CHAPTER 27
THE "TETRAPOD"

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The Tetrapod was invented twelve years ago and the first breakwater with a Tetrapod protection was built eleven years ago.

It is felt that a review of the results since obtained with these artificial blocks may be of some interest, preferably in the form of an objective practical examination of the behaviour of Tetrapod-protected structures during the past few years, and of the way in which they have stood up to bad wheather during the period. First, however, a brief description will be given of the development of the Tetrapod and the Tetrapod technique.

Most breakwaters are of the rubble-mound type, because of the very good hydraulic properties of this type of design ; the seaward slope, roughness and "porosity" of their facings are generally such as to ensure the gradual destruction of wave energy, reduce wave overtopping and reflection and minimize toe erosion risks.

Unfortunately, however, rubble mound breakwater designs vary considerably, and some of them do not successfully combine all these essential features. Following an examination of a large number of designs of this type, therefore, it was decided to try, by systematic research, to determine ways and means of improving the properties of rubble mound breakwaters, especially in respect of the following :

a) Hydraulic properties : (i) Stability of armour components.
(ii) Strength of the structure as a whole.
(iii) Reduced overtopping by waves.

(iv) Reduced wave reflection.

b) Structural make-up : (i) Limitation of individual material weights.

(ii) Convenient artificial block fabrication.

(iii) Simpler block positioning

(iv) Reduction of use of waterborne equipment to a minimum.

c) Financial aspects : Cutting of costs to a minimum.

I - THE INVENTION OF THE TETRAPOD AND THE DEVELOPMENT OF "TETRAPOD" TECHNIQUES

The direct outcome of this research was the Tetrapod, an artificial facing block with novel outlines which is particularly suitable for the construction of very stable facings or armour. A further result was the development of a new breakwater profile design and constructional technique.

The shape of the Tetrapod is the result of research in the following subjects :

I - HYDRAULICS (first and foremost) :

With its special shape, the Tetrapod lends itself to the construction of very rough facings which, being very "porous" (50% voids), are unaffected by upward pressures (up-thrust), and, where laid to a very steep slope (3/4, and even 1/1), are capable of standing up to waves of a very considerable height. In addition, a Tetrapod designed to stand up to given waves under given conditions is much lighter than a lump of rock fulfilling the same purpose.

Several different-shaped blocks had been selected to begin with, all of which had fairly similar hydraulic properties to those of the final design. The fact that the latter turned out to be the only one giving a satisfactory performance from every point of view shows that its design could not be based on hydraulic considerations alone ; strength of materials and work-site problems also had to be investigated by the appropriate specialists before a final shape could be adopted.

II - STRENGTH OF MATERIALS :

The Tetrapod has a relatively compact shape, with generously-proportioned transition sections between the legs and the central "body" of the block, which give it considerable strength ; both experimental breaking tests and work site experience have shown steel reinforcement to be unnecessary, which is a great advantage for any constructional material intended for maritime work.

The Tetrapod is very easily handled, even if its concrete is still comparatively fresh. Simple special equipment has been developed, whereby the block is lifted with its concrete entirely in compression, instead of being under tension as it would be if it merely had an ordinary steel lifting eye at the end of one of its legs for instance.

III - WORK SITE OPERATIONS :

Thanks to the symmetrical geometrical properties of the Tetrapod, it was possible to develop casting moulds (or forms) consisting of four identical interchangeable shell sections, which are simplicity itself to fit and remove.

The shape of the Tetrapod lends itself well to the concrete pouring and vibrating operations and is easy to handle with very simple equipment.

Tetrapods are very easily positioned on the structure by means of a sling. The blocks forming the first layer of the facing automatically assume the required "three legs down" position, and the second-layer Tetrapods then key into them "one leg down".

IV - AN EXAMINATION OF SEVERAL HUNDRED ORIGINAL TETRAPOD PROFILES AND "TETRAPOD"ALTERNATIVES TO CONVENTIONAL LAYOUTS

showed that the special properties of Tetrapods enabled structures to be designed along novel lines resulting both in lower costs and more convenient building operations. The main features of these new methods are as follows :

(i) They require fewer rock fill categories.

(ii) The embankment slopes are similar to the natural slope of the heaped rock fill, so that the proportions of the structure are reduced to a minimum and a very precise adjustment of its various rock fill embankments or berms becomes unnecessary.

(iii) The Tetrapod-positioning equipment need only have a comparatively limited working range.

(iv) The crest of the structure can be set at a lower level and the toe mound built up to a higher level, thanks to the considerable energy-dissipating capacity of the Tetrapod armour.

(v) The structural profile can easily be matched to the quarry output, which often cannot be determined accurately until after the construction work has started.

(vi) The structure can be built progressively from the shore outwards thus reducing the amount of equipment required (i.e.cranes etc.) and work stoppages due to bad weather to a minimum.

(vii) Where either weather, the state of sea, or financial considerations make it imperative to suspend operations, temporary breakwater heads can be built in very little time, which not only stand up very well to wave attack, but the expensive parts of which (e.g. artificial concrete blocks) can easily be recovered afterwards and re-used elsewhere.

II - RESULTS OBTAINED

The first Tetrapod patent was registered in 1950, i.e. about twelve years ago . After a certain period of cautious reserve, Project Authorities, Contractors and Consulting Engineers soon came to realize the qualities it was possible to give a breakwater by protecting it with Tetrapods, and these artificial blocks very soon came into widespread use throughout the world. This trend is still continuing at the present day.

It would of course be quite out of the question to discuss each and every one of the fifty-five structures which have either been completed or are now under construction* in such a very general review of the subject. Instead, it seems both more appropriate and interesting to analyse the behaviour of just a few representative structures ; five breakwaters which have all withstood very violent gales (in fact, probably the very worst that were liable to occur) since their completion five, six, eight, and even ten years ago will, therefore, be discussed in detail. One of the reasons for selecting these particular examples is that comprehensive objective observations by the Project Authorities concerned in respect of wave characteristics and Tetrapod behaviour are available for each and every one of them.

In order to ensure an objective assessment, two structures which have suffered slight damage since their completion will be examined, for the information they provide should be of particular interest to designers of new projects.

* At the time of writing (September 1962), ten more Tetrapod projects have been given the final "go-ahead" including the breakwater at Bayonne, which is the first new breakwater to have been built on the French Atlantic coast for very many years.

THE "TETRAPOD"

I - PROTECTION OF THE COOLING WATER INTAKES FOR A THERMAL POWER STATION AT CASABLANCA, MOROCCO (fig.1)

This project, which was carried out during the winter of 1950/51, involved the protection of the ends of the two parallel piers forming the power station sea water intake with Tetrapods. This was the first time Tetrapods had ever been used on a real-life structure.

The sea bed on which the pier heads stand is at a level of -2.5m (-8') and the spring tide high water level is at about + 4.0 m. (+13'). Maximum wave heights at sea are liable to reach 8 metres (26') and more, with periods of up to 16 seconds. At the water intake pier heads, the local depth of water limits wave amplitudes to 5-6 metres (16-20').

It was found during the design studies that 50 metric ton rectangular blocks laid to a slope of 2:3 would not provide a stable form of protection. Absolute stability under local conditions (i.e. long breaking waves, the very tight radius of pier head curvature, and the need to lay the Tetrapods to a slope of 1:1 owing to the limited capacity of the work site equipment) would have required 10 cubic metre (13cu.yds) Tetrapods. Scale model tests showed, however, that 6.3 cu.m (8 cu.yds) Tetrapods weighing about 15 metric tons were able to stand up to these conditions quite satisfactorily ; it was found that only about 6 per cent of these blocks were lost on the model under the worst possible simulated gale conditions for the pier heads. This was the solution to be finally adopted, therefore, as a result of which 256 - 6.3 cu.m (8 cu.yds) Tetrapods were positioned on the structure.

Because the crane used to position the Tetrapods only had a working range of about 4 metres (13'), quite a lot of Tetrapods tipped over when being laid and, consequently, did not "key" in properly with the others. In spite of this, however, and even though the contractors had been unable to remove the small quantities of rock from the bed as recommended in order to increase its roughness, and though the rock pile providing a backing for the Tetrapod facing was not built to begin with, less damage occurred during the initial 1951 gales than had been feared. The Tetrapod facing has remained steady ever since, and has been providing an efficient protection for the pier heads during the past eleven years, a fact which is, incidentally, confirmed in a letter dated the 3rd January 1962 from Mr. A.Desgigot the Director of the Equipment Branch of "Energie Electrique du Maroc". This is a particularly interesting result, for it is quite definite that, winter after winter, the structure has been undergoing repeated batterings by the strongest waves that can possibly occur in the shallow water in which it stands.

II - PROTECTION OF A NEW "POLDER" AT SOUSSE, TUNISIA (fig.2)

This was the second Tetrapod project to be built. The "polder" is over 800 metres (2,600 feet) long and lies to the south of Sousse harbour.

Built on the sea bed at a level of -4.5m (-15'), the Tetrapod structure is subject to attack by up to 3-3.5m (10-12')waves; as it is protecting

Fig 3

SAFI - (Morocco)

Extension of the main breakwater

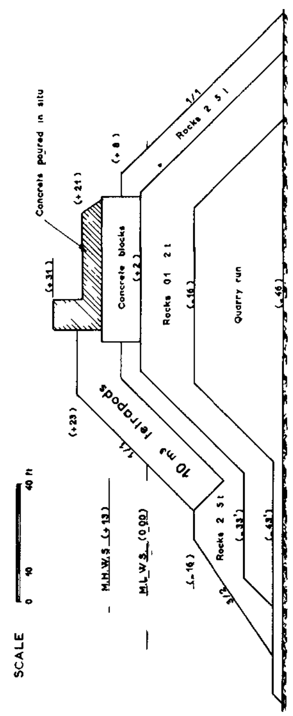


Fig 4

CRESCENT CITY - (California - USA)

Extension of the outer breakwater

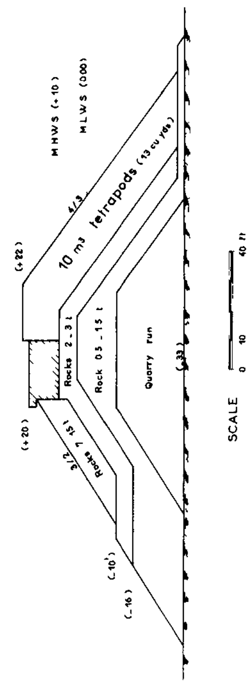


Fig 1

ROCHES NOIRES - Thermal power station

CASABLANCA - MOROCCO -

Protection of the ends of two jetties forming the side walls of a sea water intake

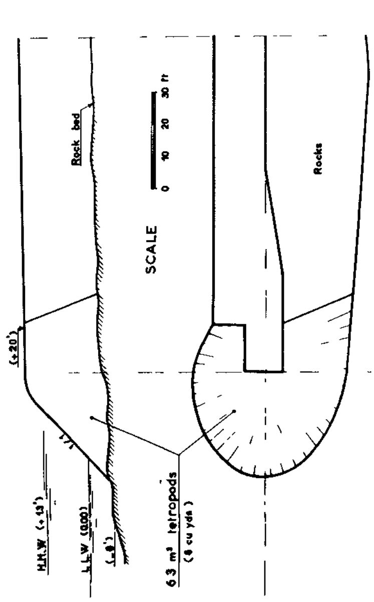
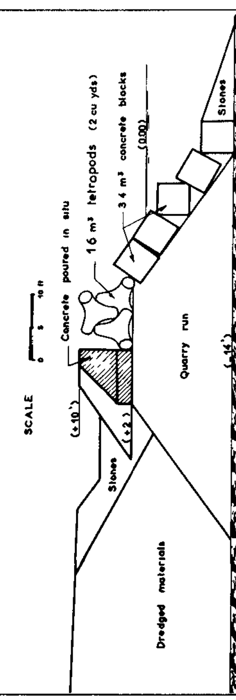


Fig 2

SOUSSE - TUNISIA

Protection of a harbour area reclaimed from the sea

Typical section



a "polder", no overtopping can be allowed.

The initial scheme provided for a facing of 8 and 10 metric ton cubic blocks, the upper part of which, however, suffered storm damage in January 1951 while work was still in progress. Subsequent investigation showed that 4 metric ton Tetrapods (1.6 cu.m or 2 cu.yds)in the upper part of the facing would both provide a very stable structure and effectively prevent overtopping.

The structure was completed in the spring of 1953, involving the use of 1550 - 1.6 cu.m (2 cu.yds) Tetrapods.

On the 12th January 1956, Mr. Raiton, the Engineer-in-charge of the Tunisian Public Works Maritime Branch confirmed that the 4 metric ton Tetrapods had provided a satisfactory replacement for the original 8 - 10metric ton cubic blocks which had proved unstable under wave action. He added that the structure had behaved satisfactorily in heavy weather, and that the Tetrapods in the facing appeared to have remained firmly in position.

III - EXTENSION OF THE MAIN HARBOUR BREAKWATER AT SAFI, MOROCCO (fig.3)

This was the fourth Tetrapod project to be carried out. It involved protecting a new 200 metre (660 feet) extension to the main harbour breakwater standing on the sea bed at a level of about -14.0 m (-46'). Spring tide high water level is at +4.0 m (+13'), and maximum wave heights vary from 7 to 9 metres, (23 to 30') with periods between 8 and 16 seconds.

The facing on the existing breakwater extended from -5.0 m to +7.0m (-16' to +23') and consisted of 45 metric ton rectangular blocks laid to form a slope of 1:2. Investigations showed that 10 cu.m (13 cu.yds) Tetrapods weighing about 24 metric tons each, laid to a slope of nearly 1/1, were not only capable of standing up to the severest wave action, but that they would also enable a substantial reduction in costs to be achieved, as they would require 5 per cent less rock fill and 70 per cent less facing concrete.

1450 - 10 cu.m (13 cu.yds) Tetrapods were used on the running section of the extension and the new breakwater head. Work was completed in 1955.

This structure gave full satisfaction during an exceptional three-day storm in December 1957, during which 9-metre (30') wave heights were recorded. This gale damaged the tip of the transverse breakwater in the harbour, which was not protected with Tetrapods at the time, but was reinforced later on.

In August 1959, Mr. Clos, the Engineer-in-charge of the Southern Area of the Moroccan Ministry of Public Works reported that observations made after the storm had shown that the Tetrapod facing had provided a perfect form of protection for the structure, and that, except for some slight local settling down, no damage to the facing (e.g. broken, displaced, or scattered Tetrapods) had been observed, even on the most exposed parts of the breakwater head.

IV - CONSTRUCTION OF A BREAKWATER AT RONGOTAI, NEAR WELLINGTON, NEW ZEALAND

This was the fith Tetrapod project to be carried out. It involved the protection of an extension to Wellington airport.

The structure stands on the sea bed at -7.0m (-23'). High water leve are +1.2m (+4'), and +1.8m (+6') at highest tide conditions. Waves breakii on the structure are up to 5 or 6 metres (16 to 20') high, with periods ranging from 7 secs. to 15 secs.

The initial project provided for a facing of 30 metric ton rectangul blocks forming a slope of 2/3. Experimental investigations showed, howeve that a facing of 6.3 cu. (8cu.yds) Tetrapods (15 metric tons) laid to forr a slope of 1/1 would be perfectly stable under local conditions.

The latter solution was the more economical of the two, and was fina adopted. 619 - 6.3 cu.m (8 cu.yds) Tetrapods were used, and work was comp ted in 1955.

The facing was seen to settle down slightly in April 1955, during the first two major gales after its construction. The amount of sag was about 1m, and occurred in places where pockets of sand occurred on the rock bed. This particular facing had been built straight on to the bed, as opposed the generally recommended practice of providing a stone blanket between th bed and the foot of the facing. No further settling has since been observe and the structure has afforded satisfactory protection without requiring any repairs or reinforcement.

V - CRESCENT CITY BREAKWATER EXTENSION, CALIFORNIA, U.S. (fig.4)

Although, unlike the four examples described above, this was not one of the very early Tetrapod projects, the behaviour of this breakwater is particularly interesting, as it has had to stand up to five very violent storms since its completion, the last of them quite exceptional.

The design study for the breakwater extension was carried out at Vicksburg (U.S.A.). Observed data and wave-hindcasting methods were used to determine the maximum wave heights the structure would have to be able to withstand without damage ; this was finally taken as 7 metres (23 feet with periods of up to 14 seconds. Spring tide high water levels are at +2.1m (+7'), and exceptionally + 3.0m (+10'). Sea bed levels at the structure range between -9.0m (-30') and -11.0m (-36').

Several schemes with rock-fill armour were investigated, but in all of them, the rock sizes available from the quarry or suitable for the handling capacity of the work site equipment turned out to be unable to provide the required degree of structural stability. The final scheme provided for a facing of 10 cu.m (13 cu.yds) Tetrapods forming a slope of 3/4. Work was completed in October 1957, with 1836 Tetrapods on the final 170 metre (560 feet) section of the breakwater and the breakwater head.

The characteristics of the five very severe storms the structure has since withstood have been reconstructed by the application of wave hind-casting methods to a point some 40 miles north-west of Crescent City, with the following results :

February 1958	Significant height	20 feet
	" period	10 seconds
	Approach direction	south
April 1958	Significant height	20 feet
	" period	13 seconds
	Approach direction	west, west-north-west
November 1958	Significant height	21 feet
	" period	13 seconds
	Approach direction	north-west
February 1959	Significant height	20 feet
	" period	13 seconds
	Approach direction	south
February 1960	Significant height	32 feet
	" period	13 seconds
	Approach direction	west

From these calculations and refraction diagrams, it appears likely that maximum wave heights of 10.5 m (35') may have affected the structure during the February 1960 gale. Photographs taken during the afternoon of the 9th February 1960 show evidence of waves breaking over depths of 12 metres (40'), and it can be estimated that at least 9-metre (30') waves were breaking on the structure at the time.

The structure and its Tetrapod facing stood up to these gale conditions very well, and subsequent inspection merely showed that a few Tetrapods had moved out of position on the seaward side of the breakwater head, which was affected by tangential wave attack, and that the whole structure had settled slightly as the Tetrapods tended to "key" together more firmly.

The need for reinforced facings on the seaward ends of such structures is made fairly plain by this example. This point will be discussed more fully later on.

VI - ANALYSIS OF TWO STRUCTURES HAVING SUFFERED SLIGHT DAMAGE

An exact analysis of possible damage is particularly important, for though the Tetrapod technique has certainly been thoroughly tested, it is nevertheless still comparatively recent. The following examination of two representative cases will provide a few useful indications in respect of breakwater design and construction.

a) Reinforcement of the South Breakwater at Wick, Scotland (fig. 5)

This was originally a vertical jetty standing on a rubble mound provided with a thick concrete facing. With the local spring tide range of 3 metres,(10') this structure had the properties of a composite breakwater on which 4.5 metre (15') 10 second period waves broke owing to the shallow depth of water in which it stood.

Wave flume tests showed that 3.2 cu.m (4 cu.yds) Tetrapods weighing about 7.5 metric tons each would provide the structure with the requisite amount of reinforcement ; unfortunately, however, the funds available for the repair scheme limited the number of Tetrapods to be used to 625, which was not enough for a facing extending all the way out to the breakwater head. The breakwater consists of two straight sections with a change of heading of about 15° from one to the other.

The reinforcement could only be taken as far as the point of junction of the two straight alignments, which happened to be a particularly vulnerable point, being affected by reinforced wave activity due to the layout of the structure.

Soon after the reinforcement work had been completed, storms in Novem ber and December 1956 damaged the end of the facing, affecting about 10 pe cent of the Tetrapods on the structure. The 3.2 cu.m (4 cu.yds)Tetrapods were displaced by the violent wave impacts occurring against the vertical wall of the breakwater beyond the end of the facing. This damage was subsequently reproduced in three-dimensional model tests, as a result of whic it was concluded that heavier Tetrapods should have been used at the end o the facing along the vertical wall.

b) Reinforcement of breakwater heads at Kahului, Maui Island, Hawaii (fig.6)

These structures, which were originally provided with a heavy rock fill armour, had repeatedly suffered storm damage, especially in 1947, 1952 and 1954.

If it is considered that waves breaking at a distance of roughly 0.4L in front of the structure are the most dangerous (L being the wave length at that point), it can be assumed that the breakwater heads are liable to be affected by waves over 10 metres in height (34'). Wave periods observed in 1947 and 1954 were 17 secs. and 18 secs.

Fig 5

WICK HARBOUR

South breakwater

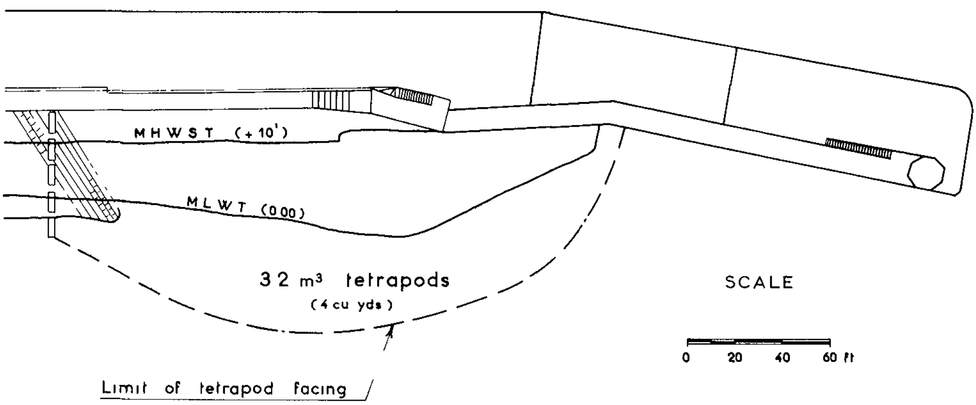
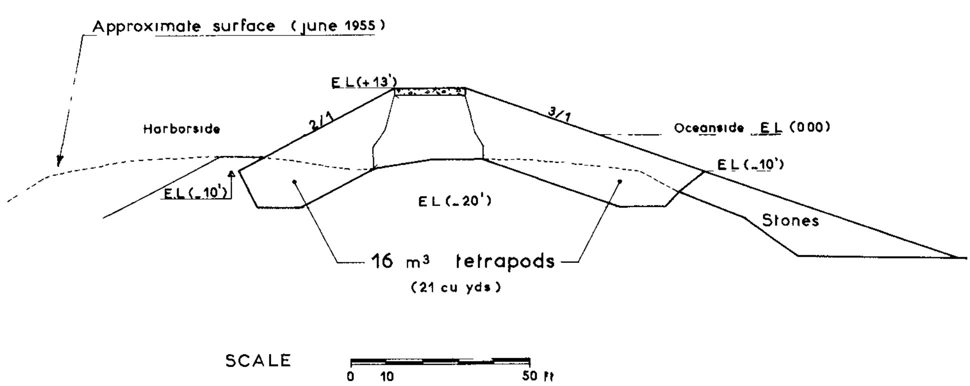


Fig 6

KAHULUI HARBOUR

Reinforcement of the breakwater heads



Before any contracts were awarded for the work, the attention of the Project Authority was drawn to the need to use Tetrapods of at least 16 cu.m (21cu.yds), and, if possible, to build the facing down to the 9.0m (-30') level. However, partly due to a shortage of funds, and partly because of the limited capacity of the available work site equipment, these recommendations could not be followed, and the Project Authority accepted the risk of damage occurring on the structure under exceptionally severe storm conditions.

Work was completed in March 1957, involving the use of 603-12 cu.m (16 cu.yds) Tetrapods (29 metric tons), with the facing only extending down to about - 3.0 m (-10'). It successfully withstood two storms in 1957, but suffered slight damage in November 1958, due to the breaking of waves of an estimated height of 7.6 metres (25'). Most of this damage occurred on an unreinforced part of the East Breakwater, in which a 20m (70') breach formed at the end of the Tetrapod facing, which provided clear evidence of the effectiveness of these artificial blocks. Six Tetrapods, which the breach had deprived of their footing, were swept away through it, and some of the Tetrapods on the breakwater head were dislodged. About thirty Tetrapods were dislodged on the West Breakwater. Altogether, about 6 per cent of the Tetrapods on the whole structure were displaced, which can reasonably be qualified as the kind of "slight damage" the Project Authority had been prepared to accept, especially if compared with the damage the structure had been suffering before it was given its Tetrapod armour.

The conclusion to be drawn from the behaviour of these last two structures is as follows :

> The breakwater head facing should definitely be made stronger than that on the running section, especially in the case of structure like the one at Wick where the facing is in front of a vertical wall and does not extend right up to the end of the structure. Experimental work has repeatedly shown that the Tetrapods used on the breakwater head should be 1.6 times to twice as heavy as those on the running section, and that it is also important that the breakwater head should be given an adequate radius of curvature.

III - THE USE OF TETRAPODS ON COASTAL PROTECTION STRUCTURES

Tetrapods have frequently been used on coastal protection works. The following are a few examples of this type of application :

I - MARINE DRIVE, BOMBAY, INDIA

Here ,7000 - 1.6 cu.m (2cu.yds) Tetrapods were used to protect a 1200 metre (4,000 feet) length of the promenade along the sea front. Their purpose was to dissipate the energy of 2 - 3 m (6-9') waves breaking against the sea wall, and to prevent waves from overtopping it on to the Drive

The protection work was completed in 1959 and has since proved to be both stable and effective.

II - SALIN-DE-GIRAUD, CAMARGUE COAST, FRANCE

The purpose of the Tetrapods in this project was to protect both the sea water intake and concentration tanks of the "Compagnie Salinière de la Camargue" plant on the sea shore. 1000 - 0.8 cu.m (1cu.yds) and 0.2cu.m (7 cu.feet) have been positioned so far, providing a form of protection which has been both more effective and less expensive than one built of natural stones, as the quarries from which these would have had to be obtained are a long way from the site.

III - ISLAND OF SYLT, GERMANY

In 1960, the sea wall in the town of Westerland was provided with a facing structure of 570-2.5 cu.m (3 cu.yds) Tetrapods, which is now being extended to the north of the town in order to prevent erosion of the dunes which protect the hinterland from flooding. It is expected that some 2000 Tetrapods will have been positioned by the end of 1962. The final structure is to be about 10 metres broad, consisting of five rows of Tetrapods in the initial layer, and four rows in the second layer, the whole standing on a fascine mattress protected with a suitable asphalt product. This structure has been erected on the part of the beach above mean sea level, in order to absorb the energy of waves occurring at exceptionally high water level conditions.

CONCLUSION

The Tetrapod is a recent invention. Though its first application only dates back to some twelve years ago, its early success was instrumental in rapidly changing the attitude of Project Authorities, Consulting Engineers and Contractors from one of prudent reserve to a realisation of its advantages. Now accepted as a useful alternative to conventional methods, Tetrapod schemes are included in tender specifications as a matter of course, frequently as the only solution to be put forward. Thus, the Tetrapod technique can be said to have entered the field of standard practice.

A careful analysis of all the local conditions involved in a project is nevertheless still most important before deciding on a given layout, as well as comprehensive experimental investigations, which generally provide the only means of ensuring that the structure concerned will be able to offer the reliability its size requires.