excessive loss of the sub-soil fines. However, the geotextile must also be permeable enough to prevent a high pressure build up within the sub-soil. This requires that the permeability of the geotextile, K_g, must be roughly five times greater than the permeability of the sub-soil, K_s.

ie, $$K_g > 5\ K_s \qquad (3.20)$$

For coastal revetment filters under strong cyclic loading, CUR-VB[8] supplies the following expression for soil tightness of the geotextile, regardless of the flow conditions:

$$O_{98} < d_{15b} \qquad (3.21)$$

However, this expression takes no account of the grading of the sub-soil.

3.4 The generation of additional stability

The stability of a concrete block revetment can be improved in a number of ways:

a) by infilling the joints with gravel

b) by the use of interlocking blocks

c) by cabling the blocks together into mats and/or anchoring the mats/blocks down.

The infilling of the joints of concrete block revetments with a mixture of sand and fine gravel is recommended by Weckmann and Scales[2], Pilarczyk[12] and Lindenberg[22]. The effect of this infilling is to increase the frictional resistance between blocks and hence produce a system whose stability is greater than that of non gravel filled systems. Pilarczyk[7] presents results for a number of different blocks which suggest that the use of gravel infilling can increase the revetment stability by between 25% and

100%. However, the gravel/sand mixture can be partly, or even totally, washed out from the joints over a period of time, and any stability increase must therefore be uncertain.

The stability of interlocked blocks formed the subject of an extensive study by Hall[27]. The results of this study have been presented by Pilarczyk[7] in terms of the parameters $H/\Delta D$ and the Iribarren number.

a) Tongue and groove blocks,

$$H/\Delta D = 4.1 \quad \text{for slope 1:2} \qquad (3.22)$$

b) Tongue and groove blocks with relief slot to reduce uplift pressures,

$$H/\Delta D = 7.3 \quad \text{for slope 1:2} \qquad (3.23)$$

c) Shiplap blocks with spacers to relieve uplift pressures,

$$H/\Delta D = 5.7 \quad \text{for slope 1:2} \qquad (3.24)$$

Whillock[16] also presented results for an interlocked block and concluded that, on flatter slopes, $H/\Delta D = 10$. This is in qualitative agreement with the values given by Pilarczyk.

Clearly the presence of a complex jointing system improves stability. However, additional measures, to relieve the uplift pressures, are required, if this extra stability is to be exploited to the full. Furthermore, the more complex the block, the more costly and time consuming it becomes to lay.

Both gravel infilling and interlocking have one further disadvantage, that is, to increase the stability of a revetment by either of these methods must necessitate a reduction in the flexibility. If the flexibility of the revetment is reduced it will have a tendancy to span voids and will thus be susceptible to wave impact loads. Despite these problems a carefully designed revetment with either infilled or interlocked blocks can successfully be used in many situations where extra stability is required.

The cabling together of loose blocks into a flexible mat is fast becoming a popular method of providing slope protection. Such cabling systems may be either one or two-directional, with the latter being particularly effective under extreme conditions. The cable, although acting principally as an aid to construction, may also help to prevent slope failure by progressive block dislodgement. However, the actual stability increase of a revetment due to the incorporation of a cable is difficult to quantify. Indeed, Lindenberg(22) makes the implicit suggestion that such systems should be designed without the cabling. Any increase in stability due to the presence of the cable should then be viewed as a bonus. Perhaps the most complete account of cabling systems is that given by Wise(28). This covers the economics and constructional details of such systems but not, unfortunately, the stability aspects.

3.5 Discussion on block stability

In previous sections of this chapter, a number of simple design expressions have been considered. These have generally been presented in terms of $H/\Delta D$, a dimensionless wave height. Flexible concrete revetment systems are, however, often specified in terms of a mass per unit area, W/A. This parameter may be compared with the notional block thickness D:

$$\frac{W}{A} = C_1 \rho_s D \qquad (3.25)$$

where C_1 is a shape coefficient specific to each type of block, and ρ_s is the mass density of the concrete used (kg/m^3).

The parameter $H/\Delta D$ might then be re-expressed:

$$\frac{H}{\Delta D} = \frac{H C_1 \rho_s}{\Delta (W/A)} \qquad (3.26)$$

The stability expressions in section 3.2 above might then be written in the following general form:

$$\frac{W}{A} = H \cdot C_1 K_1 \frac{\rho_s}{\Delta} \qquad (3.27)$$

where K_1 is a stability coefficient covering the block and underlayer permeabilities, wave period, steepness and slope effects. It might be possible to generalise design information using this approach. However, values of the coefficients are, as yet, not directly assessible in the literature.

4 HYDRAULIC PERFORMANCE OF REVETMENT SLOPES

4.1 General

Coastal structures such as sea walls when subject to wave attack, will experience wave run-up. If the structure crest is lower than the maximum run-up, the structure will suffer overtopping. This may in turn lead to flooding and/or damage to the rearward face of the structure. In the planning and design of coastal structures, especially sea walls, wave run-up and overtopping are often the two primary factors dictating the crest level of the wall. As the cross sectional area and the cost increases approximately with the square of the structure height, a clear understanding of the processes of wave run-up and overtopping is essential to the economic design of such structures.

Designers of sea walls have often attempted to design the crest level of their structure high enough to prevent overtopping. This was done by calculating a maximum run-up level and setting the crest level above it. This does, however, presuppose that a maximum run-up level may be identified. With a fuller understanding of the random nature of wind waves, it has become clear that overtopping cannot always be wholly prevented, although the mean expected overtopping discharge for a design event may be reduced to negligible proportions. The design approach for simple sea walls in the UK has therefore recently been altered to one of designing for various levels of tolerable discharge under the extreme events considered, using the method proposed by Owen[29,30]. This method was derived from analysis of the results of model tests on simple, and bermed, smooth seawall slopes, without wave return walls. For structure with parapet walls, the prediction of overtopping discharge becomes more complex. Owen[31] argues that model tests are needed to determine the hydraulic performance of such crest details. Calculations of wave run-up levels may therefore still be required for some preliminary designs, and for further analysis of structures of complex form.

Much of the literature covering wave run-up and overtopping has been considered recently by Allsop, Franco and Hawkes[36] and by Gadd, Potter, Safie and Resio[37]. The latter review however ignores the overtopping prediction method of Owen[31] and the important work on the effect of oblique wave attack on run-up and overtopping by Tautenhaim, Kohlase and Partensky[38] and Owen[31], and is therefore likely to be of restricted usefulness.

Also of importance in quantifying the hydraulic performance of revetment slopes is the degree of wave reflection, not least because interactions between the reflected and incident waves can lead to an increase in the rate of scour occurring offshore of the structure. The actual degree of reflection will vary with wave steepness and structure slope angle, and for rough and/or permeable slopes will generally be reduced by the effects of slope porosity and roughness.

4.2 Wave run-up

As outlined above, the literature on wave run-up on steep slopes, as opposed to beach slopes, has been reviewed by a number of authors recently[34,36,37]. However, relatively little has been published on the particular run-up performance of revetment slopes, other than suggested values of the roughness coefficient[31,32,35]. Some test results using regular waves are presented by Weckman and Scales[2], van den Berg & Lindeberg[3], Tuxford[4], Lindenberg [22]and Tetratech[39]. These only cover three sets of tests, two on Armorflex and one set on Petraflex. Of them, the results given by Lindenberg[3,22] for run-up on Armorflex appear most easily compared with values of relative run-up on smooth slopes predicted by methods ascribed to Hunt and to Miche and as presented by Losada and Gimenez-Curto[33]. On analysis, however, it is found that the relative run-up values presented by van den Berg and Lindenberg[3] are in terms of the maximum wave height, H_{max}. This appears to be the maximum height due to both incident and reflected wave, a somewhat unhelpful parameter. A more useful graph is presented by Lindenberg[22] in terms of the incident wave height, Hi. This graph shows relative run-up following the Hunt expression for values of the Iribarren number, Ir, less than about 2.3, as predicted by Hunt for smooth slopes. For Ir > 2.3 the relative run-up appears to follow the trend suggested by Issacson and Miche for smooth slopes. It does not therefore appear possible to distinguish any significant reduction in run-up.

Test results for Armorflex presented by Weckman and Scales[2] and Tetratech[39], and those for Petraflex presented by Tuxford[4], are less easily interpreted. These values may, however, be re-analysed to give graphs of similar form to that used by Lindenberg[22], Losada and Gimenez-Curto[33] and by Allsop et al[34]. The run-up levels on both Armorflex and Petraflex appear to be generally slightly lower, and in some circumstances greater than those given by Lindenberg[22], but the use of R/Ho rather than R/Hi does not allow comparison with any prediction method without further information.

4.3 Wave overtopping

None of the literature considered in this review specifically considers the overtopping performance of the revetment, other than as a special case of run-up behaviour. The determination of run-up performance may form an important stage in the assessment of overtopping discharge by allowing the calculation of a relative roughness factor. This factor may be defined as the ratio of a typical run-up level on the rough slope, to that on the equivalent smooth slope, for identical wave conditions. Recent work by Losada and

Gimenez-Curto[33] and by Allsop et al[34] has demonstrated that this factor is not strictly constant, but varies with different wave conditions. However, suitable values may be selected to be used in conjunction with the method described by Owen[29] for preliminary design purposes. Examples of roughness factors derived from regular wave tests are presented by Stoa[35], Owen[31] and in the Dutch code[32].

4.4 Wave reflections

The influence of the roughness and permeability of revetment construction on its wave reflection performance has received little attention in the literature. Only Lindenberg[22] presents results of test measurements on Armorflex, which compare closely with a trend for smooth slopes suggested by Greslou and Mahe[40]. A slightly more favourable comparison may be made with the simple expression for the reflection coefficient, Kr, suggested by Battjes[41]:

$$Kr = 0.1\ Ir^2 \qquad (4.1)$$

where

$$Ir = \frac{\tan \alpha}{(H/Lo)^{\frac{1}{2}}}$$

Many of the reflection measurements presented by Lindenberg appear to lie below this trend line. However, these values are generally measured with smaller waves and the values measured for larger waves lie more closely to both the suggested trend lines for smooth slopes.

4.5 Conclusions

Run-up, and hence overtopping, over a rough revetment slope may be less than over a smooth revetment of the same slope angle. However, the size of the roughness element and the effective permeability, over a wave period, of the revetment must relate sensibly to the incident wave height and period. The block size, and hence the effective roughness, is normally set by the minimum block size necessary for stability, with the application of a suitable factor of safety. This may often lead to blocks of thickness around H/5, where H is a nominal design wave height. At this ratio of block size to wave height the roughness of most concrete revetment systems is relatively low. Model tests reported in the literature generally indicate that any reduction of run-up and hence overtopping over that for a smooth slope is marginal. Similarly, wave reflections at the principal design wave periods will depend primarily on the local wave characteristics and revetment slope angle and relatively little upon the block size or shape.

5 CONCLUSIONS AND RECOMMENDATIONS

This literature review has identified a number of design factors of crucial importance to the stability of concrete block revetments. Foremost amongst these is the relative permeability of the protective surface layer and filter layers. The stability of the revetment increases as the permeability of the blocks increases, and as the permeability or thickness of the filter layers decrease. Several authors have suggested that the most stable construction would consist of close fitting blocks on an impervious foundation. However, problems then arise through erosion of the sub-soil, which would otherwise be protected by a filter layer. It is therefore recommended that research be carried out to obtain the optimum range of relative permeabilities for revetment stability.

The contradictions between the requirements for flexibility and the requirements for revetment stability have been outlined. A revetment with a high degree of interlock/interblock friction will be more stable but will have a reduced flexibility. It will therefore have a tendency to span voids, which may result from settlement of the underlayers and/or poor construction practice, and will thus be susceptible to wave impact loads. Conversely a flexible 'loose' block system may well follow the contours of the under layers, thus lessening the effect of wave impact loads, but in doing so would present an uneven surface vulnerable to wave induced drag, inertia and lift forces. The stability of such a revetment would therefore be reduced. It follows that the embankment design and preparation must ensure that only very small settlements occur. If large settlements are anticipated blocks are perhaps not the best choice of protection.

Wave period has also been shown to have an influence upon the stability of revetments. Revetments often suffer more damage at lower wave heights for the longer wave periods than for the shorter wave periods. This effect can be accounted for in revetment design by the use of a minimum stability number. However, of more practical use to the designer would be the actual stability functions, related to wave period. Therefore, it is recommended that, for the most commonly used systems, such stability functions should be obtained.

This review has also highlighted the effect of the revetment slope both upon the stability of the revetment and upon the wave impact loads. It has been suggested that the stability is greater for steeper slopes, however further research is needed to confirm this. Further research into wave impact loadings is also recommended, aimed at extending Dutch and German work to all slopes, and at obtaining a greater understanding of pressure distributions within the revetment.

From an analysis of the relatively limited data available in the literature, it does not appear that any significant reduction of run-up, overtopping discharge or wave reflections over those determined for smooth slopes should be allowed for. In the absence of suitable hydraulic model tests, predictions of run-up, overtopping, and reflections should assume that the revetment acts as a smooth slope.

Although not specifically considered in this review, the interlocking, cabling and infilling with gravel, of revetment blocks is recognised as a potential means of increasing the overall stability of revetments. However, the behaviour of such complex systems will not be fully understood until researchers have unravelled the mysteries of relatively simple, discrete concrete block systems.

The final, over-riding conclusions of this report must be that there is at present very little available in the way of a realistic design methodology for concrete block revetments. It is possible to deduce from recent publications(7, 8, 11) the existence of a coherent Dutch strategic research programme, consisting of large scale physical model testing combined with mathematical modelling of the geotechnical aspects, and aimed at providing design guidance for Dutch engineers concerned with revetments. Essential details of this programme do not however, appear to be available. Therefore, if the design of such structures in this country is to be anything other than primarily by rule of thumb, a fundamental research programme must be set up to investigate the behaviour of concrete block revetments from first principles.

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8 GLOSSARY OF TERMS

1. CRITICAL HYDRAULIC GRADIENT: The gradient at, and above, which movement of the material in which the flow is occurring commences.

2. EMBANKMENT: An artificial bank such as a mound or dyke designed to hold back water so as to prevent flooding.

3. FETCH: The distance over water on which the wind acts to generate waves.

4. FILTER LAYER: A layer of granular material and/or a geotextile laid under the protective armour layer. The filter has three main functions; (a) filtration of flow across the sub-soil/armour layer boundary, to prevent sub-soil fines being washed out; (b) drainage under the armour layer; and (c) erosion protection of the formation of the sub-soil due to water motion above it.

5. GEOTEXTILE: Synthetic material which may be woven or non-woven and used as a filter layer.

6. INTERLOCKING BLOCKS: The method by which concrete block engaged with each other by overlapping or recessing one with another.

7. INTERNAL STABILITY: A revetment may be referred to as internally stable if none of its under layer materials start migrating due to the effect of a specific water motion.

8. OVERTOPPING: Passing of water over the top of a structure as the result of wave run-up or surge action.

9. REFLECTED WAVE: That part of an incident wave that is returned seaward when a wave impinges on a structure.

10. REFLECTION COEFFICIENT: The ratio of the height of a wave reflected from a structure to the height of the incident wave.

11. REVETMENT: The facing layers or armouring systems used to protect an embankment or slope against erosion by current and wave action.

12. RIP-RAP: A layer, facing or protective mound of stones randomly placed to prevent erosion, scour or sloughing of a structure or embankment; also the stone so used.

13. RUN-UP: The rush of water up a structure on the

breaking of a wave. The amount of run-up is the vertical height above still water level that the rush of water reaches.

14. SCOUR: Removal of underwater material by waves and currents, especially at the base or toe of a shore structure.

15. SIGNIFICANT WAVE HEIGHT: A statistical term relating to the average height of the one-third highest waves of a given wave group. This is the most common definition of wave height in random sea and is approximately equal to that visually estimated.

16. SUB-SOIL (SUB-BASE): The formation on which the revetment system is constructed.

17. SWELL WAVES: Wind generated waves that have travelled out of the area in which they were originally generated. Exhibit a more regular and longer period, and have a flatter crest than locally generated waves.

18. UNDERLAYERS: All formations lying beneath the protective surface layer of a revetment. Includes both the filter layers and the sub-base.

19. WAVE PERIOD: The time interval between two successive wave crests passing a fixed point.

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Figures

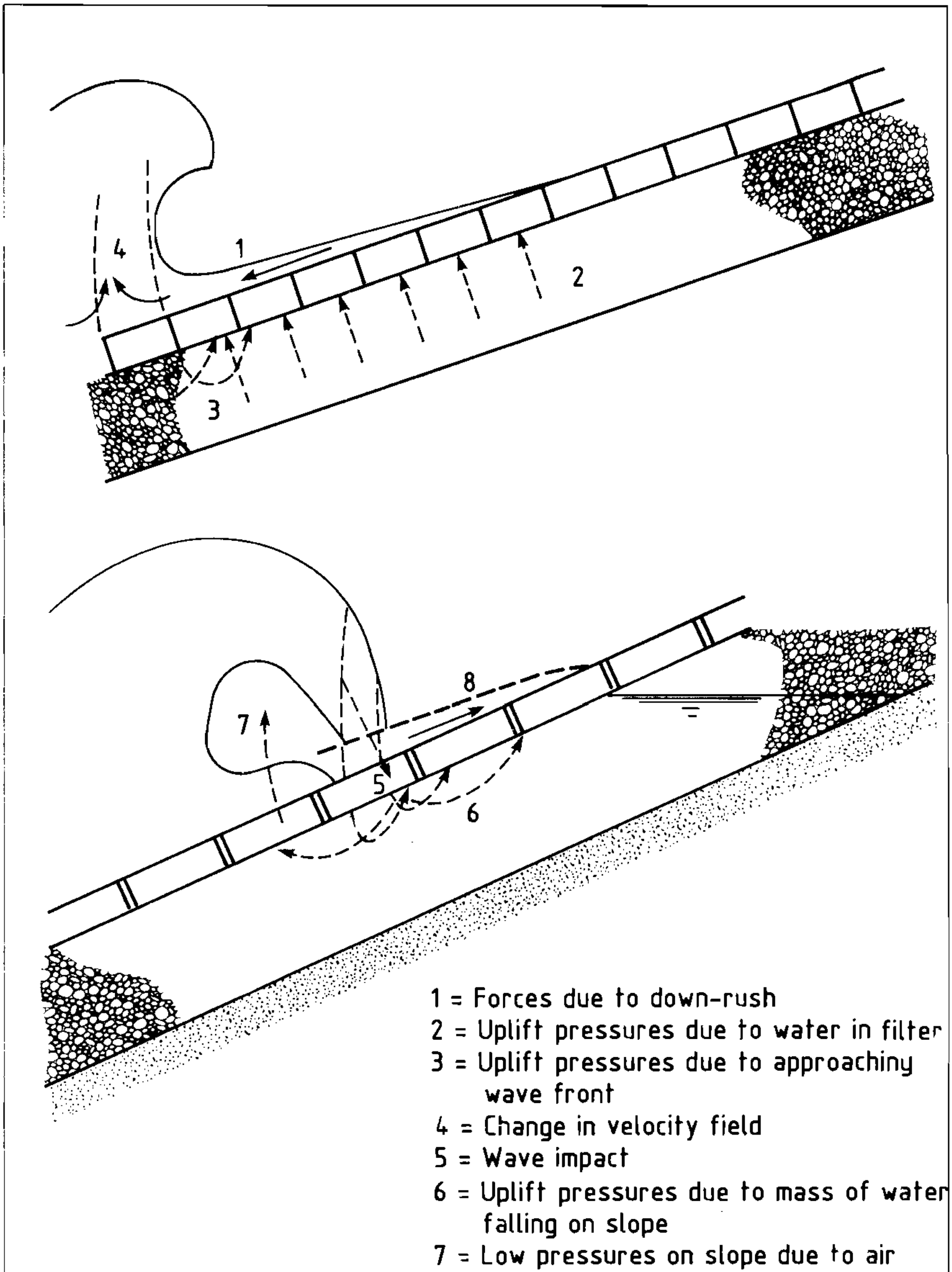

Fig 1 Schematic representation of failure mechanisms of slope revetments, after Pilarczyk (7)

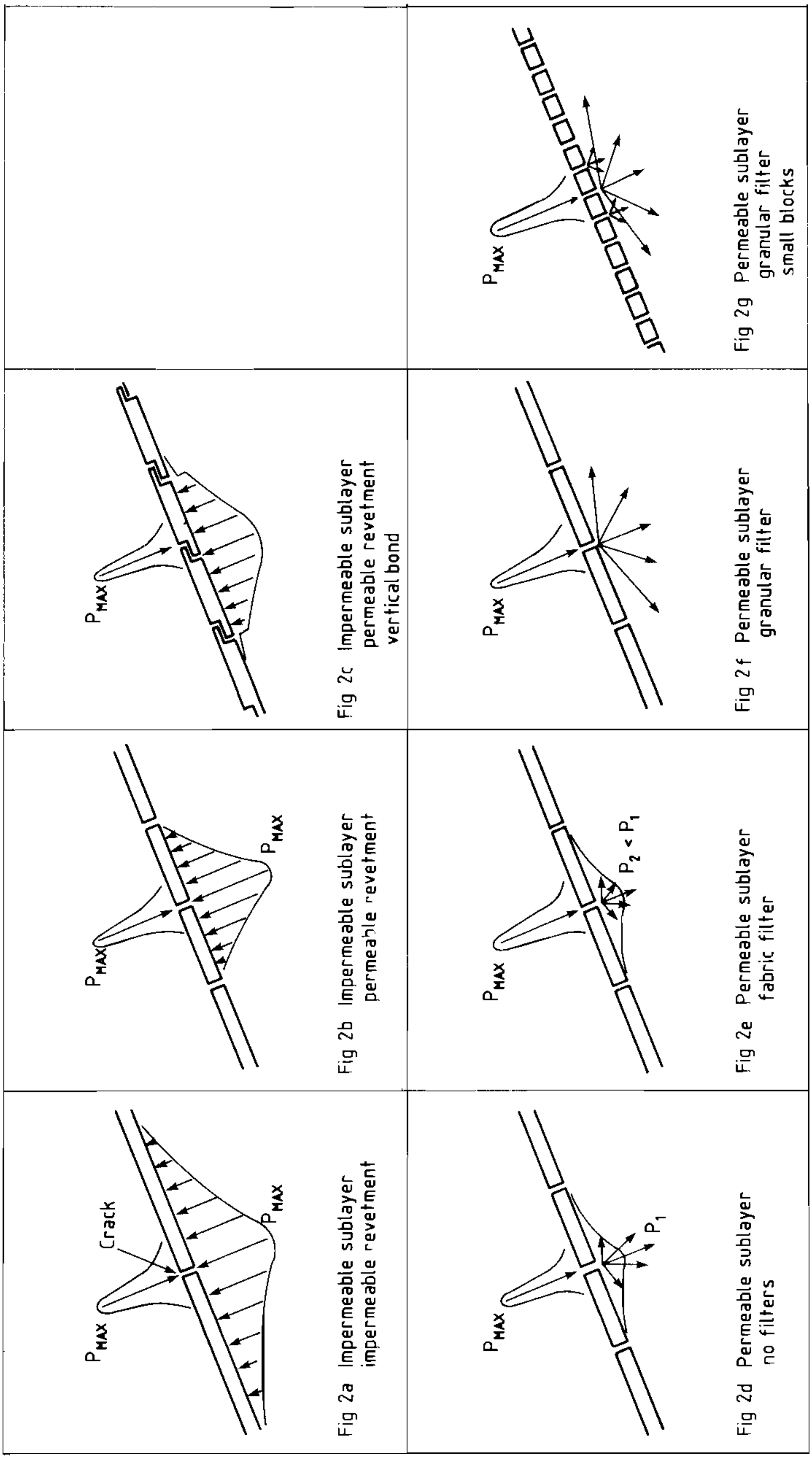

Fig 2 Wave impact pressure distributions

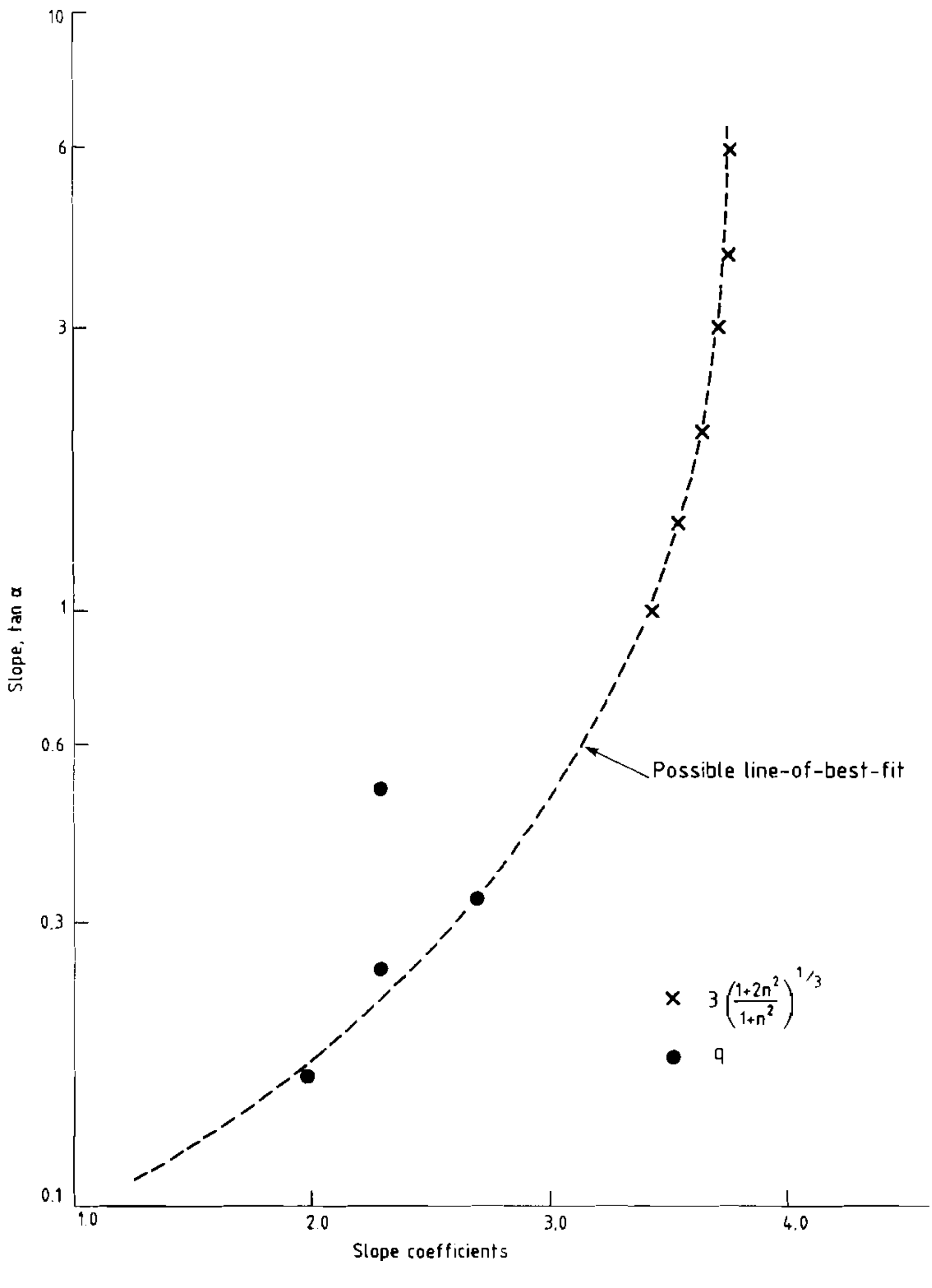

Fig 3 Slope coefficients as a function of revetment slope