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# A REVIEW OF NOVEL SHORE PROTECTION METHODS
## Vol 4 - Revetments - Text

J Welsby T.Eng
J M Motyka B.Sc (Eng)

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Registered Office: Hydraulics Research Limited,
Wallingford, Oxfordshire OX10 8BA.
Telephone: 0491 35381. Telex: 848552

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ABSTRACT

In recent years revetments have been widely used, often replacing more traditional forms of shore protection. Massive defences such as concrete sea walls will still continue to protect urban frontages. However, in rural areas, particularly where the coastline is not subject to severe wave activity significant savings can be made by using less massive revetment type protection.

Proliferation of new designs has generally outstripped the rate at which knowledge of their behaviour under wave attack is being disseminated. This report examines a wide range of revetment types, both old and new, identifying their good and bad points, where such information is available. It identifies several promising types. For example, asphaltic revetment construction has been underused in this country, compared with its wide acceptance abroad. Mattress construction, consisting of concrete modules linked by cabling, is becoming popular. However, its effectiveness in open coast situations is still open to question and such forms of construction thus need careful monitoring. Gabion mattresses are relatively cheap and are used widely, often in inappropriate locations. Many of the more traditional sloping revetments also need reanalysis since in most instances they have been designed purely on the basis of experience.

By comparison with the well documented performance of sea walls that of revetments is poorly understood. The lifespan of many of the structures presently being built is not known. Their effect on beach behaviour has only been assessed qualitatively. We therefore consider that regular monitoring of newly constructed revetments is essential.

This report was written by Mr J Welsby and Mr J M Motyka from the Coastal Processes Section of the Maritime Engineering Department, Hydraulics Research Limited, who should be contacted for further information.

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# 1 INTRODUCTION

The United Kingdom has a long and varied coastline. Stretching some 9,700km it includes stretches of cliff and marshland, sand and shingle beaches, rocky shores and saltings. Some parts of this coastline have been subject to erosion or inundation by the sea for thousands of years but it is only in recent times that man has attempted to modify natural changes.

In the past little thought was given to the effects that coast protection works would have on adjacent beaches. Massive sea walls and groyne systems proliferated, particularly in the Victorian era leaving us with a legacy of problems, such as deteriorating sea walls and beach instability due to wave induced erosion. In recent times, engineers have begun to take a more "sympathetic" approach, hoping to preserve the character of the coast as much as possible. Where conditions permit, types of coastal protection are now being tried which intrude as little as possible into the active beach zone. New materials are also being tried and tested which allow the protective works to blend with the existing coastal geomorphology.

Revetment protection is now becoming more widely used, replacing in some instances the more conventional (and expensive) reinforced concrete sea wall. Sloping revetments are usually placed on the upper parts of the beach so that waves reaching them have usually lost a good deal of their energy by bed friction and wave breaking over the lower parts of the foreshore. Some revetments rely on their roughness and permeability to further dissipate wave energy. Others are placed at such a shallow slope that wave breaking is progressive, with the wave forces distributed over a wide area of the revetment apron.

## 1.1 Purpose of the review

In 1981 the Water Directorate of the Department of the Environment commissioned Hydraulics Research Limited (HRL) to review novel or low cost methods of shore protection and assess their potential for use on the open coastline of the United Kingdom.

This is the fourth in a series of reports and for earlier reviews covering novel materials such as scrap tyres, fabric containers and gabions, see Refs 46, 47 and 71. This report differs from the others in that it concentrates on one particular type of structure and identifies the various materials used in its construction.

Because of its sheer size this report has also had to be separated into two volumes. The text, figures and plates are in this volume, while the summary sheets, giving details of site installations, are in a separate volume (Appendix 2).

The aim of this report is to bring to the attention of the coastal engineer many novel designs currently being marketed. While some general guidelines for design are included, this is not the main purpose of the study. There is however a literature review available from HRL which deals with design methods for permeable and impermeable concrete block revetments. (Ref 57)

It should be borne in mind that many of the structures described have not been widely used, and indeed many have not been tested in the UK coastal environment. The report therefore seeks to highlight rather than recommend systems which would appear to have potential for UK conditions.

## 1.2 Definition of structure type

A revetment is a facing or armouring consisting of an armour layer, an underlying filter and a protective toe, so placed that it protects an embankment from erosion by current or wave action. The surface armour layer is secured to a suitably prepared face of an existing embankment, dune or upper beach in order to stabilise its seaward face effectively. It is supported and protected at the toe and provided with adequate drainage.

There seems to be no precise distinction between revetments and sea-walls and often the same type of structure in another location bears a different name. A revetment is essentially a facing to an existing, usually sloping, embankment to both retain and protect the fill and its performance depends to an extent on the material on which it is laid. A sea wall on the other hand is usually a coast protection structure in its own right. To save any confusion, a short glossary of terms is included in Section 9. Also included in the summary sheets in Appendix 2, are structures referred to as bulkheads. A bulkhead is an American term for a retaining wall whose secondary purpose is to protect the upland against damage from wave action, (hence the reason for its inclusion).

# 2 REVETMENT APPRAISAL

## 2.1 Revetment Protection - General

There are basically three ways to deal with the problem of shoreline erosion:

1. armouring by means of a revetment, sea-wall, etc. to protect the shore directly from wave action,

2. reducing the force of the incoming waves or reducing tidal currents by some form of offshore structure, (Ref 10),

3. moving the waves seaward, away from the vulnerable parts of the shoreline by widening the foreshore by beach nourishment or by groyning.

In many cases offshore breakwaters cannot be justified on the grounds of high capital cost. They can also interrupt the littoral sediment supply by reducing the wave transporting capacity. Thus breakwaters can sometimes cause excessive accretion in their lee and erosion downdrift of the structure.

Beach nourishment is now becoming fairly widely used as a form of shore protection/enhancement. It is, however, costly and the widened beach may require regular maintenance. While nourishment is desirable from more than one viewpoint, it does have the disadvantage of not being a permanent solution to a coast protection problem.

Sea walls have for many years been used as a 'permanent' solution but in the long term their effect on the beach itself can be such as to cause serious and sometimes irreparable damage. Revetments can be considered similar to sea walls. They provide a fixed type of protection but their effect on adjacent beaches is less serious because they absorb a proportion of the incident wave energy.

Revetments can be classified as either flexible, semi-rigid or rigid. Flexible armouring such as quarrystone rubble or even gabions can cope easily with any differential settlement and still retain its armouring facility. A semi-rigid armour layer such as interlocking concrete blocks can tolerate minor distortion but excessive movement may result in block displacement with the possibility of revetment failure. Rigid structures such as reinforced concrete slabs may be damaged and fail completely under differential settlement.

Revetments should be built on relatively gentle slopes with say 2 to 4 metres of run for every 1 metre of rise to make the armouring stable and to prevent to erosion.

The embankment usually requires grading to prepare an adequate foundation for the armour layer. It is not normal practice to use revetments to protect marginally stable slopes. In such areas, where soil instability is a problem, heavier types of structures should be considered.

The roughness of the armouring can dissipate to a large extent the energy of incoming waves, minimising foreshore scour, while also reducing wave runup and overtopping. Also, revetments with a high porosity can attract a beach of finer material at their toe.

A review of revetment systems is particularly relevant at present since a wide variety of armoured facings are now being developed. Much of the low lying coastline of England and Wales (Refs 33 and 69) is protected by one form of revetting or another so there are large savings to be made by effective forms of construction.

Inter-connecting flexible concrete block systems are becoming fairly popular. Coastal engineers are also beginning to show interest in the wider application of bituminous compounds which, together with rock, sand, stone or aggregate are utilised extensively in Europe and especially in Holland. This latter form of revetment protection is reviewed in Section 3.3 (see also Ref 48).

Geotextile fabrics are also becoming widely used. Used mainly as secondary protection as filter cloth between the embankment and its surface armouring they are easy to lay and can be used to complement or supplant the traditional filter layers of gravel, sand, stone, etc. They have also been used in some countries as primary protection although this is not possible in the UK wave environment. Details of some geotextile fabrics are given in Appendix 1.

As the nature and complexity of coastal protection problems vary widely with location, it would not be feasible to specify exactly the type of armouring to suit a particular site.

What we have presented in this review is a broad description of many of the various types of protective facing in common use today, specifying where possible the design fundamentals, location, placement techniques, performance etc. This information is in the form of summary sheets which can be found in Appendix 2 (separate volume).

Revetments, as with other forms of coastal protection, can be designed to withstand the severest likely conditions. However, this is rarely economic. The various constraints which affect one's choice are described in such text books as "Sea Defence and Coast Protection Works" by Thorn and Roberts (Ref 65). The Shore Protection Manual (Ref 21) also takes a comprehensive look at design practice. Some general design aspects are also given here in Section 4. As mentioned earlier, design guidelines can be found in the HRL report No SR 54 (Ref 57). This gives a number of stability criteria for permeable and "impermeable" concrete blocks as well as describing the hydraulic performance of some of the blocks currently in use.

## 2.2 Revetment materials

A wide range of materials have been used to construct revetments. They include:

(a) Bitumen (in conjunction with other materials)
(b) Bricks
(c) Cement mortar mix (in fabric containers)
(d) Clay
(e) Concrete (in-situ or as pre-cast blocks)
(f) Geotextiles
(g) Resin (in conjunction with other materials)
(h) Rock
(i) Rubber tyres
(j) Rubble (concrete, asphalt, bricks, etc)
(k) Soil cement
(l) Steel (usually in sheet pile form)
(m) Timber (either as piles, cribworks, breastworks, or slatted revetments)

In the wave environment experienced around the UK coastline, geotextiles, resin, rubber tyres and soil and cement are generally not suitable, while fabric containing sand or cement should be used only in sheltered waters or at the upper limit of the tidal zone.

Of the revetment types mentioned above, timber and rubble are widely used. Where readily available, rubble or quarry stone can also make economical revetments. Bitumen can also be used either as a grouting medium or in conjunction with aggregate to form a paving surface.

## 2.3 Revetment permeability

Although revetment facings come in a variety of materials, shapes and designs they fall naturally into one of two categories:

<u>Permeable</u>

This type of armouring is usually flexible, having an "open" protective layer enabling water to flow in and out of the structure. It is usually in the form of discrete elements, including

1. dumped or placed rock, stone or rubble, which are the most common type of protection,

2. gabions used in basket or mattress form and filled with rock or stone,

3. concrete blocks which are individually pre-cast. They can be in the form of interlocked or integrated mattresses or of free standing units,

4. stone layers grouted with "under-filled" asphalt to allow permeability,

5. fabric containers filled with sand or sand-cement mortar (sandbags, Longard tubes, etc), which can be considered semi-permeable,

6. asphaltic materials such as Fixtone, a patented gap-graded asphalt-stone batch mix (see Glossary). These are also permeable.

It is usual for permeable revetments to incorporate a filter (see Appendix 1) consisting of one or more layers of stone and/or a geotextile fabric. This is needed not only to prevent the leaching of fines from within the embankment but also to act as a sub-base protection. Filters also act to relieve hydrostatic pressure from within the embankment.

Other types of permeable structures include wooden breastworks, either of sloping or vertical construction, and sometimes with an open slatted framework to enable beach material to pass through, accrete behind it and stabilise a cliff toe. These are widely used and are often employed to protect soft cliffs, sand dunes, etc. Solid posts are now being manufactured from synthetic materials (recycled plastics) which are claimed to be very nearly rot and corrosion proof. These would appear to be particularly useful in situations for example where the revetment is regularly immersed in water. Apart from their resistance to chemical attack they would no doubt be "indigestible" to marine borers. Consisting mainly of polymer products they can be machined with woodworking tools and the cost (in July 1984) of a post 0.1m x 0.1m x 3m for example would be about £8.00. We know of only one location to date where they are currently in use (as groynes) in a marine environment.

Impermeable

This type of protection generally prevents water from flowing through the sublayers, so that hydrostatic pressures have to be relieved by drainage outlets.

Impermeable revetments are usually constructed of:

1. Concrete slabs either jointed or unjointed, laid in-situ or pre-fabricated.

2. Concrete or stone blocks butted to each other and jointed with either bitumen or sand/cement mortar.

3. Brickwork or basic construction blocks usually overlapped or laid in herringbone fashion and grouted in place within preformed panels.

4. Cement or over-filled bitumen grouted stone or rock.

5. Rolled asphaltic concrete.

6. Clay banks with no protection other than perhaps a grassed surface.

It has been found (Ref 73) that close fitting blocks on an impermeable foundation are more stable than those placed on a porous filter layer. The limited inflow of water due to the close fit of the blocks and the short duration of the wave impact, can be readily accommodated by quite small movements away from the impervious foundation. When lifting of individual plain blocks was observed, the movement was small and the restraint required to hold them in place was not large. When placed on a permeable foundation such blocks may be moved by internal water pressures.

In the following chapter various revetment types are examined. These include interlocking blocks which can be permeable or impermeable, depending on design type. Integrated or mattress type blocks are also examined, all of which are permeable, requiring a filter cloth beneath. Finally single block systems are described. These are held in place by their weight or by grouting to each other. They can be either permeable or impermeable again according to design.

# 3 REVETMENT TYPES

## 3.1 Pre-cast concrete armour units

Concrete block work, both unconnected and interlocking, is a popular form of revetment protection both in Europe and America. Its relatively low overall cost has stimulated interest, coupled with the fact that the quality of concrete blocks has improved in recent times as has the efficiency of the manufacturing process. The units are fairly easy to install, with the aid of a crane or dragline. For the mattress (integrated) type, laying and installation is not generally labour intensive although a spreader bar is required to lay the mattress in position. The laying of the smaller unconnected blocks may be more labour intensive, but many are light enough to be able to be laid by hand.

Many different kinds of revetment block are in current use but there are three basic types:

**Interlocking** - Interlocking can be in plan, as in the case of the Armorloc system (see page 11) where the units are held together by dove-tail joints. There are also armour units which interlock in elevation e.g. shiplap type jointing. (Figs 3 & 4)

**Integrated** - Blocks which are connected by cable or wire to form a mat. In some designs the cables are used to give an even laying of the mat. In others cables form an integral part of the structure and are used to withstand damage (i.e. by spreading wave induced forces or settlement over a wide area).

**Free blocks** - Placed abutting one another in a prepared panel or bay and sometimes bonded together with cement or bitumen (Plate 10).

It has to be said that the majority of these types of armouring are not suitable in situations with a severe wave climate. However, they will normally withstand low to moderate wave activity. For example, a section of integrated type Petraflex and Armorflex revetment has been installed south of Hunstanton in the Wash Estuary, see summary sheet 7 (Volume 2). Here wave heights are limited by the extensive offshore sand banks. Built in 1984 the revetment is being monitored by Hydraulics Research Ltd on behalf of the Ministry of Agriculture, Fisheries and Food. It would appear from these inspections that wave forces are absorbed more on the wooden piled toe than on the revetment slope itself. This revetment is therefore likely to remain 'untested' until the area is exposed to extremely high tide levels combined with strong wave action.

Another revetment of similar design was installed on the North Wales coast at Llanddulas to protect a waste tip, see summary sheet 9. This has withstood wave action for a number of years although damage is now taking place because of differential settlement due to loss of back fill (see Plate 8).

Stability of concrete blocks depends on:

1. Effectiveness of the interlock design.
2. Size and weight.
3. Friction between each block.

The size of the block is limited by the weight of panel that can be lifted and placed without damage which in turn limits the inter-block friction. The ideal element is one that can fail structurally and be removed by wave action without causing progressive failure or damaging adjacent units.

Our review has, however, revealed very few general design equations, the choice of type and size of block being largely based on experience. A review by McCartney (Ref 42) in 1976 provides some comparison between different revetment types but does not include the more recent block designs. Because of the lack of design guidelines one has to seek the manufacturer's advice on the method of construction, filter type, etc, once the type of block is chosen. Some manufacturers advocate filling the interstices with loose gravel. This reduces flexing and thus possible displacement of the underlying filter material but increases the risk of 'arching'. It should also reduce fatigue and degradation by ultra-violet light of the synthetic cables where these are fitted to hold the blocks in place as a mattress. Gravel or soil will both wash out in a moderate to high wave environment.

Design charts relating wave height to system weight are available from revetment block manufacturers and Wise (Ref 77) gives development parameters for a number of integrated flexible revetment systems. Such charts should be used with caution as this type of revetment design is still in a stage of infancy.

### 3.1.1 Interlocking single layer systems

These are probably the most common systems in use today. The blocks are generally square or rectangular in shape, having either shiplap (see Figs 3 and 4 and Plate 1) or tongue and groove jointing (see Fig 1 and summary sheet 10).

The tongue and groove type connection can be either wedge shaped, bull nosed or circular. Stability depends largely on weight and the strength and durability of the interlock. Both shiplap and tongue and groove types have been tested in the laboratory. Using regular waves, the Coastal Engineering Research Centre (CERC) investigated, on a slope of 1 in 2, hand produced shiplap blocks weighing 68kg and machine produced bull nosed tongue and groove blocks weighing 34kg. The results are given by J V Hall in Ref 31. Following this initial testing the shape of the tongue and groove block was modified to allow more flexibility (see Fig 1). Smaller scale tests (1 in 24) have been conducted at HRL, details of which are given in Refs 37 & 74. Reference 37 describes field trials with blocks 0.46m square by 0.15m thick with a diagonal overlap of 0.08m in which the blocks withstood waves up to 1.2m before being lifted and permanently displaced. This gave a block thickness/wave height ratio of 1:8.

Intended for use where the wave climate is not severe, interlocking blocks are usually laid in panels and the end blocks secured by concreting in.

The advantages of this type of block are:

(a) they can be laid by semi-skilled labour;
(b) they have the ability to flex and thus tolerate some degree of settlement;
(c) they are not jointed with mortar so hydrostatic pressures are more easily released;
(d) they can be lifted and replaced if damaged, although how easily would depend upon the type of interlock.

The disadvantages of both shiplap and tongue and groove types are that:

(a) they cannot adequately follow large changes in the sub-layer. The tongue and groove type would tend to bridge a hole beneath and fail without warning;

(b) sand or gravel can get between the interlock making it inefficient;
(c) extensive settling leads to block separation and makes the shiplap jointing inefficient;
(d) repairs to the underlayer could be a problem;
(e) another weakness in the shiplap blocks is that tilting about the diagonal is possible. Once this occurs material can build up in the joints causing permanent displacement and eventually failure;
(f) shiplap joints are particularly vulnerable if the blocks are laid with their overlaps facing seaward as they can then be lifted by the breaking wave.

Few general design criteria are available for this type of protection, the guidelines being based generally on experience, supported in some instances by model investigations, see Ref 57. In all cases, the type of sub-layer and its permeability, together with the permeability of the filter and the blocks themselves, are important factors in the overall performance of the revetment itself.

The following are a selection of the types of blocks which are now manufactured:

**ARMORLOC**

Produced by Nicolon BV of Holland, this pre-cast cellular type concrete block is usually installed on a woven filter fabric. It is suitable for sheltered waters only and designed for areas where access for heavy vehicles is impracticable or where the small size of the sea defence installation renders heavy equipment uneconomic. Suitable for hand laying, they are manufactured as single blocks, their dovetail configurations allow flexibility in the longitudinal and transverse plane. Interlocking occurs in plan only, however, so there is the possibility of blocks being lifted out by wave induced pressures.

Block data: 301.5mm x 403mm and 100mm thick
Weight - 14kgs each = 150kg/m$^2$ of surface area

Application: We know of no sites where this material has been used on the open coast.

**CONTROL BLOCKS**

These are similar to the standard building construction block described in Section 3.1.3, except that protrusions along the edges provide tongue and groove interlocking (in plan) between blocks (see Fig 1). Information on these can be obtained from Ref 22 and in the summary sheets in Appendix 2 (Volume 2).

These blocks are of cellular construction and are being used as revetment protection along the banks of Lake Superior, USA to combat cliff erosion resulting from direct wave attack. There are no large water level fluctuations in the Great Lakes (maximum seasonal fluctuation is 0.8m) and the greatest problem is damage caused by wind induced waves (maximum wave heights approx 1.5m).

Block data: 400mm x 200mm x 200mm thick (small)
400mm x 300mm x 200mm thick (large)

Weight - not known

Application: Port Wing, Lake Superior, Wisconsin, USA

**DOUBLE WEDGE**

These are of Czechoslovakian design and are heavy units which are set alternately as rows and columns (see Plate 9). They rely on their mass and their overlap for stability. They have been used at Felixstowe to protect low cliffs against wave attack.

Application: Felixstowe, Suffolk. See Plate 9.

**GRASSBLOCK**

Produced by Landscape Grass (Concrete) Limited, these pre-cast concrete units come in a range of sizes. Grassblock 103 available with either a solid or open matrix. It has shiplap type interlocking (i.e. in the vertical plane).

It is generally recommended that the solid matrix block be underlain by 10-20mm of sand fill. These blocks are currently being used by Anglian Water in Norfolk.

Block data: Grassblock 103 - 406mm x 406mm x 103mm thick

Weight - 24kgs

Application: Burnham Overy, Norfolk (open matrix), 1979.
Sheerness, Kent (solid matrix) 1982/1984.

**LOK-GARD**

A precast concrete block developed and patented by the Coastal Research Corporation of Glen Burne, Maryland USA.

These tongue and groove type interlocking blocks have been used in America on Tilgham Island, Maryland where they were installed along 244m of shoreline as a 1 in 2 slope revetment. Details of this revetment are given by Mohl and Brown (Ref 44) and McCartney (Ref 42). It is specified that the design must incorporate both filter and toe protection. Prototype scale tests have also been carried out on this type of block by Hall (Ref 31).

Block data: 580mm (top) and 630mm (bottom) long by 220mm wide and 140mm thick

Weight: 34kgs

Application: Tilgham Island, Maryland, USA

**SCAN-GABIONS**

Produced by Scan Gabions A/S of Copenhagen it is termed a "flexible slab" system. They consist of reinforced, cellular concrete blocks which are inter-lockable on four sides to give a continuous construction. Specified for use as coastal protection. They can also be linked one on top of the other to give two or more layers thickness. Cellular, to allow the relief of hydrostatic uplift pressure, they are normally laid on a suitable filter. Designed for use in inaccessible areas they can be produced in a variety of different sizes weighing from 55kgs up to 4 tons and up to 2000mm x 2000mm x 600mm thick.

Block data: Standard size 500mm x 500mm x 150mm thick

Weight - 60kgs (standard size)

Application: Sites not known in this country.
Jutland, Denmark 1982

**SEBLOC**

A patented concrete block armouring produced by RBS Brooklyns. Developed from the "Dytap" block with a shiplap type joint along the longer side (see Glossary). It is designed for use primarily as coastal revetment protection although the manufacturers state that "Sebloc should only be used in the 'breaking wave' situation. It is not designed to withstand unbroken head-on impact". The revetment slope should not exceed 1 in 3 when used on the exposed coast. It is a solid interlocking pre-cast block, factory produced for use as a flexible revetment in coastal waters as well as in more sheltered areas such as estuaries, docks, marinas, etc. The blocks are laid, dry-jointed, singly within a panelled area having toe capping and panel beams. Sebloc units can also incorporate a wave energy dissipator if required. These blocks stand proud of the revetment, hence reducing wave run up (see Plate 11). Generally used on slopes of 1:6 or shallower.

RBS Brooklyns also produce "Dytap", a patented interlocking solid block, as well as "Dymex" an interlocking cellular type block. Normally both types are used for earth bank protection above normal water levels in canals and estuaries. The Dymex blocks can be covered over with soil and seeded both for added protection, and for aesthetic purposes.

| | |
|---|---|
| Block data: | Sebloc 558mm x 278mm. Thickness ranges from 125mm to 200mm plain, 225mm to 300mm dissipator |
| | Weights: 44 to 83kgs (larger/heavier blocks manufactured if required). |
| Application: | Southsea, Hants (see Plate 11) |

**SHIPLAP**

Perhaps the forerunner of the interlocking impermeable block system, introduced by the Kent Rivers Catchment Board in the late 1940's. This has the simplest form of interlock and is designed for hand placement. Used extensively along the Kent coast from the early 1950's onwards, this type is still in use today. Basically it consists of slabs joined one to the other (as shown in Fig 3 and Plate 1) and offset to provide a mechanical interlock with adjacent blocks, thus giving two way interlocking. The blocks are laid in staggered fashion (often on a thin layer of weak concrete) in panels and constrained by toe capping and end beams. The peripheral blocks are sometimes concreted in and some blocks are made with a central hole to allow tubular steel stakes to be driven through for added anchorage. Plate 2 shows a typical shiplap revetment at Pett, Sussex.

Block data: 380mm x 380mm x 150 or 200mm thick

Weight: not known

Application: Sheerness, Kent

See also Grassblock (another form of shiplap block).

Note: Shiplap blocks used in the USA (see Ref 30) range in size from 200mm by 400mm x 500mm to 910mm by 910mm x 360mm and weigh from 34 to 726kgs. Cost is claimed to be 50% less than riprap.

**SVEE-BLOCK**

These near-cubical shaped concrete blocks are patented by R Svee of the Technical University of Norway. They have openings normal to the revetment face to facilitate the relief of hydrostatic pressures. Conceived in the early 1960's they have been subjected to extensive model tests (see Ref 61) but have not, as far as we know, been used on the open coast as revetment protection.

They are designed to be closely packed in continuous rows (see Fig 1), the blocks of any one row interlocked to prevent any individual block from being forced out of the layer without moving several blocks in the same row. However, there appears to be no interconnection between adjoining rows.

**TERRAFIX**

A patented trapezoidal shaped block developed initially for use in the Mittellandkanal, West Germany, (Ref 32). The system consists of two complementing components, a non-woven geotextile filter layer overlaid by pre-cast interlocking concrete blocks. These are moulded with conical pegs at the front and matching holes at the rear (see Fig 1). The blocks are interlocked and laid as mattresses by a crane and spreader bar. In use since the early 1970's in canals and waterways as bank protection. Model studies have been carried out to investigate the resistance of this revetment system against high current velocities and wave attack.

The makers are not known to us although Erosion Control Products of West Palm Beach, Florida manufacture them in the USA. Referred to in a paper given at the 1984 PIANC Conference (Ref 32).

Block data: NV12 type - 660mm x 140mm x 120mm thick

Weight: 23kgs.

**TRI-LOCK**

A relatively new form of erosion control system from Ardon International designed and patented in the USA, it comprises two interlocking concrete components roughly triangular in shape, a lock block and a key block. Each component is keyed into two others in jig-saw puzzle fashion. The blocks are laid on a suitable filter fabric and have holes through which to thread cable if required. The system can be hand assembled or pre-fabricated on the filter and laid as a mattress. This block protection is designed for waterways, drainage channels and river embankments.

The only data we have is in the form of a promotional pamphlet.

| | |
|---|---|
| Block height: | 0.1 to 0.3m |
| Modules: | 0.4 or 0.8m |
| Weight: | 156 to 439kg/$m^2$ |
| Standard mat: | 1.4 to 2.1m wide, up to 14.6m long |

Applications: Not known.

**WALLINGFORD BLOCK**

A pre-cast fully interlocking concrete unit designed at Hydraulics Research Limited, Wallingford (Ref 73). Each block when placed diagonally in position, is symmetrically restrained from vertical movement by the two blocks on either side; these in turn being weighted down by the one at each end. It is designed to protect embankments against wave attack on slopes that do not exceed about 1 in 4. The blocks, shown in Fig 2, can also be laid on steeper slopes. A report (Ref 74) on model tests, recommends that block thickness should not be less than one sixth of the breaking wave height.

The dimensions and proportions of a Wallingford block can be varied to suit different circumstances of wave height, foundation stability and method of construction. Dimensions given below are for a small block that could be used in situations where maximum wave heights do not exceed 1.8m.

Block data: Overall dimensions - 300mm x 600mm x 150mm thick (see above).

Application: Field trials on the Wirral Peninsula, at Leasowe Bay.

**WESSEX BLOCK**

A pre-cast concrete block manufactured by Landscape Grass (Concrete) Limited. Of "shiplap" type design, it interlocks both laterally and longitudinally and is normally placed by hand within concrete edging strips and on a prepared base so as to form a panelled revetment. These solid blocks, shown in Fig 3, have been used as revetment protection by the Wessex Water Authority.

Block data: Wessex 380mm x 380mm x 150mm thick

Weight: not known

Applications: Kingston Seymour, Somerset
Tidal defences on the River Thames.

### 3.1.2 Integrated single layer armour units

This type of system consists of "columns" and "rows" of preformed concrete blocks linked together by cable rope or wire or alternatively secured to a special type of filter mat by epoxy resin. Blocks can also be linked longitudinally by cable and interlocked laterally. With all these types the armouring is both flexible and pervious, the blocks being of cellular construction. A typical revetment using Dycell blocks is shown in Plate 6.

The cabling, which is threaded through special ducting in the blocks, is an aid to rapid placing of the mats. It also connects the mats together in the lateral direction while the cable ends or loops are used for anchoring. This prevents progressive block displacement. Wear and tear on the cables would seem to be a weak point in the design and where synthetic fibres are used they can be subject to:

(a) degradation, due to exposure to ultra violet light;
(b) fatigue due to continuous flexing and chafing caused by wave action;
(c) abrasion by the beach material;
(d) vandalism in that they can easily be severed;
(e) exposure to chemical attack in a marine environment.

The working life of any cable is very difficult to predict, depending not only on the type of material used and the blocks to which it is attached, but also on the wave climate and the beach material. Wise (Ref 77) suggests a working life of 50 years for some designs. This is based on river and canal usage, however, and the lifespan will clearly be far less on the coast. One way to prolong the life and give added stability to the structure is to fill the block interstices with gravel or if out of reach of normal wave activity, to grass the revetment face.

The following are a selection of the types of blocks which are now manufactured:

**ACZ-Delta**

This design was developed by ACZ Marine Contractors BV of Holland. It is basically a geotextile filter fabric onto which rectangular blocks of truncated pyramid shape are formed in herringbone fashion. Connection between blocks and filter is by polyamide cords woven into the filter fabric with loops at the points where the concrete blocks are to be formed. The loops are held upright while the concrete is poured into a mould placed on the mat. The completed mat is transported to the site and placed by crane and spreader onto a gravel bed. The gaps between the blocks are then filled with crushed gravel to prevent degradation of the filter by UV light and to increase the overall stability of the revetment. One disadvantage of this type of protection is the difficulty in repairing a damaged filter cloth.

Prototype tests have been carried out in the Netherlands and form the basis of a paper by Pilarczyk (Ref 54) while another type of ACZ Delta mat is discussed by Dore, Bartels & Schuit (Ref 25). Used only, as far as we know, as bank protection in rivers and canals and for bottom protection on the Eastern Scheldt Storm Surge Barrier in the Netherlands.

| | |
|---|---|
| Block data: | 200mm x 400mm (base), 155mm x 355mm (top) x 160mm thick |
| | Weight: 190kg/m$^2$ of surface area |
| Application: | No coastal application known. |

**ARMORFLEX**

Introduced onto the European market in 1982, from the USA, these machine-compressed concrete blocks, which can be either cellular or solid, are shown in Fig 6. Marketed here by MMG Erosion Control, they are linked longitudinally by polyester or stainless steel cables and laterally by their interlocking (in plan) profile, to form a flexible and permeable mat, usually 6m x 1.2m or 6m x 2.4m. The mats are transported to the site and placed on a woven geotextile filter using spreader beams. They are butted together and linked laterally by their cables.

Suitable for sheltered or semi sheltered coastal waters, they can be covered with gravel to enhance stability and anchored at top and toe. Additional anchoring can be made with screw anchors through the mat. Armorflex also supply individual blocks, these being interconnected by special plastic pins. Weckman and Scales (Ref 70) give design guidelines and details of model tests.

Recommendations on design can be obtained from the manufacturers, but a couple of hydraulic points from the above tests are worth mentioning:

(a) Slope - a 1 in 3 slope was found to be the most stable of those tested.

(b) Wave action - The greatest damage for a given wave height will occur with the steepest waves.

Block data - 330mm x 300mm x 90 or 120mm thick

Weight - 15 to 25 kgs depending on type
150 to 250 $kg/m^2$ surface area depending on type
Filter recommended - woven geotextile.

Application - Heacham, Norfolk, (Armorflex 180), 1984 on the eastern shore of The Wash.

Holland, Essex, (Armorflex 150) 1984 above sea-wall (in splash zone).

Llanddulas, Clwyd (Armorflex 180) 1984, see Plate 8.

Lytham St Annes, Lancs, (Armorflex 150) 1984.

Summary sheets 7 and 9.

**PETRAFLEX**

A flexible system designed in the USA (in 1979) and marketed in the UK by Ardon International. The factory made cellular concrete blocks (see Fig 6), are linked by a rectangular net of 'parallel fibre' polyester ropes running laterally and longitudinally through plastic lined conduits in each block, to form mats normally 2.4m wide and up to 12m long. Laid on a prepared slope by crane and spreader bar, the mats are underlain by a synthetic filter, butted together and secured to each other by fastening the protruding cables together using crimped aluminium ferrules. Longitudinal connection may also be made in a similar manner. Anchorage requirements vary considerably depending upon site conditions.

Design charts are available based on large scale model testing carried out in the USA. During these tests, a Petraflex mat 7m x 3.5m was laid on a 1 in 3 slope and subjected to both regular and random waves. (See Reference 68).

The blocks come in several sizes and weights some of which are noted below.

Block data (a) Type H91824 - 457mm x 610mm x 220mm thick

(b) Type H41212 & H51212 - 305mm x 305mm x 100 & 155mm thick

Weight 14 kg (H41212)

Filter type - woven or non woven geotextile specified according to soil type and supplied or approved by Ardon

Application - Huntspill, Somerset (type (a)), see Plate 7
Heacham, Norfolk (type (b)),

Summary sheets 7 and 8.

3.1.3 Single block systems

This type differs from the others in that the blocks are unconnected and surface friction forces keep them in place (although in many cases the gaps between each block are grouted to enhance stability).

When solid blocks are used, the revetment face is virtually impermeable, with the danger that hydrostatic pressures can build up if the blocks are laid on a permeable sub layer. To combat this, they can be laid on an impermeable embankment such as clay. Alternatively permeability can be increased by choosing cellular type blocks. The stability of these types of blocks under wave action is reported on by Whillock in Reference 74 and test results on the different block systems are given by McCartney in Reference 42.

**ANGLIAN BLOCK**

This is a solid block recently introduced by Landscape Grass (Concrete) Limited. It has a square base and is tapered to allow for grouting with concrete or asphalt mix.

A perforated concrete block is also produced by this company. It is square in plan with holes drilled at intervals to allow the release of hydrostatic pressures. These blocks are normally used above the high water line usually to protect earth embankments.

| | |
|---|---|
| Block data | (a) Anglian blocks - 380mm x 380mm x 127 or 88mm thick<br>(b) Perforated blocks - 600mm x 600mm x 60mm thick<br><br>Weights - not known |
| Application | (a) not known<br>(b) tidal defence on River Thames |

**ERCO BLOCK (GOBI BLOCK)**

A concrete block patented by Erco Systems of New Orleans, USA. (Also know as the Gobi block.) It can have either straight or bevelled sides with a raised cobble like top and with vertical holes to allow the release of hydro-static pressures (see Fig 7 and Plate 3). Erco blocks can be either hand placed and bolted together or glued to filter cloth strips.

They are used as revetment protection in the USA but only, we think, in sheltered areas (max design wave height, 1.0m).

There are several site descriptions given in the summary sheets in Appendix 2 which also give details of a larger block of this type called Jumbo blocks. These are also normally bonded to a filter cloth carrier strip. Further descriptions can be found in Reference 22. Infilling the blocks with sand or gravel increases revetment stability.

| | | |
|---|---|---|
| Block data | | Individual Erco block 200mm x 200mm x 100mm thick<br><br>Weight - 6.3 kgs (straight sided)<br>- 5.4 kgs (level sided)<br><br>Individual Jumbo blocks<br>600mm x 400mm x 150mm thick<br><br>Weight - 52.2 kgs |
| Application | (a) | Erco blocks - Lake Pontchartrain, Fontainbleau State Park, Louisiana, USA |
| | (b) | Erco mat - Lake Pontchartrain, Fontainbleu State Park, Louisiana, USA |
| | (c) | Also being tested by Wessex Water Authority, Somerset. |
| | (d) | Gobi block - Holly Beach, Louisiana, USA |
| | (e) | Jumbo block - Lake Pontchartrain, Fontainbleau State Park, Louisiana, USA |

Summary sheets 3, 4 and 6.

Note: This type of block is now thought to have been discontinued.

**BASALTON BLOCKS**

Developed in the Netherlands, these concrete prisms are based on the shape of the natural basalt blocks. This impermeable type armouring is for use where settlement is not expected. Produced in various sizes and weights, they are tapered slightly to allow for grouting (see Fig 8). Normal Dutch practice is to underlay the blocks with 0-60mm dia graded stone about 300mm thick. Tested at the Delft Hydraulics Laboratory (Ref 24).

**ESSEX BLOCK**

A pre-cast concrete block designed originally for use in estuaries and for sites with low to moderate wave conditions. Normally asphalt jointed, these free-standing blocks, shown in Fig 9 and Plate 2, are in use at Pett Level on the East Sussex coast. At Pett, a two-stage revetment was in a relatively severe wave climate so the lower slope blocks are larger. In estuarial conditions the blocks are usually small and for moderate wave climates such as at Reculver in Kent, 380mm cubed blocks were employed. These were placed by hand and asphalt jointed after priming (see Ref 49).

Block data: (a) 305mm x 305mm x 115mm thick (standard)
(b) 610mm x 610mm x 200mm
(c) 305mm x 305mm x 305mm
(d) 380mm x 380mm x 150mm
(e) 380mm x 380mm x 380mm

Weights - not known

The blocks in use are as follows:

(a) Pett Level sea-wall - upper slope, see Plate 2
(b) Pett Level sea-wall - lower slope
(c) Tendring, Essex - seaward slope
(d) Tendering, Essex - back slope
(e) Reculver, Kent

**MONOSLAB (TURFBLOCK)**

A cellular pre-cast concrete block produced by Grass Pavers Limited of Royal Oak Michigan, USA. Designed primarily as paving for car parks, the blocks are constructed with slots to allow for filling with soil and seeding (Fig 7). In this instance, as the summary sheet in Appendix 2 shows, the blocks were used in an attempt to reduce cliff erosion on the shore of Lake Superior, Wisconsin, USA (Ref 22). The blocks are designed for hand placement on a filter with the long axis parallel to the shoreline.

Although probably useful in a very sheltered location they can not be recommended for coastal defence against storm waves and tidal fluctuations because their interlocking depends on friction alone.

Block data: 600mm x 400mm x 115mm thick

Weight: approx 45 kgs

Filter: non-woven geotextile

Application: Lake Superior, Wisconsin, USA, 1978

Summary sheet 11.

**SEABEE**

A patented hexagonal concrete block system introduced in Australia some years ago. These pre-cast blocks range in weight from 4kgs to 4 tonnes! Used with some success in Australia and described in detail by Brown in Refs 14 and 15. Really more of an armour block than revetment protection which the manufacturers hope to use in a wide range of wave conditions. It is not thought that there are any currently in use in the UK. They also manufacture smaller units for "1 or 2 metre waves". These thin-walled multi-cell units are extruded from clay as "ceramic Seabees" for use as shoreline protection.

**STANDARD CONSTRUCTION BLOCK**

A cellular concrete block used in the USA but not, as far as is known, in this country. They are placed by hand, butted together on a filter cloth with the hollow facing upward and with the long side perpendicular to the shoreline (see Fig 7). They have, as far as we know, only been used as lakeside protection. The summary sheet on model tests in Appendix 2 shows that block displacement can occur with wave heights of only 1.3m and with failure occurring at wave heights in excess of 1.65m. This type of protection would therefore stand little chance in UK coastal conditions.

| | |
|---|---|
| Block data: | 400mm x 200mm or 300mm x 200mm thick |
| | Weight: 15kg |
| Application: | Lake Pontchartrain, Louisiana, USA<br>Stuart & Jensen Causeway, Florida USA |

Summary sheet 1.

3.2 Fabric containers

These include the sand-bag and the Longard tube, see summary sheets 20 to 23. Formed of synthetic fabric and sewn into bag or tube shape they are filled on site with sand or a lean sand-cement mix. When used to form a revetment facing they are usually laid on a prepared slope, sometimes on a filter cloth and then connected back into the embankment.

A novel form of dune toe protection was tried in Auckland, New Zealand in 1979. Sand filled fabric tubes covered with an anchored filter were installed just beneath the sand at high water mark at the foot of the dunes. Although not wholly successful, it was deemed useful as a short term measure and withstood storm wave attack in February 1980. (Ref 78)

We know of only one site in this country where they have been tried (sand bags at Eccles in Norfolk, see Plate 17).

Common modes of failure include:

1. displacement of the smaller types by wave action,

2. damage to all types by floating debris or vandalism,

3. degradation of material due to exposure to ultra violet rays,

4. loss of inter-bonding between cement filled bags due to settlement.

Various methods have been tried to overcome these problems. Longard tubes for instance, have been coated with a sand-epoxy resin, (although this does not appear to deter vandals). On one site in the USA a Longard tube was encased within an aluminium sheath. This was badly damaged and had to be removed as it posed a danger to bathers.

For more information see Ref 47 in this series of reviews which covers sand or mortar filled fabric bags (Ref 47). There is also a wide range of text books and papers covering the use of geotextiles, including those by Pilarczyk (Ref 54), Hall (Ref 29), Rankilor (Ref 58) and Charlton (Ref 20).

Included also in this report but not in Ref 47, is a fabric type mattress, known as a Profix mat. This form of protection is in use in canals in the Netherlands. We know very little about this material but like the other fabric types, we doubt that it would stand up to coastal conditions.

**FABRIFORM**

Fabriform is manufactured by Dowsett Prepakt (UK) Ltd. These fabric mattresses consist of two interwoven layers of single and double layer filter cloth. The cloth is laid on a graded revetment slope and filled with concrete. The mattress, usually about 1.65m wide, is laid up and down the slope and interlocked to adjoining panels. When filled its nominal thickness is about 100mm, and it is used principally in sheltered waters. In more exposed areas, concrete revetments up to 500mm thick have been cast. A report on Fabriform protection (Ref 36) in November 1982 compares its performance against other types of revetment protection.

In exposed locations it is faced with rock or pre-cast concrete armouring. It is not, however, thought suitable in its present form, to withstand a coastal wave climate. One advantage with this type of construction is that it can be laid and filled under water.

**LONGARD TUBES**

These two ply fabric tubes are used as groynes and offshore sills as well as revetments. In Denmark, a structure consisting of three 1.0m dia tubes stacked in pyramid fashion and 100m long was laid parallel to the contours of a sand beach above the waterline. Placed about 15 years ago on the Thyboron Barrier Beach on the North Sea coast we have not as yet been able to find any information as to its subsequent performance.

Longard tubes are pumped full of beach sand which is injected as a slurry. They need some form of toe protection to prevent scour otherwise they will tend to roll. They are also vulnerable to damage by vandalism or floating debris.

Several installations have been tried in the USA mostly on the Great Lakes and the results are summarised in Appendix 2. More details are given in Vol 2 in this series. There are also tests being carried out in Italy on a number of Longard tube installations.

**PROFIX**

A sand filled, flexible, synthetic mattress developed in the Netherlands by Zinkcon International BV and used as protection in rivers and canals. The mattress is constructed by sewing together two layers of polypropylene filter cloth to form a series of porous longitudinal tubes which are then filled on site with sand in the form of slurry. The top of the mattress can then be covered with a felt layer to deter degradation by ultra violet light, and to encourage vegetation. Experiences with this type of embankment protection are given by Tutuarima and van Wijk in Ref 67. Clearly this mattress is not suitable for the marine environment in its present form.

**SAND BAGS**

As revetment protection they can be either stacked in pyramid form and backfilled, or laid blanket fashion on an embankment slope. Tested at several sites in the USA and one in the UK (at Eccles, Norfolk) where sand-cement bags were in use both as a sea-wall and as sand dune protection, see Plate 17. The sea-wall at

Eccles is currently being replaced by a conventional concrete one after at least four decades of use.

A sand-cement mortar in the ratio of about 10 to 1 is recommended as the fabric bags deteriorate fairly rapidly and if filled with sand the structure would of course quickly collapse.

Several examples of sea-walls bulkheads, or revetments are described in the summary sheets in Appendix 2 and reviewed in Volume 2 of this series (Ref 47). It is a highly labour intensive form of construction but can be useful as temporary protection.

**STABILENKA**

This is a polyester fabric that is strong enough to be used as an alternative to the traditionally used fascine mats. It has been used for silt screens, bitumen bags, filled foundation mats, grout cushions and gravel tubes on the just completed Eastern Scheldt Project in the Netherlands. It is manufactured by Enka Industrial Systems of Holland and supplied in the UK by MMG Erosion Control.

Applications: Blue Anchor Bay, Somerset
Milford on Sea, Hants.

### 3.3 Bitumen

Bituminous mixes are widely used in the Benelux countries and Holland in particular. Over the last thirty or forty years many techniques have been developed in the application of bituminous mixtures in a number of important coast protection schemes. As the Dutch have no stone quarries they have to augment imported armour stone and also to utilise dredged sand and gravel. This allows the use of smaller stones than would otherwise be possible.

Asphalt grouting reduces the maintenance cost of conventional stone pitching by improving the stability of free standing stones. Its effectiveness is enhanced because when cooled the grout has a high elasticity modulus when subjected to sharp loadings such as wave attack while retaining a high viscosity enabling it to accept moderate settlement. Full grouting does, however, make the revetment impermeable which will alter its properties possibly leading to excessive hydrostatic pressures if used on the wrong sub-base.

Another form is known as pattern grout where the interstices between the stones are filled to between 50 and 70% of their volume. This is said to be the optimal figure to establish permeability but maintain stability. The principles of pattern grouting are derived (see Ref 23) partly as the result of model tests. Prototype results confirming the tests are given by Wenstenenk in Ref 72.

A detailed report on a visit to Holland and Belgium to inspect some of these types of sea defence is given in Ref 48. A useful reference book on bitumen in hydraulic engineering was produced in 1959 by Baron W F von Asbeck (Ref 6). This has since been revised and updated (Ref 62). It would seem that the design of bituminous aprons is still based largely on experience so it is clear that specialist advice should be sought on all aspects of design.

An asphaltic revetment, built in 1958-1959 (see Ref 6) at Vlissingen, Holland and designed by the Delft Hydraulics Laboratory, is shown in Fig 13. Although it requires regular maintenance it has had a long design life.

In the USA there are very few cited examples. In the Shoreline Erosion Control Programme (Ref 22) there was only one field installation, on the shores of the Great Lakes, where asphalt mastic was used as shore protection and then only to seal the voids in a rubble mound groyne. This structure incidentally functioned very well although it was noted that the high cost of the asphalt mastic at current prices made it uneconomical as a 'void sealant'.

In the UK, bituminous compounds for coastal protection are not widely used, although of late they seem to be creating interest. Von Asbeck back in the late 1950's quotes several UK sites where bitumen in one form or another had been used. They include asphalt jointed ragstone pitching along the Thames Estuary and at Holland on the Essex coast. Sites where asphalt-jointed concrete blocks are used as revetment protection include Canvey Island (see Plate 4), Felixstowe (see Plate 5) and at Pett Level, Sussex. Asphalt grouted stone revetments were also constructed around that time on the Lincolnshire coast and in Wessex.

Since then, three major sea defence schemes have been built in this country at Caister on the Norfolk coast and more recently at Porthcawl, Glamorgan and Prestatyn, Clwydd. At Caister on Sea, just north of Great Yarmouth, a series of storms, combined with tidal surges in 1978, reduced a 350m section of very old concrete sea-wall to rubble. It was decided to replace the collapsed section with a sloping revetment of mastic grouted limestone rock and a flexible, horizontal sand mastic toe. The toe was linked to the revetment by a polypropylene mat, and designed to flex under the expected beach level variation. Unfortunately, during a period of beach lowering, remnants of old sea defences became exposed, damaging the flexible toe. The flexible mat was subsequently replaced by a trenched stone-grouted toe. The scheme has fared well since this modification was undertaken, see Plate 12.

At Porthcawl, on the south coast of Wales, an asphaltic concrete revetment has been constructed in front of the existing vertical sea-wall. The revetment profile was designed to allow incoming waves to break on its seaward face, the wave energy dissipating, to a large extent, on the 'hogs back' slope, see Plates 14 to 16. This particular area is exposed to Atlantic swell and damage to the original sea-wall was so severe that its steel reinforcing had become exposed. The new revetment, built on the lines of an existing scheme at Vlissingen in Holland (see Ref 48) is the first of its kind in the UK and its performance, which is being carefully monitored should give an indication of the viability of this type of structure in a UK environment.

The third revetment has just been completed at Prestatyn, in North Wales. Here a comprehensive scheme of sea wall renewal and foreshore management will extend over several years. The first stage was the demolition of 450m of a rapidly deteriorating 30 year old concrete sea wall and replacement with a much less steep revetment. The revetment is of open stone asphalt, 700mm thick laid at a gradient of 1 in 4. Above this is an apron of asphaltic concrete, 300mm thick with also a 1 in 4 slope. Topping this smooth upper revetment is a pre-cast concrete wave return wall. Offshore significant wave heights can reach 6m in this area with a predicted tidal range of 8.4m (springs) at Liverpool.

We see no reason why asphaltic revetments such as these should not be successful in the UK other than perhaps because of cost. Bitumen is expensive and specialised plant has to be sited fairly close to the intended structure. It has, however, distinct advantages over randomly placed stone in that it becomes much more stable but still retains a certain flexibility. It can also be repaired fairly quickly and in certain circumstances asphaltic compounds can be placed under water, thus avoiding the need for coffer dams.

As with most other structures, regular inspection and maintenance is most important. Methods of repair are given in Ref 62.

Design methods, based on model tests at the Delft Hydraulics Laboratory are given by T A W in Ref 62. This gives advice on how to determine the necessary thicknesses required for a particular revetment as well as other useful information.

## 3.4 Gabions

Now a widely used form of shore protection, gabions are fully reviewed in Volume 3 of this series (Ref 71) and examples given in summary sheets 15 to 19 inclusive.

Gabions fall basically into three categories:

**Maccaferri type** - can be in either box or mattress form and are constructed from galvanised steel wire, woven into a mesh and coated with PVC for added protection.

**Welded type** - again supplied in either box or mattress form, they are made up from high tensile steel wire electrically welded at each intersection, galvanised and/or PVC coated.

**Plastic type** - constructed from corrosion resistant heavy duty plastic mesh and supplied in either box or mattress form.

The mattress type, filled with small rocks or cobbles, are usually placed over a filter on a prepared and dressed slope. Box type gabions are normally stacked in staggered fashion against an embankment, usually with a gabion mattress as toe protection.

The advantages and disadvantages of gabion revetments are described in detail in Volume 3 mentioned above. One obvious advantage however is that a gabion structure can be built without the use of heavy machinery. Kamphuis (Ref 39) discusses the performance of various gabion structures constructed in the somewhat sheltered waters of the Great Lakes of North America.

**GABIONS - MATTRESS**

The Maccaferri type 'Reno' mattresses are possibly the most common type in use today. They are box gabions whose depth, compared to width and length, is small. Individual cages are wired together to form the mattress. Care needs to be taken when siting this form of revetment protection as wave action will tend to move the rock or cobble fill, causing internal abrasion and leading to the destruction of the wire cages in a short space of time. Also on steep slopes they are not particularly stable unless securely anchored as the rock fill tends to migrate downhill.

Bitumen grouting is sometimes used in an attempt to stabilise the fill although good penetration is difficult to achieve and the bituminous skin tends to spall off under hydrostatic pressure, sometimes tearing away the PVC coating in the process.

For effective protection the type of filter fabric used beneath this relatively thin armouring must be carefully considered and adequate toe protection must also be given so as to prevent uplift.

Gabion mats are generally too thin to withstand wave attack in all but a mild climate.

Application: Oak Harbour, Washington, USA
Chesil Beach, Portland, Dorset
Burry Port, Dyfed, Wales

(See also the summary sheets in Appendix 2).

**GABION - BOXES**

Normally square or rectangular in shape and usually stacked against an embankment in staggered fashion to form a revetment/retaining wall. The gabions most generally used in inter-tidal areas are the Maccaferri type.

Box gabions are available in a variety of sizes and are assembled on site where they can be filled with rock or stone, the lid wired on and the baskets wired together to form the desired structure shape. For sites which are out of reach of normal wave activity, the welded type of cage is often used. This type of revetment is not normally constructed in the inter-tidal zone due to the abrasive action of the beach material and the forces imposed on the baskets by wave action. Corrosion by salt water also affects both the Maccaferri and the welded type gabions.

Application: Overstrand, Norfolk (retaining wall using the welded type gabion) for example

(See summary sheets in Appendix 2.)

GABIONS - PLASTIC

(a) **Geocell** - a cellular type mattress made from high tensile plastic grids akin to a series of open top boxes or a gabion mattress without lids. Laid on a stone blanket, each box is partly filled with stones. Heavier armouring can then be used to complete the filling. This design is clearly not suitable in the intertidal zone where wave motion would soon empty the cages.

(b) **Netlon type** - high tensile plastic formed like a conventional gabion. They have been used above the high water line in several places around the coast. We could not recommend their use where they are subject to wave action.

Application: Brancaster, Norfolk (b) type
Anderby, Lincs. (See Plate 21.)

(See summary sheet 15 in Appendix 2).

3.5 Rock

The quality of the rock armouring is most important and is usually tested in accordance with British Standard BS 812, for apparent relative density, water absorption, aggregate impact value, percentage fines, soundness and its aggregate abrasion value. If several sources of suitable stone are available, then igneous rock should be chosen as it is generally more durable. For a more detailed description of the use of rock in revetment design, see HRL report SR 11 (Ref 5).

The advantages of a randomly placed stone structure include:

(a) a rough surface layer which reduces wave run-up by dissipation of wave energy;

(b) flexibility and the ability to conform to settlement;

(c) structural integrity maintained even if damaged when designed properly;

(d) minor damage easily repaired, provided the underlayers are not exposed;

(e) easy to construct and normally requiring a small labour force.

**ROCK LAYERS**

With this type of protection the armouring is graded, with the layers of stone becoming larger from the embankment core outwards. Armour stones forming the outer layers of the structure must be large enough to withstand the expected wave forces with little or no movement (see Refs 63 and 65). The core is sometimes protected by placing a geotextile filter fabric between it and the first rock layer. Procedures for selecting the required stone weights can be found in books such as the Shore Protection Manual (Ref 21) or the CIRIA report (Ref 63).

Rock revetments are used widely around the coasts of the world including the UK and often provide an economic solution where rock is available locally.

**RIPRAP**

One of the simplest forms of protection, and can be of almost any form of rock processed from a quarry and used as a protective layer or facing. It is usually randomly placed on an embankment to prevent erosion or scour. The thickness of the protective layer should be at least twice the thickness of the 50 percent rock size. A guide to design is given in a variety of books and papers, ie Thompson and Shuttler (Ref 63), Muir Wood and Fleming (Ref 49), Thorn and Roberts (Ref 65) and the Shore Protection Manual (Ref 21).

Quarrystone blocks can be individually placed and either keyed into place by smaller stone wedges or jointed by asphalt grout. At Minehead, large cobbles gleaned from the foreshore were placed on a prepared embankment to form a revetment on the backshore. Large quarried rock was placed in a trench at the toe and appears to be performing satisfactorily retaining the cobbles in place.

The cost of the types of armouring mentioned above will depend on the distance between the site and the nearest supply source.

Application: Minehead, Somerset (see plate 22)
Doniford, Somerset
West Bay, Dorest
Christchurch Bay, Hants

**RUBBLE**

At numerous sites around the country protection consists of rubble which can be of rock or stone fragments, broken concrete, brick, asphalt, etc. It is not aesthetically pleasing and would clearly be unsuitable on an amenity beach. It can, however, be a cheap form of emergency or temporary protection. It is sometimes just tipped as a waste material and grouted into place by ready mixed concrete.

Application: Shoreham, Sussex

**STONE PITCHING**

Usually used in sheltered or partially sheltered environments, stone pitching consists of regular shaped stones placed on the clay face of an embankment and keyed by wedge shaped rocks driven between the stones. It would be of little use in a coastal environment as one displaced block could lead to the collapse of the whole facing.

Stone pitching can have the gaps filled with asphalt or cement. This type of revetment is in use on the Isle of Sheppey (Ref 65). It has also been widely used in the Benelux countries where large stone is not readily available.

This form of protection is aesthetically pleasing and can have a long lifespan, especially when hard material is used. It does require more careful placement than many other forms of construction and is rather labour intensive for present day usage.

## 3.6 Timber

A material used extensively in coastal structures, the most popular type being the 'greenheart' variety. Various revetment/protective structures are in current use and they include:

**Timber revetments** - numerous examples of this type of structure can be seen on the coast of the UK as beach protection, see Plate 18. Such revetments have also been used to protect eroding cliffs (Plate 19) and the seaward face of sand dunes (Plate 20). Some designs differ from the normal revetment in that they are free-standing, and usually constructed at the toe of the cliff or dune. With a usual slope of about 40° they can be open slatted (either vertically or horizontally) to allow fine beach material to settle out behind them. The space between the cliff and the revetment can be backfilled. If the revetment slope is made steeper wave reflection can be a problem, scouring the beach in front of the structure.

**Timber cribwork** - this is a permeable, box section structure, normally placed parallel to and away from the toe of an eroding cliff, and sometimes filled with large stones or concrete blocks. An example of this type can be seen at Mundesley in Norfolk.

**Timber breastwork** - this looks somewhat like a shore-parallel groyne with vertical king posts and horizontal slats. Generally designed to protect the toe of eroding cliffs. Relatively impermeable although water can get through the wooden planking sometimes causing damage. Not suitable for sand beaches and not ideal for shingle.

**Timber posting** - these are a series of posts set in lines parallel to the shore and acting as low permeable screens. Often used on shingle beaches; not particularly effective on sand beaches except as sand fencing.

For more details of the general use of timber in a coastal situation, the reader is referred to Hester (Ref 34), Oliver and Brown (Ref 51) or TRADA (Ref 66).

## 3.7 Other types

A wide range of other low cost methods of shore protection have been tried in recent years in North America, where large areas of the coastline is in private ownership. A manual giving details of many of these structures was prepared by the US Corps of Engineers and published in 1981 by Moffatt and Nichol (Ref 22). Constructed principally, but not always, in sheltered waters, these structures include many designs built on the shores of the Great Lakes where their main problem is cliff or bluff erosion caused by wave action.

A wide variety of materials have been tried and the more 'out of the ordinary' include:

Soil cement
Concrete pipe 'nami rings'
Building blocks
Scrap tyres
Steel fuel barrels
Corrugated metal pipes, and
various forms of matting (nylon, fibre-glass, steel, aluminium, wood, etc).

A selective number of these novel, if not effective, methods of protection are given in the summary sheets in Appendix 2. Those using scrap tyres and fabric containers are described in our previous reviews (Refs 46 and 47 respectively).

**FUEL BARRELS**

Installed as both groynes and revetments on the western coast of Alaska in the Chukchi Sea. Used chiefly because of their availability, cheaply, in very large quantities, they were set in double rows on the beach and filled with beach shingle. They proved to be quite effective although further monitoring is needed to determine the effect of rusting on their lifespan.

They are not aesthetically pleasing however and their use is limited to Arctic regions because of their proneness to rust in more temperate zones as the summary sheets indicate (see also Ref 22).

| | |
|---|---|
| Data: | 55 gallon steel fuel drums (discarded by the oil industry) bolted together to form diaphragms in which to encourage accretion. |
| Application: | Kotzebue, Alaska, USA |

**NAMI RINGS**

Used only, as far as we know, on the shores of Lake Superior, Michigan, USA, these patented short sections of concrete pipe, were placed vertically, directly on to a filter cloth, overlying an 0.1m thick sand bedding layer. The revetment slope was 1 in 10 and the rings, placed side by side were designed to accrete sand and prevent wave uprush from eroding the cliff face. The revetment was not, as the summary sheets indicate, entirely successful. Model tests were carried out in 1973 prior to the prototype installation. The results of these tests are summarised by McCartney in Ref 42. Because of their shape they can be susceptible to abrasion and damage in anything but a sandy environment.

Earth filled concrete pipes similar to Nami Rings (old culvert pipes) have also been tried at Beach City, Texas on the Gulf of Mexico. The performance of this type of protection was not good, see Ref 22.

| | |
|---|---|
| Data: | Nami Rings - 760mm dia, 300mm high and 80mm thick. (See Fig 12). |
| | Weight: 120kgs |
| Application: | Little Girl's Point, Lake Superior, USA |

| | |
|---|---|
| Construction: | 1974, each ring costing $8, overall revetment cost $16 per square metre |
| Culvert pipe: | 910 to 2290mm dia, 1200mm or so long. |
| | Weights: various. |

**SCRAP TYRES**

This type of coastal protection is reviewed in Volume 1 of this series. Since that study a new design has been installed as a revetment at Inverness. Constructed as a bund containing over 20,000 old tyres, it is being utilised to reclaim a section of land inside Inverness Firth where there are maximum estimated wave heights of about 2m. The revetment, placed at right angles to the shoreline, consists of a fairly steep embankment with large anchor tyres built into the core and linked to smaller horizontally placed tyres at the revetment face by polypropylene rope. One side wall was cut out of each tyre to allow for filling with compacted gravel. The rest of the bund is made up with around 10,000$m^3$ of sandy gravel. The revetment is 2.85m high and 340m long.

A somewhat similar form of protection was tested at Oak Harbour, Washington, USA, where gravel filled rubber tyres were stacked on posts. In this case the gravel fill washed out of the tyres, the tyres collapsed and the backfill was washed out.

Other types of scrap tyre protection involve bolting the tyres together and/or injecting sand-cement mortar. These experiments were not entirely successful, see Volume 1 (Ref 46) of this series and Ref 22.

| | |
|---|---|
| Data: | Inverness site |
| Cost: | £68,000 - 1984. |

**SOIL CEMENT**

Used in the USA as slope protection on dams, soil cement strips are made up of between 7 and 15 per cent cement with soil or beach sand as aggregate. Usually compacted in layers and formed in stepped fashion.

The cement and soil can be mixed on site or at a central plant and require more cement when used with beach sand lacking fines. Toe protection would be needed to avoid settlement, cracking, loss of bond, etc. We know of no coastal site in the UK where this type of protection is currently in use.

McCartney (Ref 42) gives an estimated design wave height for zero damage as around 1.5 to 2m.

Details of this type of protection is also given in Wilder and Dinchak (Ref 75).

# 4 REVETMENT DESIGN

## 4.1 General criteria

The elements common to most revetment types include:

(a) A suitable foundation or core.

(b) Surface layer of armouring.

(c) Filter of rock or fabric. This being needed not only as bedding for the surface armouring but also as a means of preventing leaching of the core material through the armouring. The hydraulic design of the filter layer is therefore just as important (and probably more difficult to assess) as the design of the surface layer.

(d) Toe protection and anchorage is necessary to give stability to the lower part of the revetment, which is usually the area subject to the greatest hydrodynamic forces. Also, it helps to prevent uplift and washout of the lower bedding layer.

(e) Protection of the flanks to prevent possible isolation on an eroding coastline.

(f) Protection of the rear face of the revetment against overtopping, etc.

There are, however, many instances where revetments in rural areas, consist of little more than an armour layer laid directly on the embankment core.

There are many books which provide guidelines on hydraulic and structural aspects of design. These include the American 'Shore Protection Manual' (Ref 21). A current HRL literature review of concrete blocks also provides guidelines into the design of free standing armour units (see Ref 57). Unfortunately, reports generally are unable to give guidance on the cost/benefit aspects of design and on the environmental/amenity issues. However, this is not surprising since such factors are site specific and time dependent (i.e. the cost depending on the market value of materials at the time of construction).

## 4.2 Design aspects

The parameters which need to be established are:

(a) Wave exposure. The design wave height and period, the type of wave energy spectrum, the directionality of wave attack etc.

(b) Tidal conditions. Tidal conditions including the statistical occurrence of extreme tidal levels, surges, etc.

(c) Beach characteristics and the characteristics of the embankment on which the revetment is to be laid.

The design wave conditions can be analysed using prototype wave data or, alternatively, prediction can be made from climatic recordings. A decision needs to be made as to whether some degree of overtopping can be tolerated. Wave and tidal analyses as well as structural considerations will determine what the lifespan of the revetment is likely to be. A very useful aid in the design process is the examination of alternative designs using hydraulic or numerical models. Hydraulic models have traditionally been used to assess the stability of revetment armour units, the volume of wave overtopping under given hydrodynamic conditions and also the effect of the structure on the adjacent coastline, on beach levels in front of the revetment, etc. Recent advances in numerical modelling allow one to assess the effect of structures on adjacent beaches.

Experiments on the articulated units have not been carried out to such a degree that one could compare the hydraulic performance of differing types of revetment. Model tests have been carried out on Armorflex matting (Ref 70) which show, not surprisingly, that wave type is an important factor. It was found that plunging waves have a significant effect on the degree of erosion and that the design conditions should take into account the maximum wave steepness likely to occur at the site. Other model tests are given below, together with references:

| | | |
|---|---|---|
| 1. | Armorflex mattress | - Refs 7 and 70 |
| 2. | ACZ - Delta mattress | - Ref 25 |
| 3. | Profix mattress | - Ref 67 |
| 4. | Riprap | - Refs 1, 2, 13 21, 22, 35, 42, 52 and 63 |
| 5. | Wallingford block | - Refs 73 and 74 |
| 6. | Shiplap type block | - Ref 30 |
| 7. | Seabee block | - Refs 14 and 15 |

Predicted tidal ranges can be found in the Admiralty Tide Tables while observed tidal conditions can be obtained, for certain areas, from the local council or regional water authority. The Institute of Oceanographical Sciences can also analyse surge conditions etc.

Computers are increasingly being used to store beach information. This can be analysed statistically to determine the likelihood of underscour, the magnitude of beach level variation that one is likely to encounter in a given timespan etc. Numerical models of beach plan shape evolution are now widely used to assess the changes that are likely to take place, for example, at the junction between a "solid" revetment and a soft coastline adjacently. It may also be necessary to consider water velocity on the front slope, in terms of beach scour potential, wave reflection and impact pressures; these being commonly tested using hydraulic models.

To perform well, from a hydraulic viewpoint, the revetment should be:

(a) stable under the action of waves/tidal currents,
(b) rough and permeable to reduce wave run-up and reflection,
(c) flexible enough to adjust to minor settlement and scour.

Model tests should give the answers to some of these questions but there are other factors which can only be resolved by field monitoring of existing structures eg soil stability, apron deformation and structural wear and tear.

## 4.3 Modelling

Physical modelling is a useful aid for assessing the complex interaction between structure and adjacent sediment movement. Models can be very useful in assessing the differences of an armour layer's performance for different permeable layers. Problems can arise, however, when small scale models are used. Owen and Summers (Ref 53) separate those aspects of hydraulic performance and block stability that may be adequately modelled in scale tests and those for which prototype scale testing is more appropriate. Owen and Summers also consider the feasibility of prototype testing and make proposals combining testing in both laboratory and in the field to enable production of design guidelines for interlocking or integrated concrete block flexible armoured revetments.

Laboratory tests of some types of placed block revetments are covered by Lindenberg (Ref 41), and den Boer, Kenter and Pilarczyk (Ref 9), while Kostense and den Boer (Ref 40) discuss scale effects of modelling block systems. They conclude that tests with undistorted scales of up to 1 to 10 probably give acceptable results. They also analyse results of 1 to 25 tests and consider that the scale in these models is too small, especially for porous block systems where surface tension needs to be taken into account. The scaling limits are not defined between these two categories.

Although many of the more recent block designs have been tested in the laboratory, very few have been monitored in the field. The only prototype data found in this review (which are in the low cost category) was in a paper by Pilarczyk (Ref 54) but this was for revetments in a shipping canal.

Materials including gravel, riprap, placed blocks and various mattress types of protection have been tested in the large flume in Holland and the results published by the Delft Hydraulics Laboratory (Refs 9, 40, 56 and 60).

Many studies such as this have also been carried out at HRL and publication lists are available from our marketing department.

## 4.4 Toe protection

Special consideration must be given to the protection of the revetment toe since this zone has different design requirements than the upper slope. This part of the revetment is subject not only to hydraulic forces but also the changing beach levels and abrasion and scour.

Toe scour, the most common problem, is caused principally by wave breaking and the consequent wave run-up and run-down on the embankment leads to erosion at the beach interface. This is aggravated by wave reflection from steeply sloping embankment faces. In general the flatter, rougher and more permeable the revetments surface, the lesser is the foreshore erosion.

There are several ways in which one can protect the toe of a revetment. Probably the most commonly used form of protection is the cut-off wall. It can be used not only to protect the revetment when storm and wave action have lowered the foreshore but also to act as the bottom panel in which the blocks are contained and to ensure that the armouring does not shift seaward under wave action. Piles can be of timber, steel or concrete and their working like will depend ultimately on the abrasive quality of the beach material and the degree of salt water corrosion. Steel and timber can be coated to provide protection. This type of structure can be difficult to repair and is usually allowed to deteriorate until replaced.

Details about various forms of piling can be found in the following references and include:

Steel - Ref 45
Timber - Refs 34, 51 and 66
Concrete - Refs 3, 4, 43 and 76.

Other forms of toe protection are described by Thorn and Roberts (Ref 65) and in the Shore Protection Manual, Volume II (Ref 21). McCartney (Ref 42) also gives details and recommendations which include:

(a) using flexible aprons which will adjust to the beach profile

(b) burying the toe to a depth greater than the maximum likely beach lowering

(c) weighting the revetment toe with rubble, rocks, etc. This not only reduces beach erosion but enhances the stability of the embankment core against sliding etc.

(d) cut-off walls as described above, including reinforced concrete piles or retaining walls to prevent toe scour.

(e) an offshore sill designed to trap sand between it and the revetment toe.

Finally, a general rule-of-thumb maxim to determine the amount of toe scour below the natural bed can be found in the Shore Protection Manual (Ref 21). It can be taken as about equal to the height of the maximum unbroken wave that can be supported by the original depth of water at the toe of the structure.

## 4.5 Anchorage

Toe design should provide good stability and prevent collapse by undermining and scour. Many manufacturers will provide recommendations on anchorage requirements which may also include suitable wood or metal stakes or driven ground anchors. Ardon International who manufacture the integrated flexible block system "Petraflex", generally suggest a design which incorporates a steel tube or bar pre-cast into a header beam or located in-situ. In addition, they have developed a pre-cast anchoring and panel connecting block which can be located at the toe end of a panel system or within the panel itself allowing additional anchors to be placed as necessary. This is explained more fully by Tuxford in Ref 68. Integrated systems are usually anchored by burying their upper and lower ends in trenches or held in place by screw anchors.

If a substantial cut-off toe is provided, then hooks or bars attached to the revetment block panels can be bolted or welded to it. Similarly, at the top of the embankment, if a wave return wall or a concrete apron is incorporated, then the system can be attached or embedded into this.

Other block systems are stabilised, either by their own weight, by interlock with each other and/or by driving stakes through the armour and into the embankment beneath.

## 5 SUMMARY OF FINDINGS AND RECOMMENDATIONS

1. The high cost of traditional forms of coast protection has led to the development of many new revetment designs in recent years, especially those using pre-cast concrete units. These may rely on friction, interlocking, and/or inter-connection between adjacent modules for stability. Some new revetment types have not been tested either in the laboratory or in the field. Design is often based on experience with other similar blocks or on extrapolation of formulae such as the Hudson equation. The same can be said for other forms of revetment protection such as asphaltic mixes, where again design criteria are few.

2. Of the many designs that we have examined, we consider that there is potential in those revetment systems which are flexible, move en masse under wave impact and are designed so that loading is spread over a wide area. Interlocking units such as the Wallingford block, for example, are so shaped that displacement of an individual block is counter-acted by the restraining weight of the surrounding ones. The degree of interlocking should be such that even if one unit is broken and displaced the revetment remains 'knitted' together.

3. Shiplap blocks are widely used in estuaries where they can be particularly effective. However, most only have overlaps on two adjoining edges, hence there is a tendency for them to rotate diagonally. Once a small degree of displacement has taken place, fine material will tend to infill the gaps and make the blocks less stable. This type of revetment will not always follow changes in the level of the sublayer and spanning of cavities can occur.

4. Tongue and groove blocks usually have connections on opposite sides. With some designs the short sides interlock while the long sides just butt against each other. This gives strength in the plane of the slope but none parallel to it. Because the blocks are normally laid in strips from the toe upwards, differential movement between adjoining strips can cause stresses on the underlying filter which may result in loss of fill. The tongue is also a point of weakness since it is not normally reinforced. Movement of the panels can allow pebbles to be trapped in the

interlocks and this can lead to chipping of the concrete so that in time the degree of interlock is reduced. This type of blockwork tends to bridge cavities or holes and makes the armour surface appear more rigid than it is. Thus damage to the sublayer is not always evident by inspection of the revetment face.

5. Many of the non-interlocking blocks now on the market are designed primarily for sheltered areas such as canals and river banks. In order to achieve good block to block friction, the plan area to depth ratio needs to be small. Thus upgrading these designs for increased wave exposure is likely to lead to large block dimensions, which will take many designs out of the 'low cost' category.

6. One method now being used to improve the stability of small blocks is the addition of cables threaded through the blocks. Such mattresses can be relatively simple to install. Cabling allows light blocks to be used to withstand wave forces, since uplift pressures etc, are distributed over a wide area of mat. One disadvantage of these systems is that the cables need to have a high tensile strength and also have to withstand wear and tear caused by block movements or indeed vandalism. Some nylon ropes are also prone to degradation by UV light. One serious maintenance problem is that of repair to the sublayer if settlement or leaching takes place.

   The quality of the concrete in mattress blocks can be poor. This can be detrimental in two ways; firstly beach material can quickly scour the block face and secondly when the sub base settles and allows the blocks to jam against each other they can easily become chipped or crack.

   Despite these drawbacks this type of revetment is relatively cheap and can be installed rapidly. We would recommend that detailed monitoring of such revetments be carried out to determine the design life of such structures under varying wave exposures.

7. Stability of individual blocks can also be improved by asphalt grouting of the interblock spaces. When cooled, an asphaltic grout has a high elastic modulus, hence, under short period loading it is able to withstand wave impact forces. It also acts as a plastic material with

a very high viscosity under prolonged loading, hence it allows the revetment to adjust to sublayer settlement. In the Netherlands, asphalt grouting has proved to be a suitable technique for reducing the maintenance of stone pitched revetments. However, most of the revetments using grouted blockwork have been constructed in estuaries and areas of low to moderate wave activity. Until such revetments are monitored in more harsh conditions it is difficult to extrapolate their usefulness for areas of moderate or high wave activity.

8. Asphaltic mixtures have been used much more widely in the Netherlands than in the United Kingdom. For example, Fixtone, a patented name for a gap graded stone asphaltic mix has been found to form a good revetment material in inland waterways and canals abroad. Its use is presently being extended for inner harbour protection, see Plate 13 and might also be suitable for upper embankment protection on open coasts. It is said to be able to resist currents up to 6m/s and wave heights of at least two metres. Because of its permeability it requires a filter to prevent leaching of the sublayer. Fixtone can also be prefabricated on a suitable filter cloth and the mattress which is formed can be laid under water. It has been used in this form as toe protection against tidal scour. A thick mattress layer would be needed to give toe protection against wave attack, and clearly there is a possibility of rupture of the fabric under these conditions. Although tests have been carried out at full scale in the Delft Hydraulic Laboratory large wave flume, the upper design limits for this type of material are as yet undefined.

9. Asphaltic concrete revetments have been widely used in the Netherlands, but in conditions somewhat less severe than those on the UK coastline. Recently, a revetment was constructed at Porthcawl in an area subject to Atlantic waves. It protects a near vertical concrete sea wall which was formerly being abraded very rapidly by beach pebbles. The asphaltic concrete surface is resilient to some degree. It has been designed with a relatively flat slope so as to minimise wave impact forces. We consider that this revetment should be carefully monitored to ascertain its design life under what are very harsh environmental conditions.

10. A field programme has been conducted by the US Army Corps of Engineers (with the private land owner in mind) into various methods of low cost shore protection for areas of low to moderate wave activity and generally a small tidal range. Rubble revetments were effective and were a good method of disposing large quantities of building material, but on an open coast the tipping of rubble is unacceptable from an amenity viewpoint. The grinding down of builders rubble by regular wave action is also likely to pollute the beach. We would not recommend this form of protection except as an emergency measure, for example, where breaching of a revetment or beach ridge is imminent. Under such conditions the rubble should be grouted to keep it in place.

11. Gabions can be used successfully under relatively low wave energy conditions, and in the UK they can be used as a temporary protection or as permanent works on the upper part of sand beaches where the baskets can become covered and protected with wind blown sand.

12. The use of synthetic fabric containers filled with sand is described in an earlier report. Presently all types of fabric containers are susceptible to damage by wave borne debris, by vandalism, or by rupture due to differential settlement, earth pressures etc. We would not recommend their use except as emergency works. Fabric containers can be filled with a mortar mix to make fairly robust structures, but interblock bonding is usually less than perfect. The cost of filling such containers with weak cement may well take such structures out of the low cost category.

13. The usefulness of scrap tyres in coastal revetments is by no means proven and we have reservations about their effectiveness in the intertidal zone. Extensive laboratory and field studies will be needed before this very readily available material can be used for combatting shoreline erosion.

14. Our review shows that many new revetment designs are being brought onto the market, many of which are untested prior to manufacture. We would recommend that existing field installations should be monitored before large scale projects of this type are undertaken. Many traditional designs are based largely on experience at a particular location. In several instances it has

been found that revetments which appeared to work well at one site proved to be unsuccessful at others. There is much scope, therefore, for refining existing designs and making them more cost effective. There is scope for both field monitoring and testing in the laboratory to improve existing designs.

# 6 CONCLUSIONS

This review has highlighted a number of revetment designs which show promise as a form of coastal defence. We do not intend to give an exhaustive list of all such structures here. However, the following types particularly appear to have potential as open coast defence:

1. Asphaltic revetments - This form of protection has already proved a versatile defence. There are many designs including:

   (a) a patented mix of gap graded stone keyed together with asphalt called 'Fixtone'. This form of protection has however yet to be fully proven on the open coast;
   (b) stone asphalt, a dense gap graded mix containing stone, sand, fines and bitumen; and
   (c) asphaltic concrete using a mixture of stone, sand fines and bitumen with a voids ratio of 3 to 6% after compaction.

   Sand asphalt while not of the same durability, is useful as a filter or embankment core protection.

2. Cable linked concrete blocks are useful in areas of moderate wave activity. They are relatively cheap to install and cope with minor changes in revetment profile. However, it is thought that existing designs could be improved by increasing block size and improving the quality control of the concrete.

3. Timber revetments are built largely on experience. Increased efficiency could undoubtedly be obtained by a more careful design. This is an area which requires further research since there are large stretches of coastline protected by timber revetments which in many cases are not performing to their full potential.

4. Rock revetments are widely used in areas where this material is easily available. Many structures are based purely on past experience and a "low-tech" design approach. Providing such structures are maintained and repaired after storm damage, there seems little need for expensive and complicated design methods, for example, in rural areas or areas of low risk.

5. Gabions and gabion mattresses have been used successfully on the upper parts of sandy beaches. Regular maintenance of such structures is essential as failure can be rapid.

6. Many of the flexible block designs which rely on interblock connections have been used successfully in estuaries. Such designs might be applicable to coastal situations by increasing the block dimensions. Upper design limits in terms of wave heights for many of these blocks are not known. These designs would require model or field testing to determine their performance.

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## 9 GLOSSARY OF TERMS

| | |
|---|---|
| Articulated | Having joints. |
| Breastwork | a palisade-type structure usually made up of wooden stakes |
| Bulkhead | A structure of wood, stone or concrete erected along a shoreline primparily as a retaining wall with its secondary purpose to arrest wave action and erosion of the land. |
| Cribwork | A structure composed of frames of timber laid horizontally into which is placed rock, stone, broken concrete, etc., to act as protection to a cliff toe. |
| Fascine mattress | Bundles of brushwood bound together to make a foundation mat to protect the bed of a channel against erosion. [or side slopes] |
| Integrated | Joined together by cable, rope or wire. |
| Interlocked | Inter-meshing or keying in of adjacent blocks. |
| Overfilled | In this context, a mastic asphalt poured hot onto rocks, etc. to penetrate fully and act as an impermeable matrix. |
| Reticulated | Divided into mesh like compartments |
| Revetment | A facing of stone, concrete, etc., to protect an embankment or shore structure against erosion by wave action or currents. |
| Riprap | Broken stone or boulders placed compactly or irregularly on an embankment for protection against wave action or currents. |
| Rubble | An accumulation of rough rock or stone fragments can also be of broken concrete, brick, asphalt etc. |
| Sea-wall | A coastal wall built to provide protection against erosion or flooding. |

| | |
|---|---|
| Shiplap | An interlocking type block (see Fig 1). |
| Slatted revetment | A free standing structure placed in front, but seaward of a cliff face to break the brunt of wave action and to allow beach material to accrete behind it. |
| Under filled mix | In this context it is usually a lean permeable sand-asphalt mix. The sand grains are covered with a thin film of bitumen giving it a void percentage of around 40%. |

## 10 ADDRESSES

**ACZ Delta Mats** - (concrete filled fabric mattresses)

ACZ Marine Contractors BV
Gorinchem
The Netherlands

**Armorflex & Armorloc** - (integrated and interlocking concrete block systems)

M M G Erosion Control Systems
Waterloo House
Kings Lynn
Norfolk PE30 1PA

Tel: 0553-774423

**Petraflex** - (integrated concrete block systems)

Ardon International Limited
14 St Johns Road
Tunbridge Wells
Kent
TN4 9NP

Tel: 0892-36133

**Scan-Gabions** - (interlocking concrete slabs)

Scan-Gabions A/S
Tagensvej 83D
2200 Kobenhavn N
Denmark

Tel: Denmark 01-834219

**Seabees** - (hexagonal free standing concrete and ceramic armour units)

Seabee Developments
179a Kimbolton Road
Bedford
MK41 8DR

Tel: 0234 47840

**Sebloc, Dytap, Dymex and Dycel** - (integrating and interlocking block systems)

RBS Brooklyns Limited
Revetment Division
5 North Street
Taunton

Somerset TA1 1LH

Tel: 0823-51451

**Landscape Grass** - (free standing and interlocking concrete blocks)

Landscape Grass (Concrete) Ltd
Walker House
22 Bond Street
Wakefield WF1 2QP

Tel: 0924-374818

**Longard Tubes** - (fabric sand or mortar filled tubes)

Aldek A/S
Thorslundsvej 7
P O Box 190
DK 5100 Odense C
Denmark

**Macaferri Gabions** - (flexible wire mesh type)

River and Sea Gabions (London) Ltd
2 Swallow Place
London
W1R 8SQ

Tel: 01-629-8528

**Gridweld Gabions** - (semi rigid welded type)

G K N Gridweld Engineering
Woodhouse Lane
Wigan
WN6 7NS

Tel: 0942-44071

**Netlon Gabions and Linmat** - (plastic mesh and tubing)

Netlon Limited
Civil Engineering Dept
Mill Hill
Blackburn
BB2 4PJ

Tel: 0254-62431

**Tensar** - (geocell mats and mattresses)

Netlon Limited
Kelly Street
Blackburn
Lancs  BB2 4PJ

Tel:  0254-62431

**<u>Fabripakt Fabriform</u>** - (fabric mattresses filled with mortar)

Dowsett Prepakt Limited
Market Flat Lane
Scotton
Knaresborough
North Yorkshire  NG5 9JA

Tel:  0423-864061

**<u>Colcrete Grouting</u>** - (insitu concrete) and
<u>Colcrete mats</u> - (concrete within fabric mats)

Colcrete Limited
Bryant House
Strood
Rochester
Kent
ME2 3EN

**<u>Mono Blocks</u>** - (interlocking concrete blocks)

Mono Concrete Limited
Epic House
Lower Hill Street
Leicester
LE1 3SH

**<u>Gobimat</u>** - (concrete blocks bonded to filter fabric)

These are no longer manufactured here

**<u>Paraweb</u>** - (synthetic geotextiles)

ICI Fibres
Geotextile Group
Pontypool
Gwent  NP4 OYD

Tel:  04955-57722

**<u>Lotrak</u>** - (geotextile products)

Don & Low plc
P O Box 54
South Ward Road

Dundee
DD1 9JQ

Tel: 0382-27311

**Enkamat** - (geotextile matting)

M M G Erosion Control Systems
Waterloo House
Kings Lynn
Norfolk PE30 1PA

Tel: 0553-774423

**Stabilenka** - (fabric mats)

M M G Erosion Control Systems
Waterloo House
Kings Lynn
Norfolk PE30 1PA

Tel: 0553-774423

**Propex** - (geotextile fabric) &
**Geoweb** - (plastic grid confinement system)

Ardon International Limited
P O Box 111
Tunbridge Wells
Kent TN4 9NW

Tel: 0892-36133

**Terram & Filtram** - (geotextile fabrics)

I C I Fibres (Geotextile Group)
Pontypool
Gwent
NP4 0YD

Tel: 04955-57722

# Figures

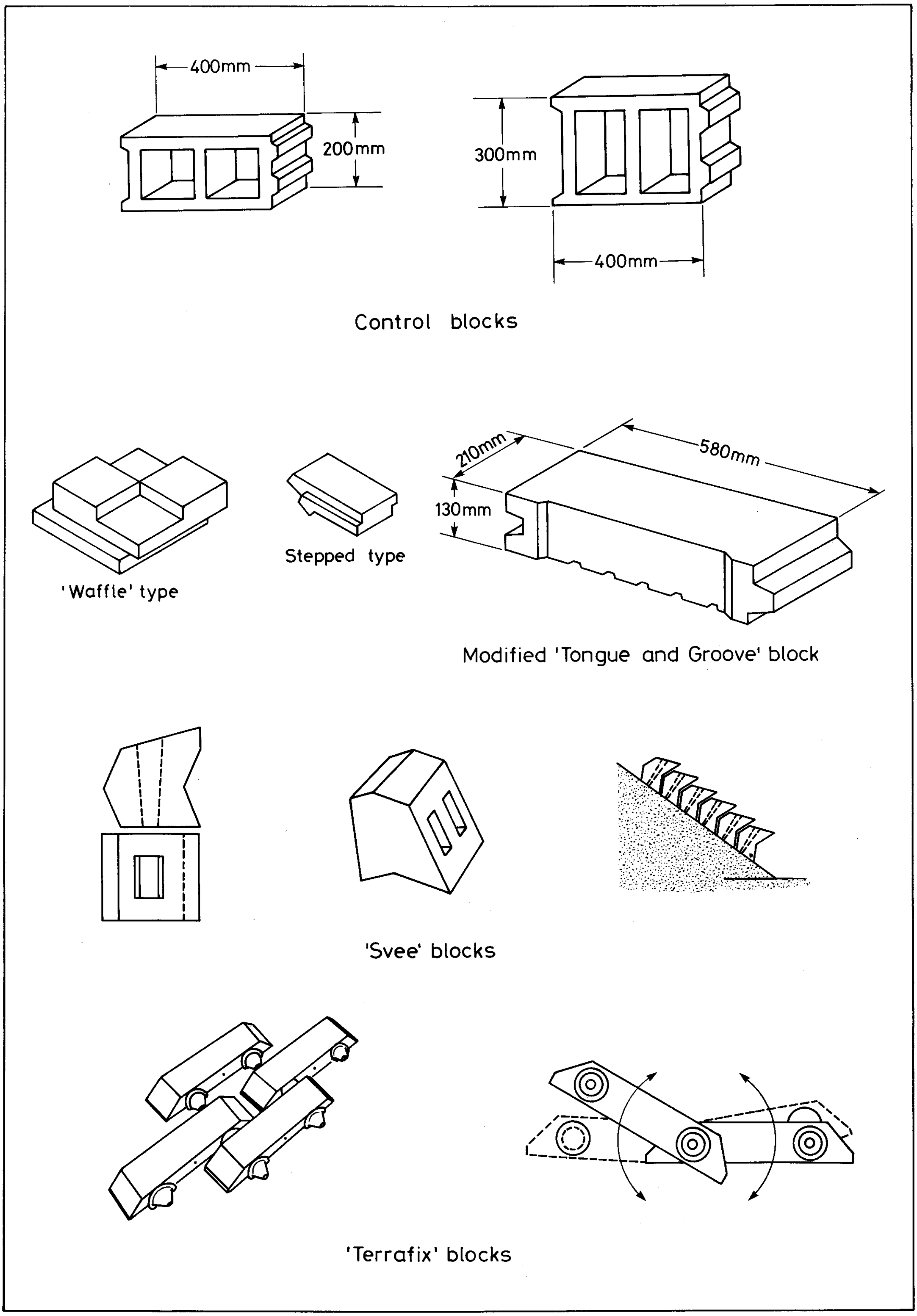



Fig 1 Concrete revetment blocks (interlocking)

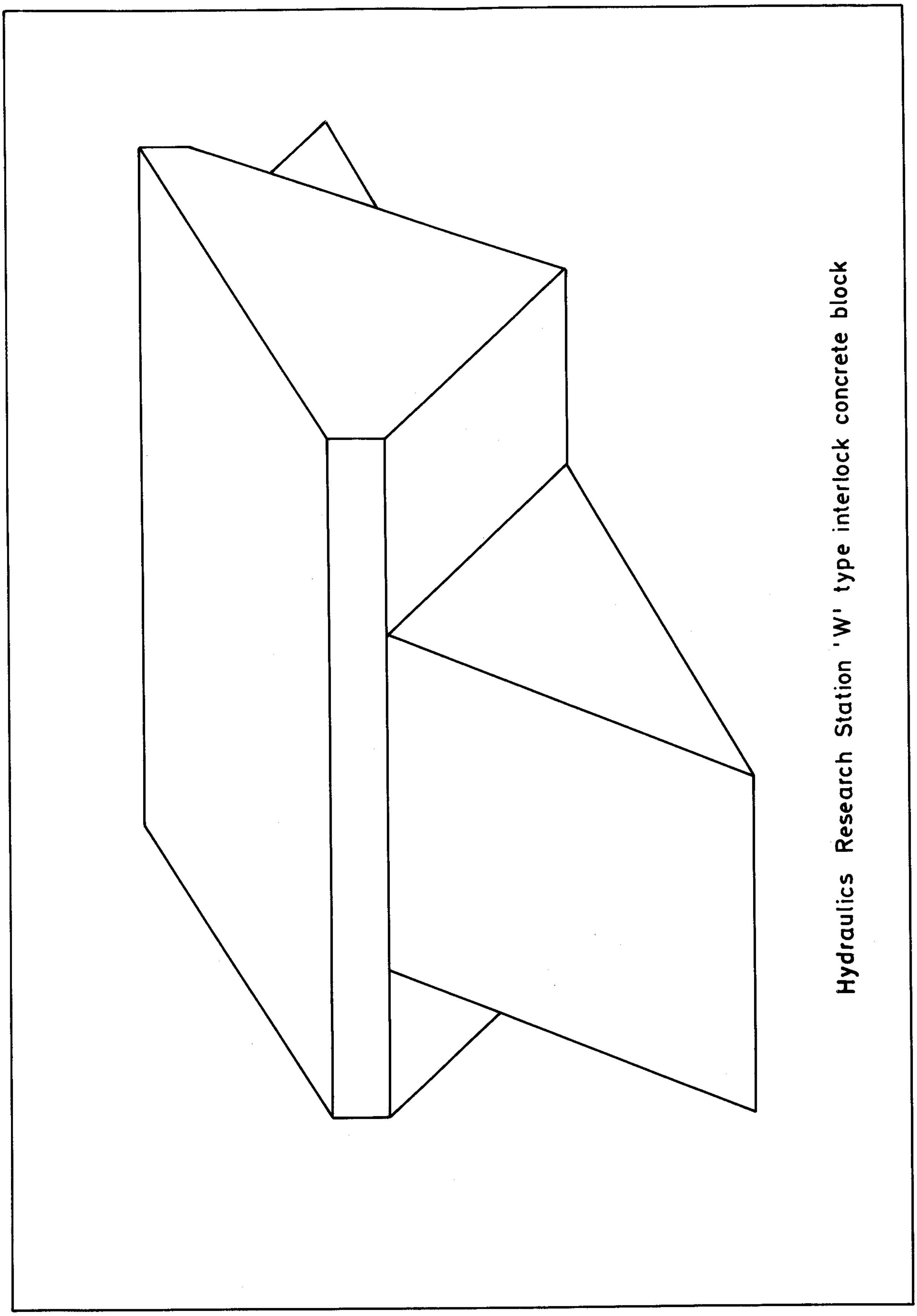



Fig 2 The 'Wallingford' block (interlocking system)

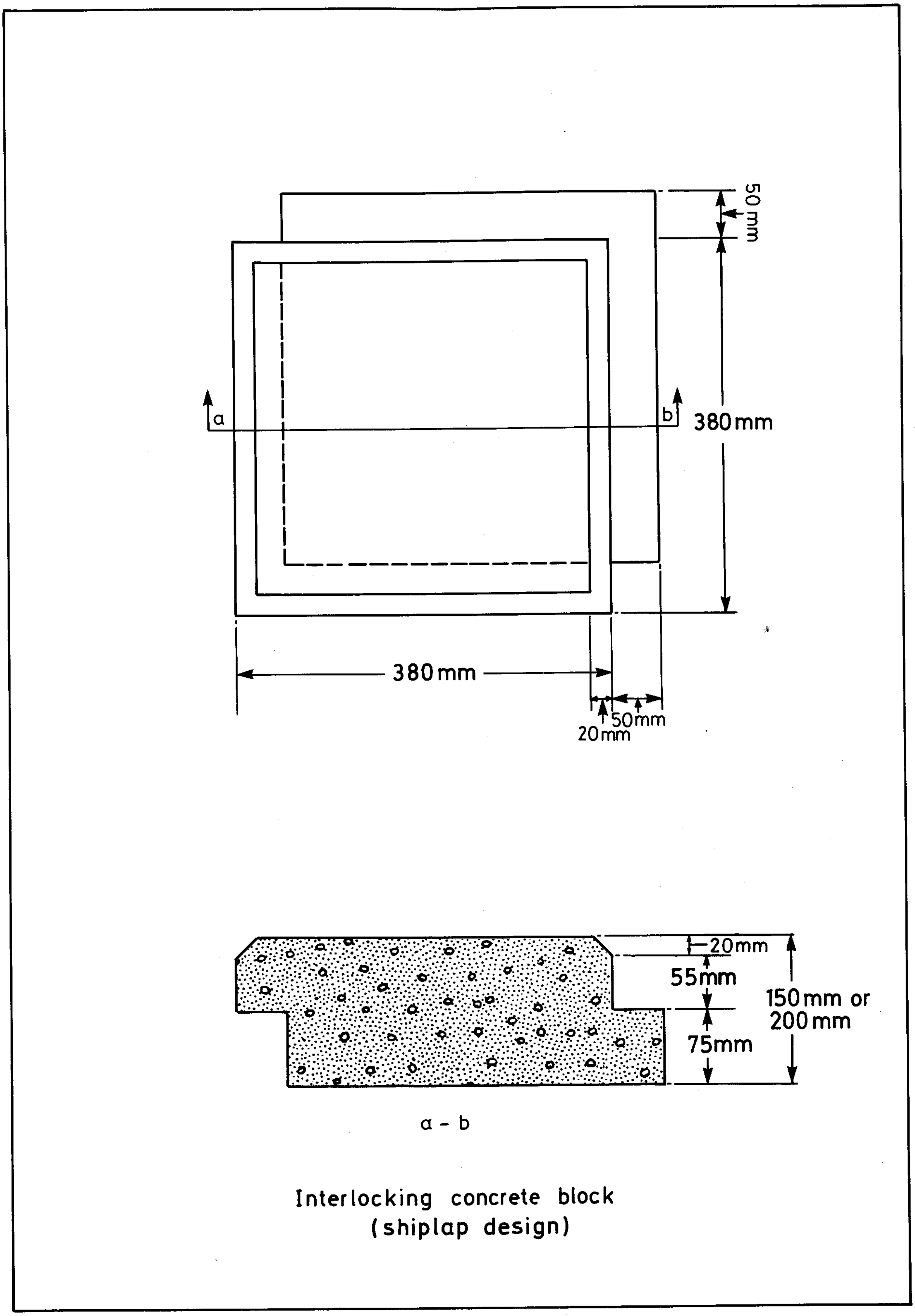



Fig 3 The 'Wessex' block ( interlocking system)

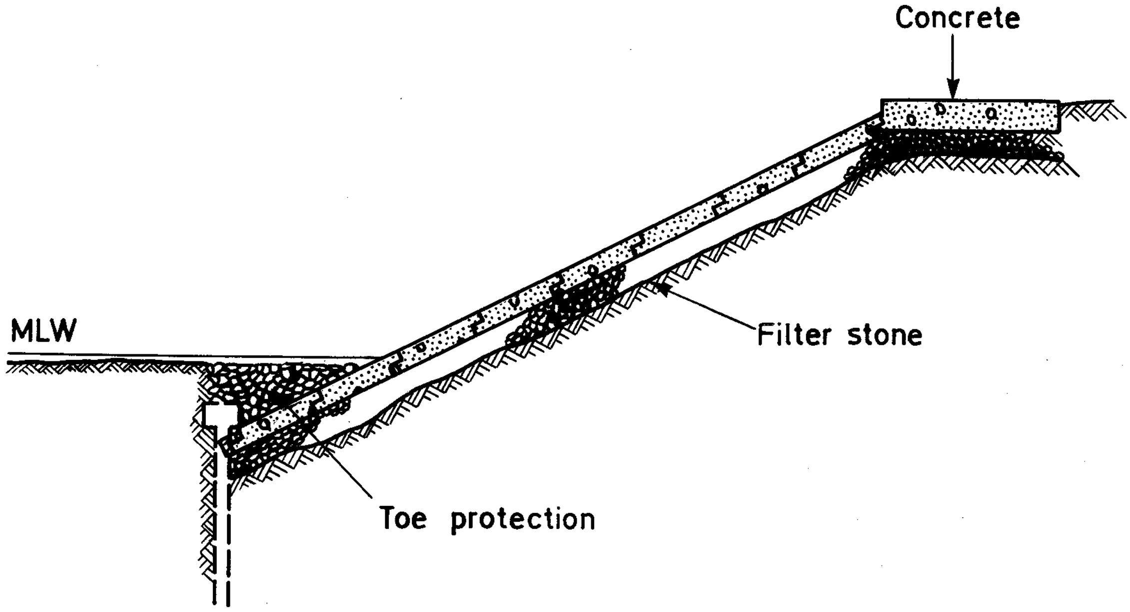



Fig 4 Interlocking concrete block revetment

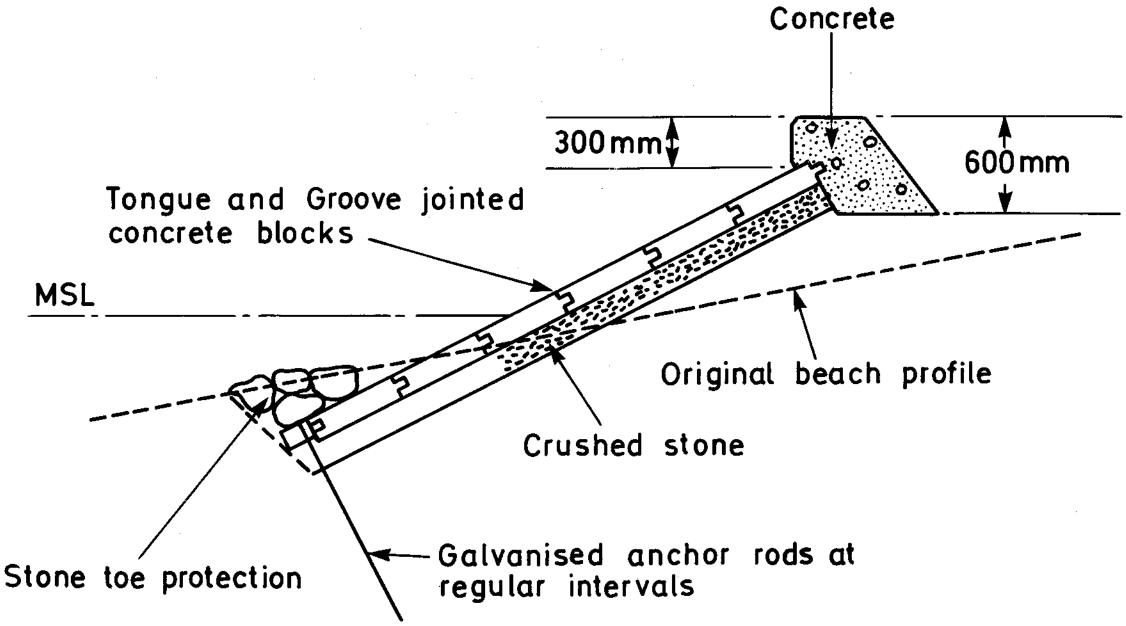



Fig 5 Typical 'Tongue and Groove' concrete block revetment

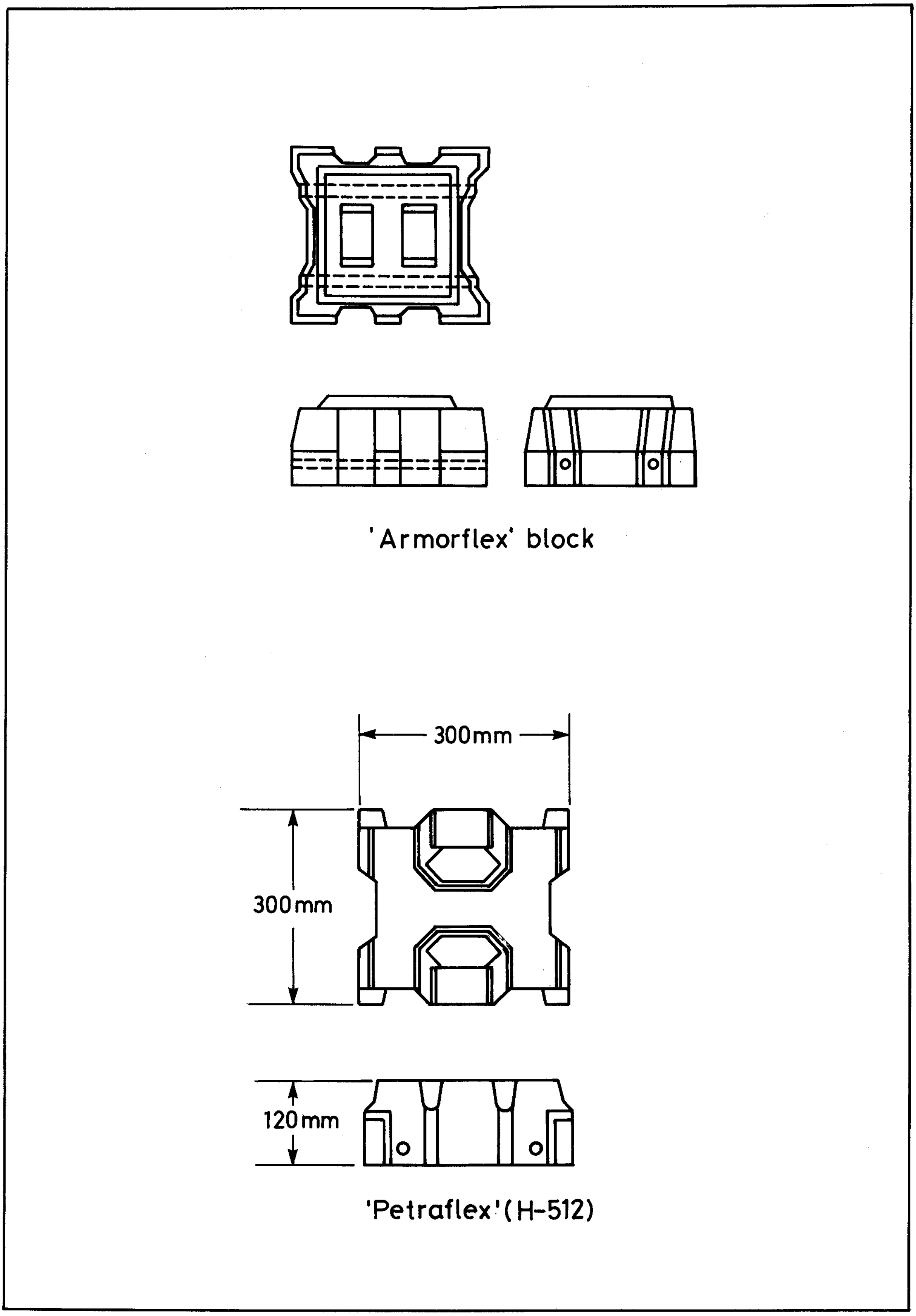



Fig 6 Concrete revetment blocks (integrated system)

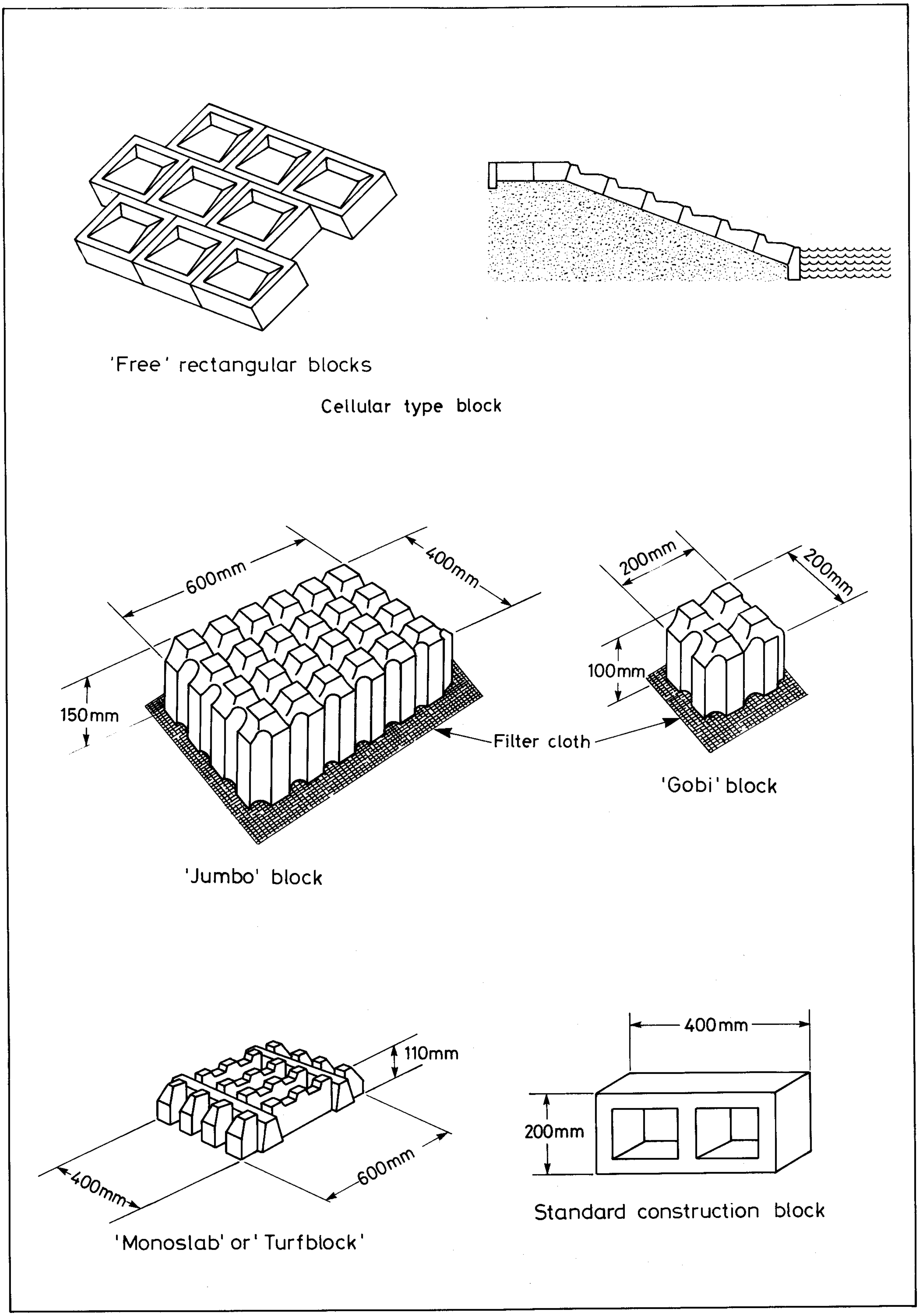



Fig 7 Concrete revetment blocks (free standing)

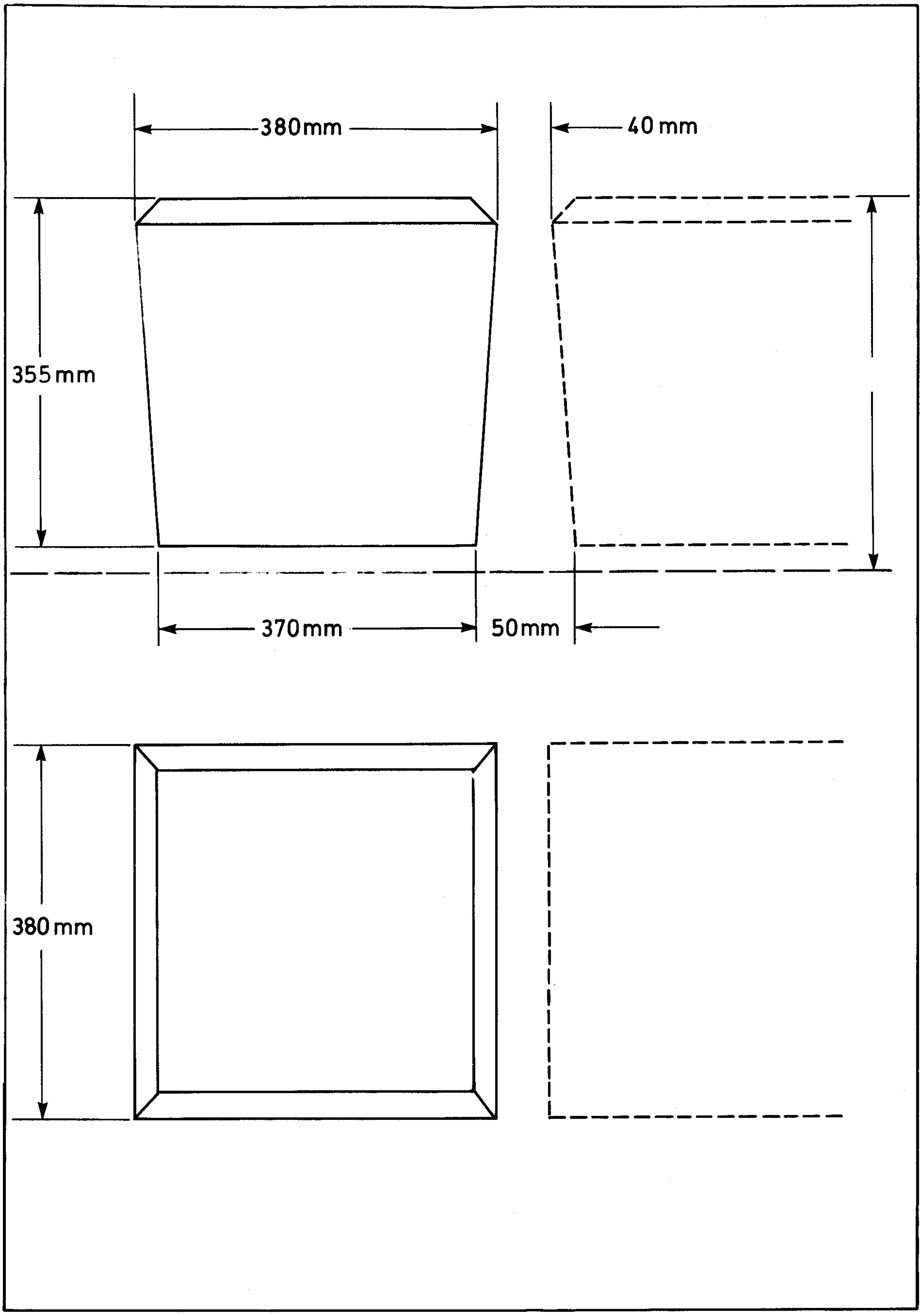



Fig 8 Basalton type blocks (free-standing)

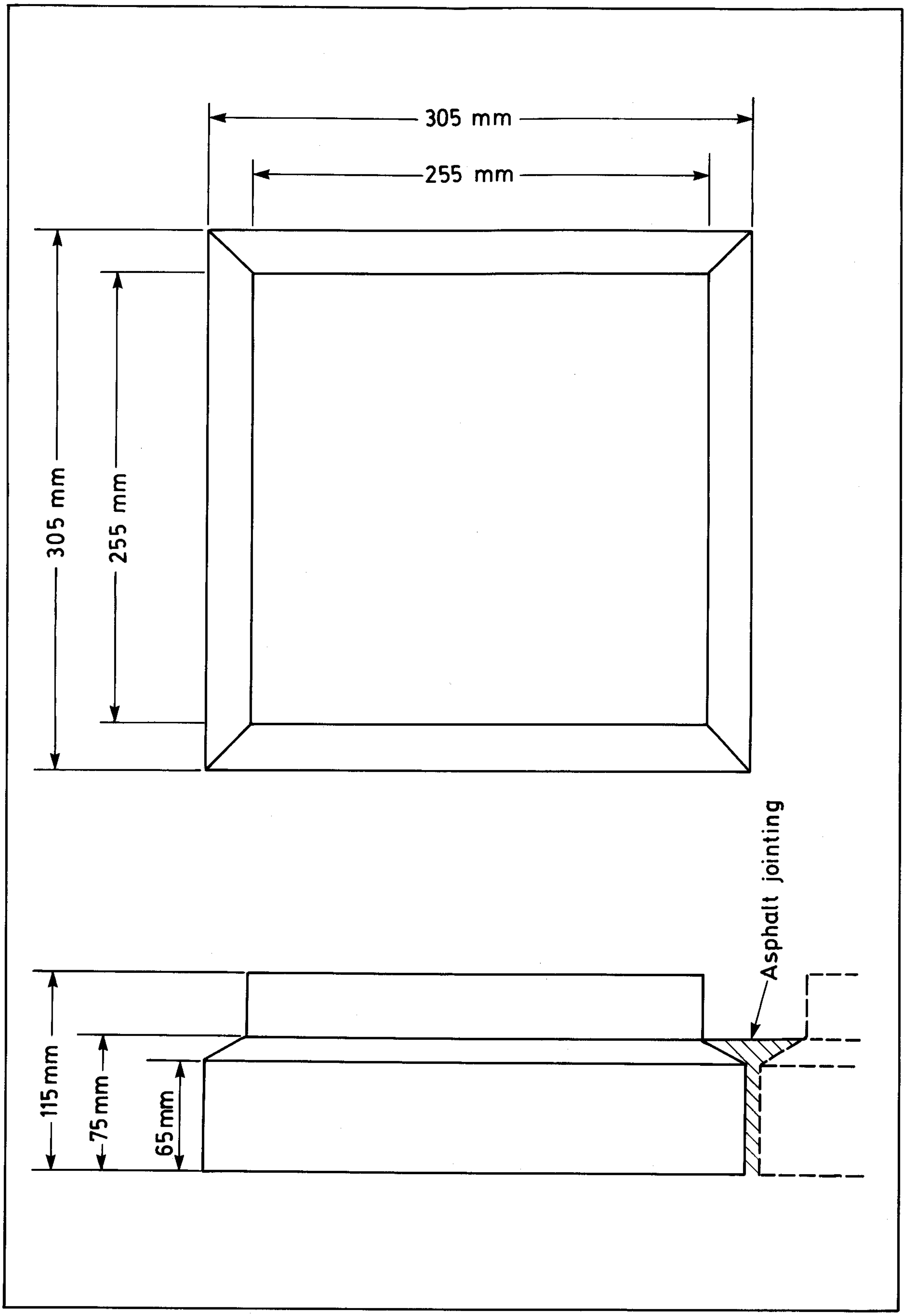
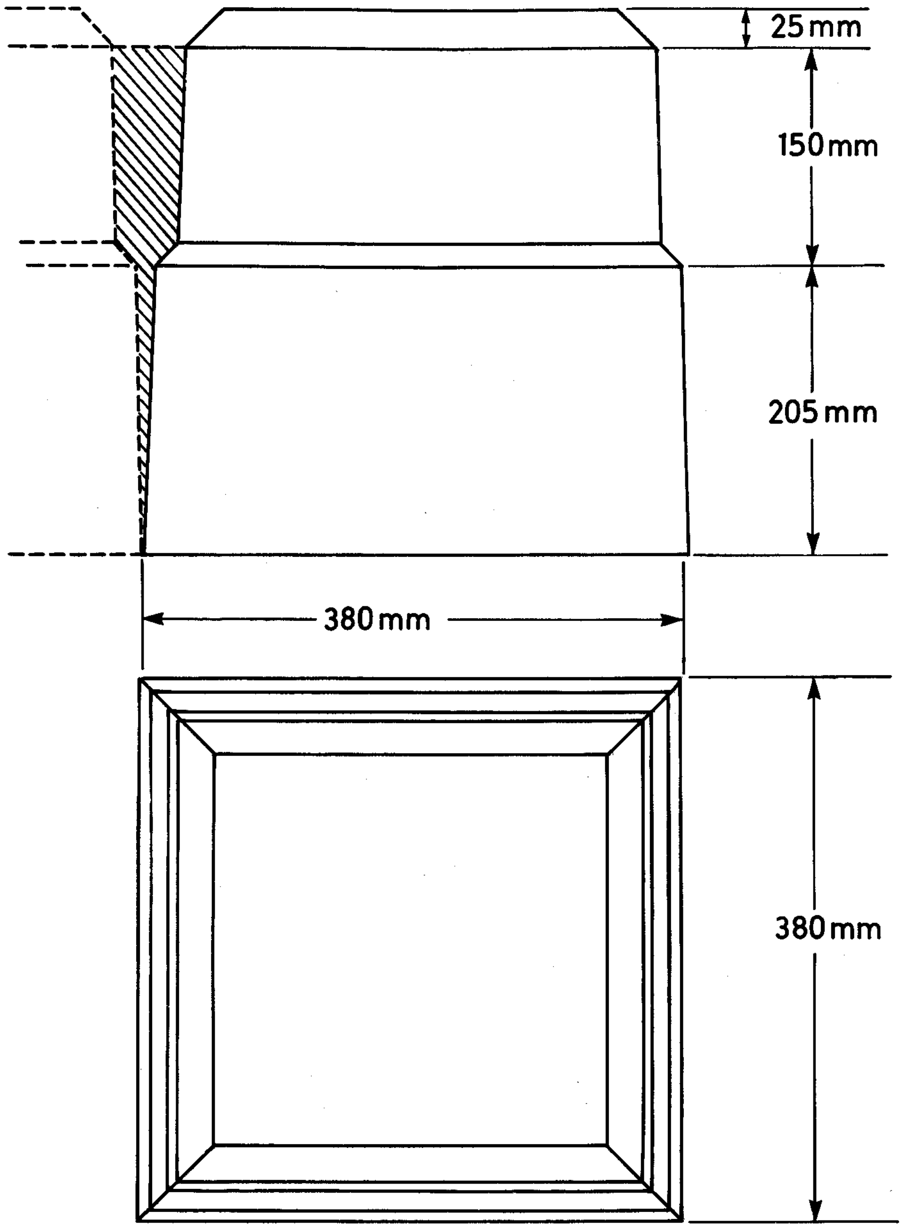



Fig 9 The 'Essex' block (free-standing)




Heavier 'Essex' type block for exposed sites

Fig 10 Northern Sea wall type 'Essex' block (free standing)

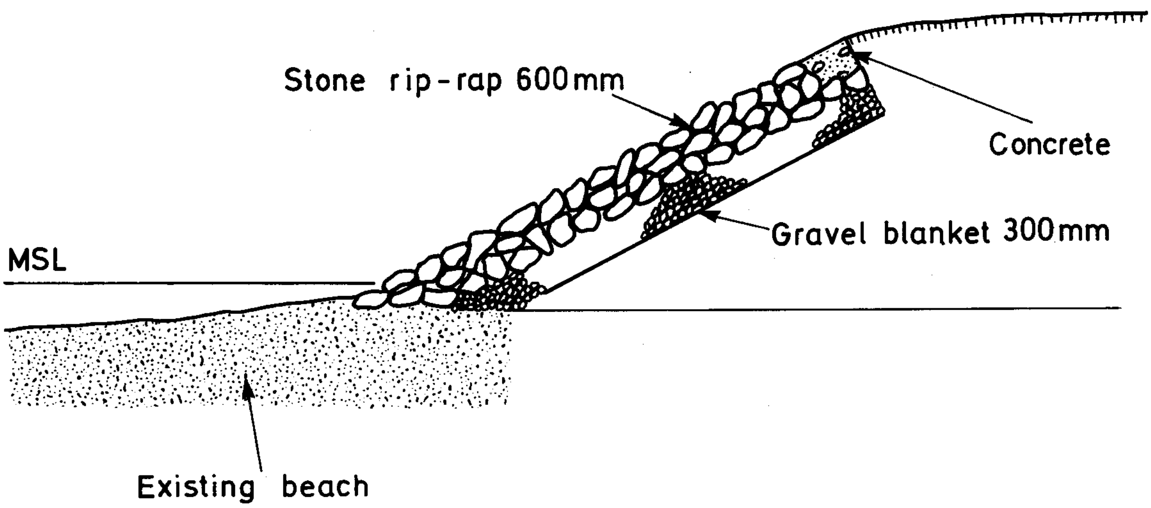



Fig 11 Typical 'Rip-rap' revetment

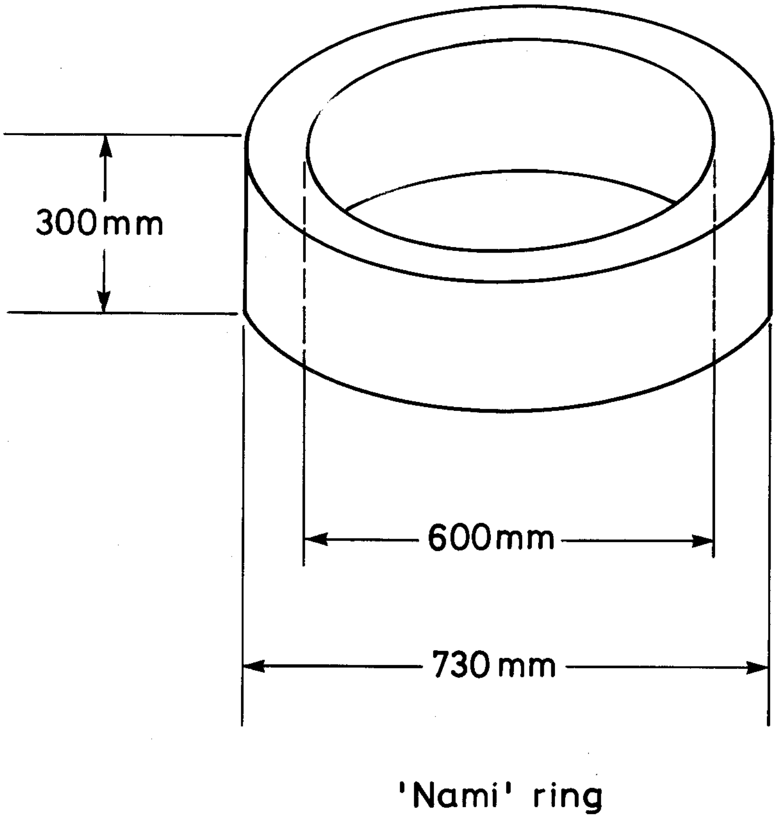



Fig 12 Concrete revetment block (Novel type)

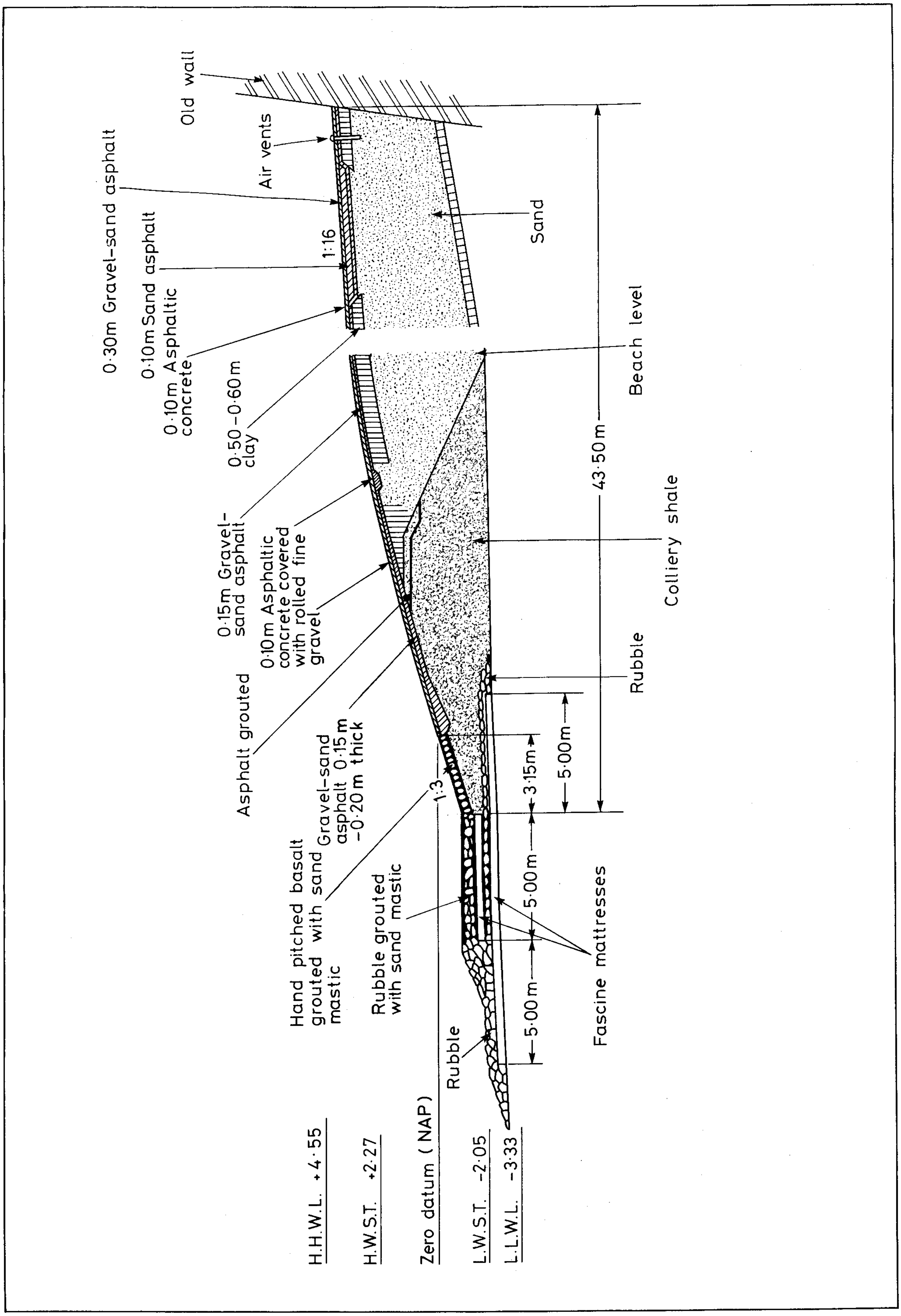
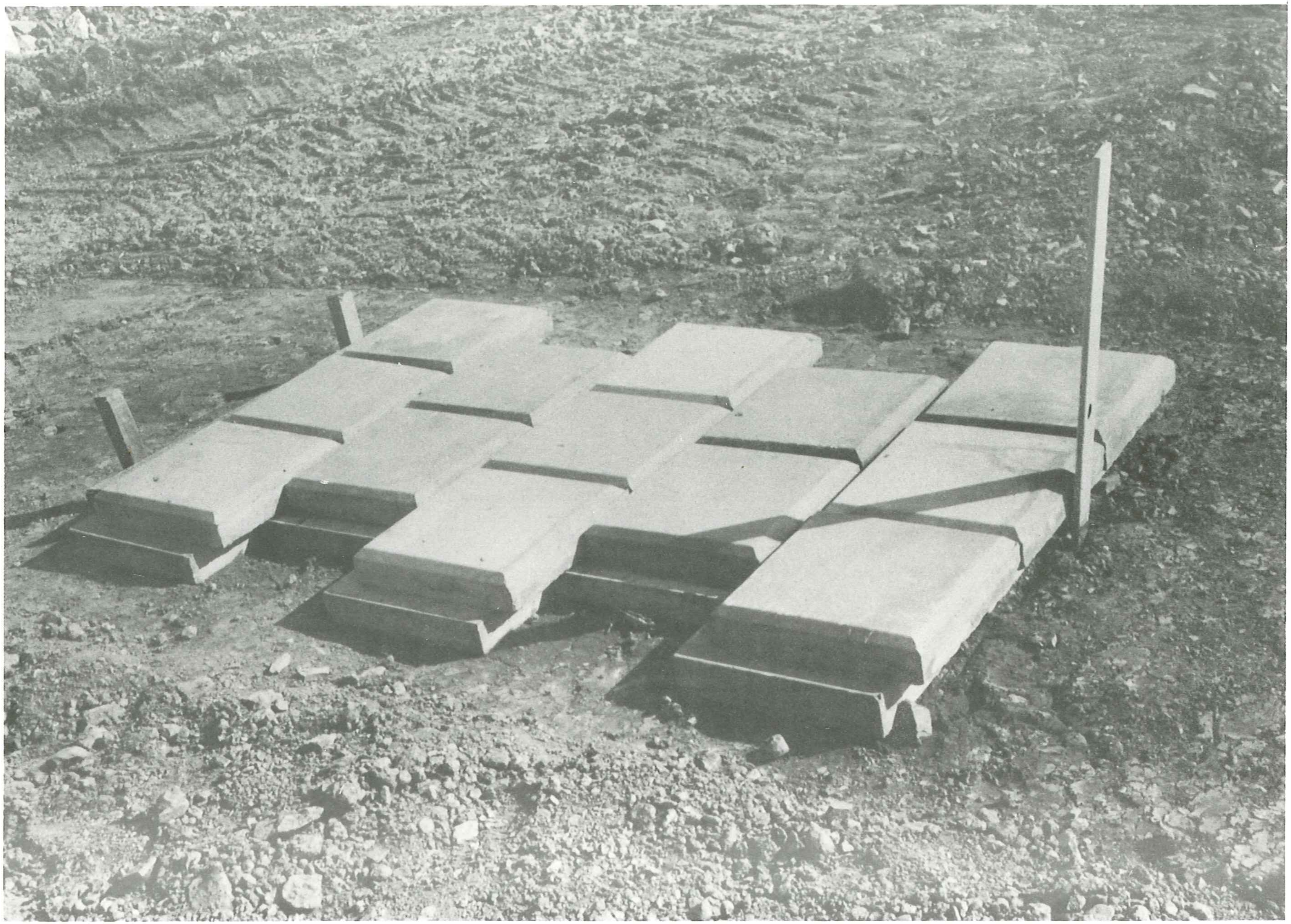
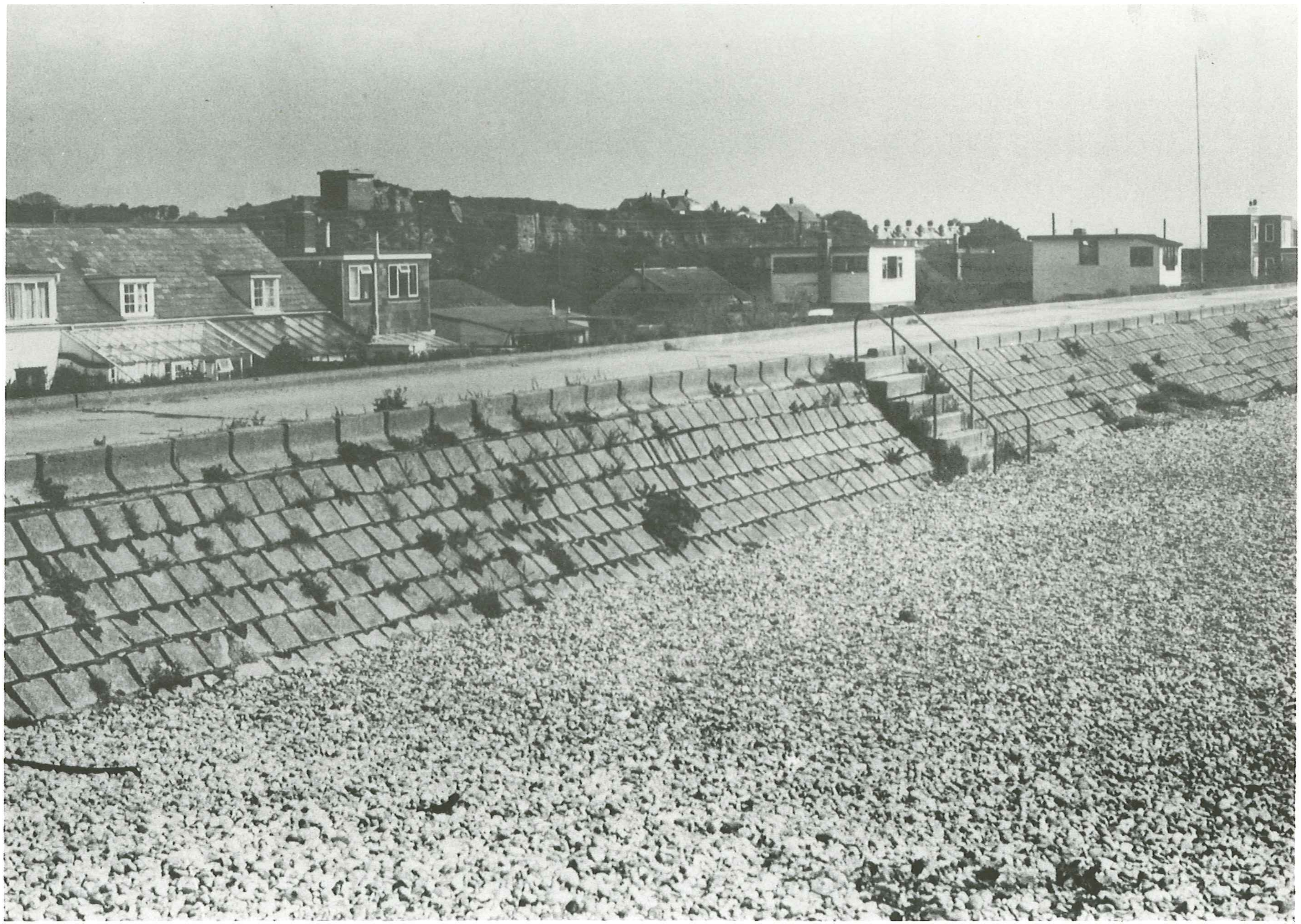



Fig 13 Asphaltic revetment, Flushing, Holland

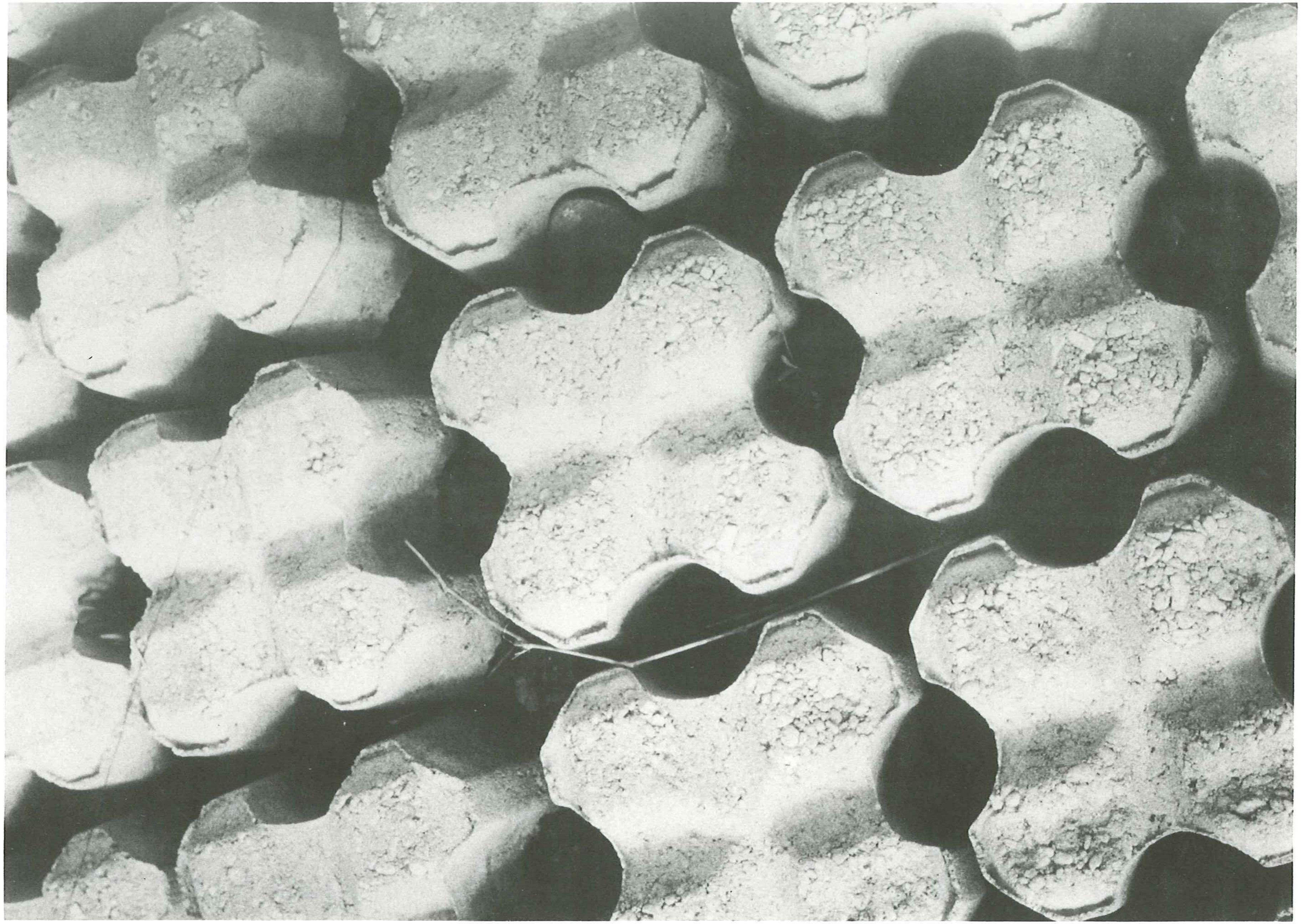
# Plates



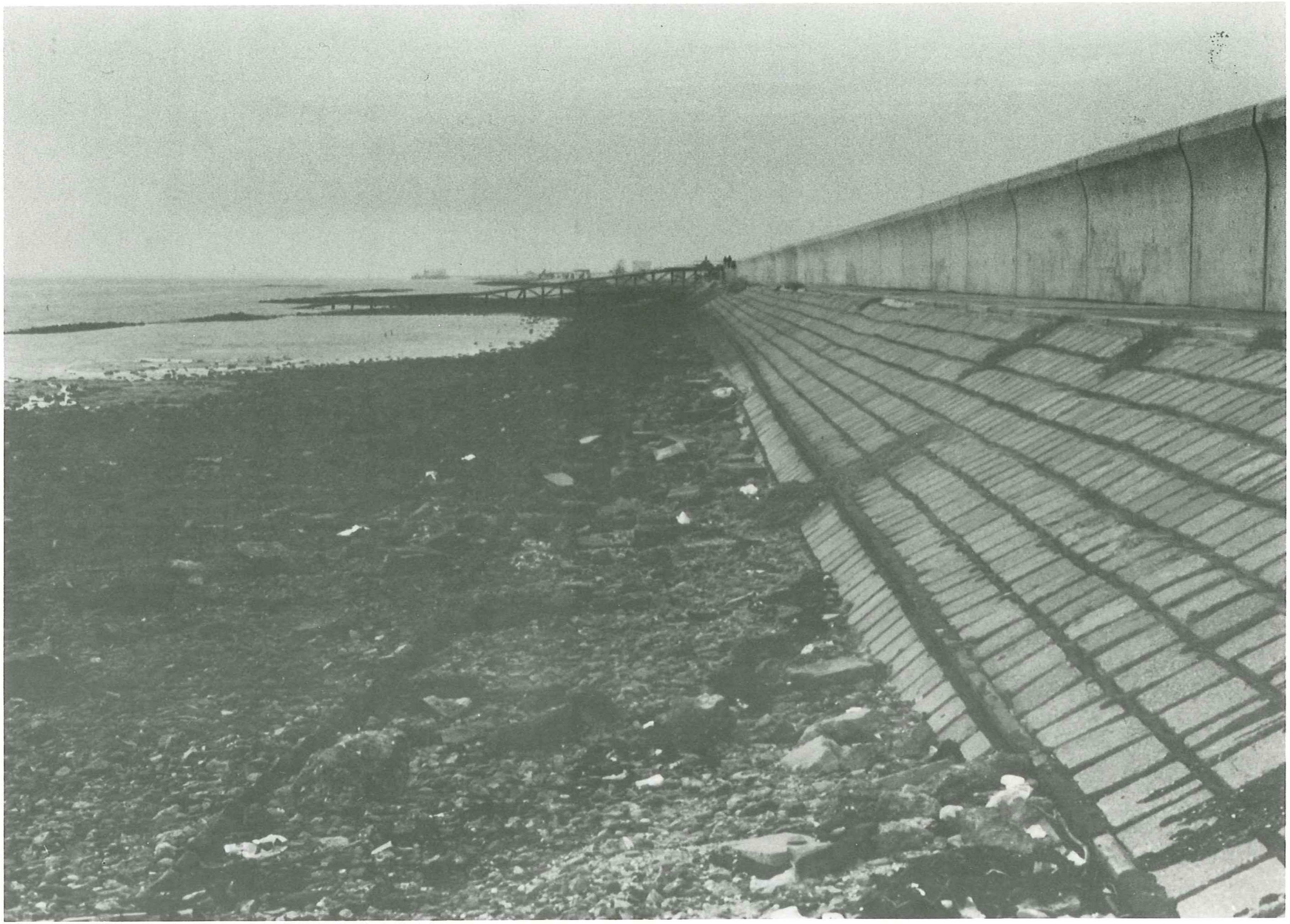
1. Shiplap blocks showing interlock



2. Shiplap revetment - Pett, Sussex

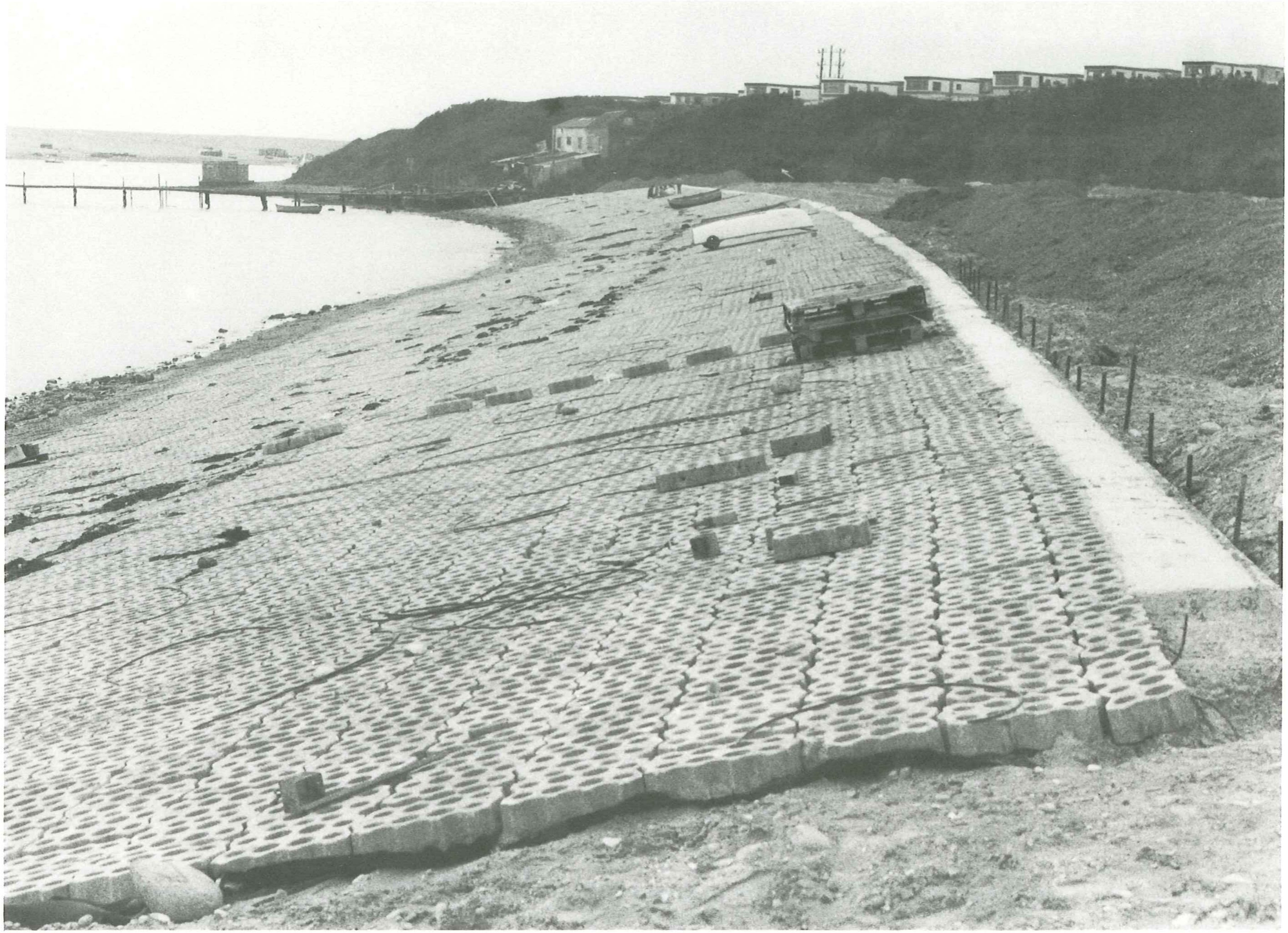


3. Gobimat revetment - Huntspill, Somerset



4. Asphalt grouted blocks - Canvey Island, Essex

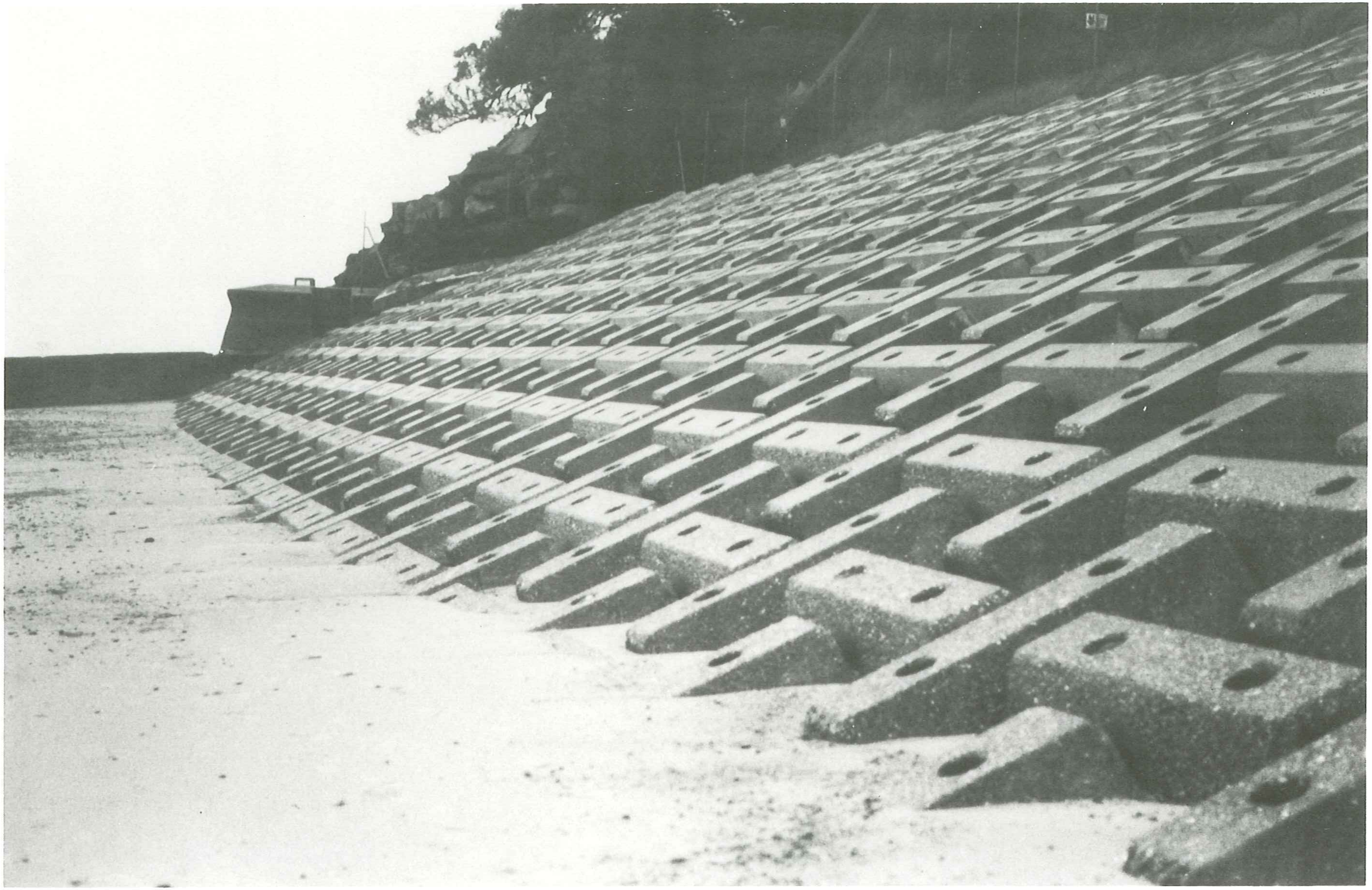
5. Asphalt grouted blocks - Landguard Point, Felixstowe, Suffolk



6. Dycell revetment - Portland, Dorset

7. Petraflex revetment - Huntspill, Somerset

8. Armorflex revetment - Llanddulas, Clwyd



9. Double wedge block revetment - Felixstowe, Suffolk

10. Block revetment - Dengie Peninsular, Essex

11. Sebloc revetment with wave dissipators - Southsea, Hants

12. Asphaltic revetment - Caister, Norfolk

13. 'Fixtone' revetment - Zeebrugge Harbour, Belgium

14. Asphaltic revetment under construction - Porthcawl, Glam

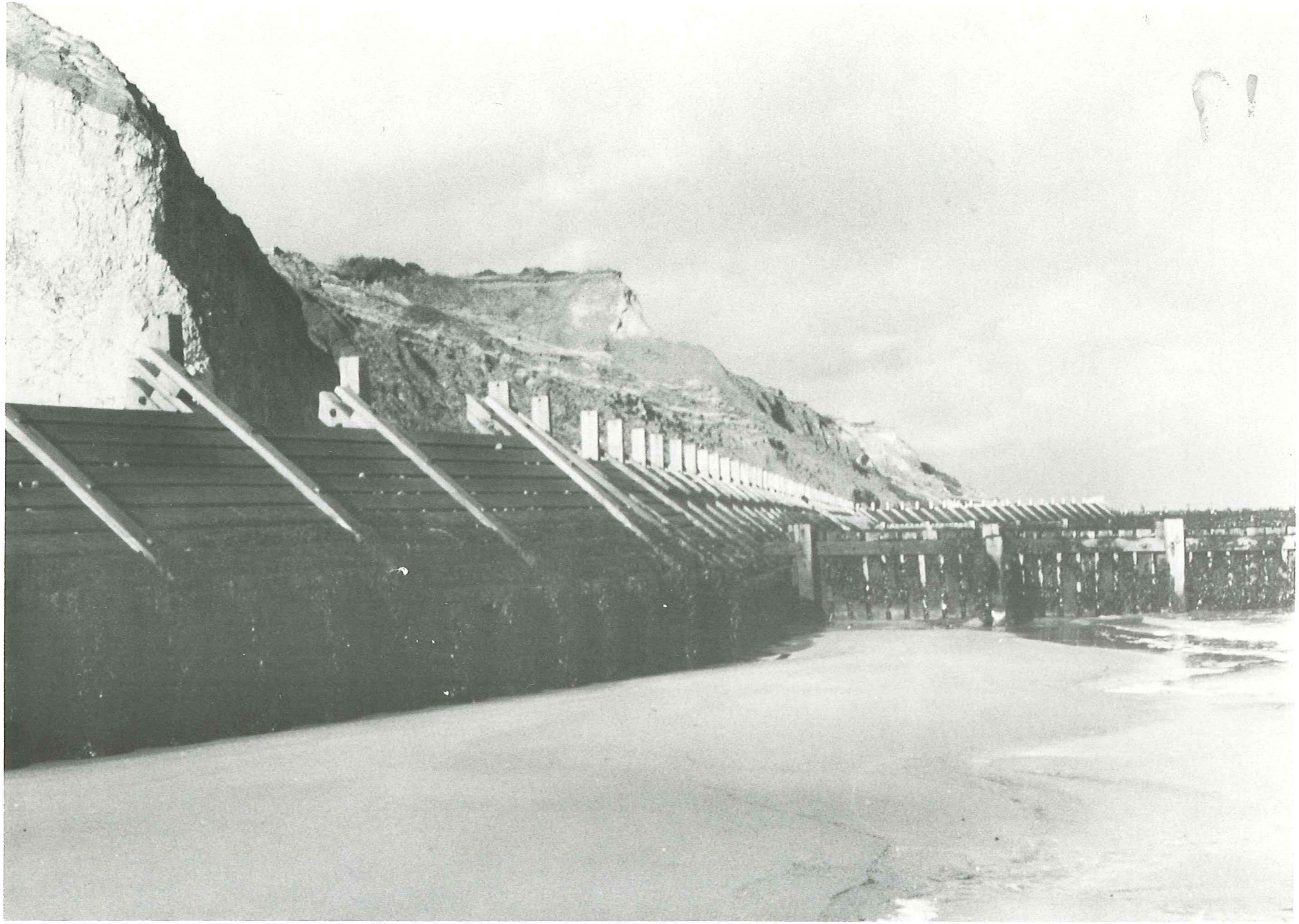
15. Asphaltic revetment showing surface finish - Porthcawl, Glam

16. Asphaltic revetment showing wave run-up - Porthcawl, Glam

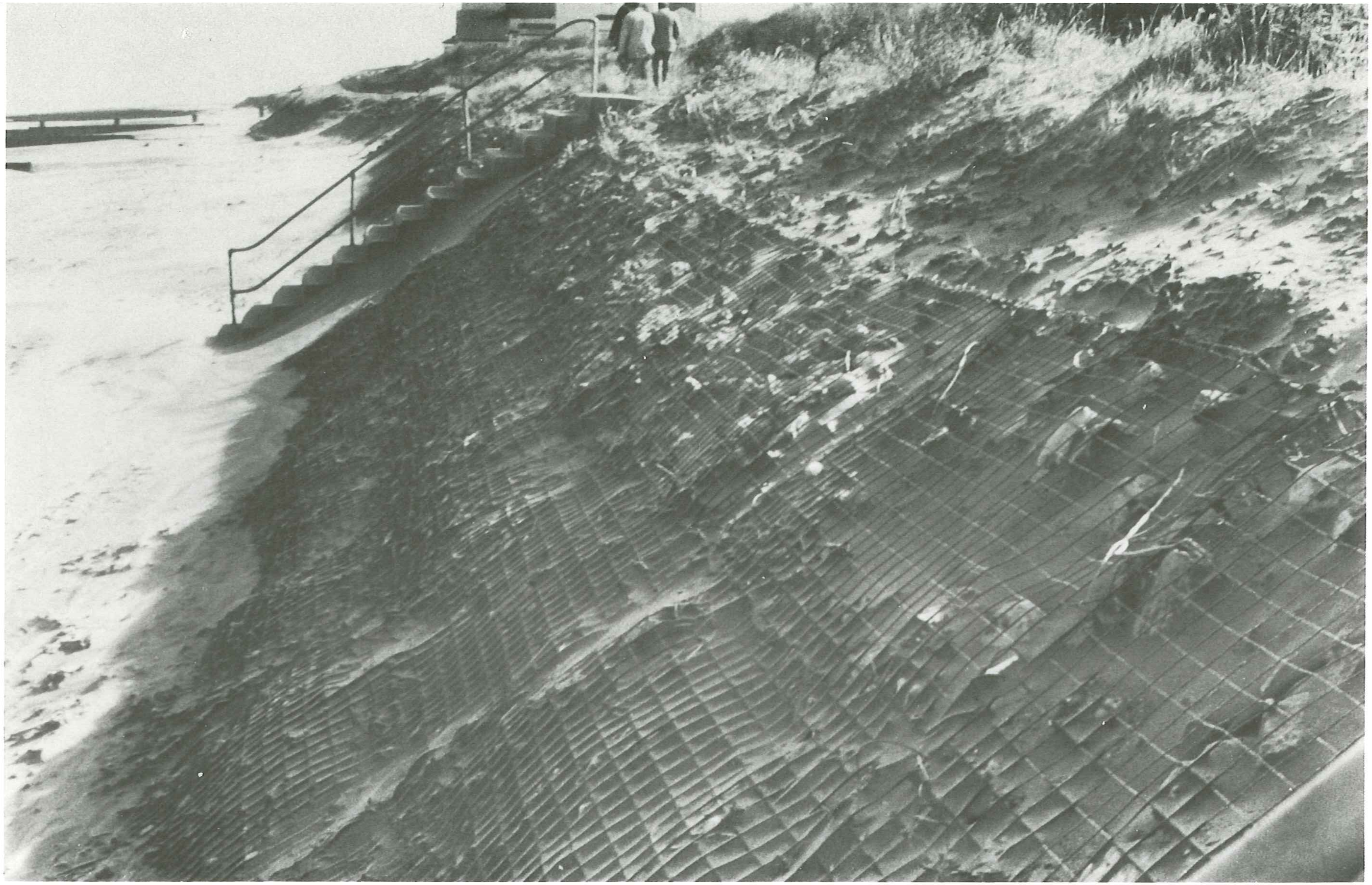
17. Sand-cement bag revetment - Eccles, Norfolk

18. Timber revetment - Deganwy, Gwynedd

19. Timber revetment - Hayling Island, Hants



20. Timber revetment - Mundesley, Norfolk



21. 'Netlon' gabion mattress - Anderby, Lincs

22. Cobble revetment with quarrystone toe - Minehead, Somerset

# Appendix

# APPENDIX 1

## Filter design

**APPENDIX 1**
**Filter Design**

**Filters**

Relief of water pressures and the prevention of soil loss is important in any structure and particularly in a revetment which depends for its success on the stability of the embankment core. Filters, play a large role here and can be described as a transitional layer of sand, gravel, small stones or fabric (or a combination of these) placed between the embankment and its protective armouring. Its purpose is also to distribute the weight of the protective armouring and keep settlement down to an acceptable level.

The success or failure of a revetment may well depend upon the correct selection of filter material. Of late, geotextile filters are becoming more popular. These are fabrics, usually made up of synthetic fibres, and designed for a variety of different sub-soil and armouring systems, the main attraction being the elimination of a series of stone or sand layers which need careful (and time consuming) laying. It therefore makes a construction quicker, easier and cheaper The designer usually works out the graded aggregate filter requirements and then selects if appropriate, a suitable equivalent filter fabric from data provided by the filter manufacturers.

While the chosen filter will incorporate the correct hydraulic characteristics, it will also be necessary to ensure that it has an adequate structural strength. Thus, it may require a cushioning layer so placed to prevent damage to the filter by angular point loads. Filter fabric is not generally compatible with heavy construction and tracked vehicles.

It is recognised that geotextiles used as filters are not a panacea for all foundation problems and tests have shown that a dynamic environment can, in some instances, effect an unacceptable head loss across them leading to rupture of the membrane. A comparison of gravel and cloth filters is given by Dunham and Barretts (Ref 26) who also give details of placement.

**Aggregate**

This form of filter has, in the past, consisted of materials such as sand, gravel or small stone or a combination of these. They are individually laid on a particular sub-soil following general guidelines laid down by Terzaghi, or from reference books such as the US Army Corps of Engineers, Shore Protection Manual (Ref 21). Guidelines for specific revetment design i.e. riprap, are available in CIRIA report No 61 (Ref 63), written by Thompson & Shuttler

There are two main disadvantages when using aggregate filters;

1. Granular material which is intended to stabilise the sub-soil whilst also allowing permeability would normally have to be lain as quite a thick layer.

2. The finer particles, under continuous wave action, tend to get virtually washed out making the layer less efficient after a number of years.

The type of filter selected will depend on the embankment gradation and the armouring characteristic of the protective revetment. It will obviously depend very strongly on the incident wave characteristics. Filters are laid in successively coarser layers starting from the (finest) underlying material which should be capable of retaining the embankment core. The outer (coarser) layer must be stable under the prevailing open boundary conditions while the intermediate layers will depend upon the size of the underlying material. Whilst it may prove to be adequate under 'normal wave attack' the filter may become damaged under exceptionally severe storms. Once this happens it may be necessary to remove the armour layer and re-grade the filter layer or layers.

**Geotextiles**

The use of synthetic filter fabrics has increased significantly in recent years. There is now a wide variety of woven or non-woven fabrics available, the majority of which are made from polymer products i.e. polyester, polymide, polyethylene, polypropylene and polyacrynitrile. The properties of the various fabrics vary, but their basic function is to separate, filtrate when necessary and reinforce. With proper installation they can provide security against the loss of retained material in a more positive manner than would be possible with an aggregate type filter. They also have tensile strength.

There are disadvantages however, and these include:

1. Deterioration under ultra-violet light (bio-deterioration).

2. Leakage due to inadequate overlap of adjoining filter sheets

3. Abrasion by beach material or by the core material.

4. Decrease in permeability in the long term, due to clogging of the pores of the filter cloth.

Synthetic fabrics can be woven, knitted, welded or spun-bonded, the type most appropriate depending on the composition of the embankment and the type of armouring required. For more information on this subject the reader is referred to Rankilor (Ref 58).