CHAPTER 28

TETRAPODS*

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INTRODUCTION

The tetrapod is no longer entirely a new-comer in the field of marine construction. The sea water intake of the Roches Noires thermic power station at Casablanca, North Africa, the first structure for which tetrapods were used, was constructed nearly four years ago. However, it is of interest to recall the ideas which stimulated the invention of this new type of protection.

The following remark made by engineers specializing in marine work undoubtedly points to the origin of this invention: "The rectangular or cubic artificial blocks normally used are nearly always less stable than natural rocks of the same unit weight, and of random shape, used under the same conditions." This fact, observed after systematic studies and comparisons and both confirmed and amplified by scale model tests, obvicusly constituted a real challenge to the science of engineering. To take up the challenge, it was sufficient to state clearly the question: what would be the best form for an artificial protecting block? It was also necessary to have the tools needed to make a practical study of the different block shapes under consideration. These conditions were fulfilled in the Neyrpic Hydraulics Laboratory. It was obvicusly impossible to test a series of chosen shapes in a haphazard manner. On the contrary, one of the first steps taken by the laboratory technicians was to establish a list of the properties desired in the new block. A brief review of these properties is given below.

CHARACTERISTICS OF THE TETRAPOD

PERMEABILITY

Protecting revetments for marine structures should not be impervious because of the possible occurrence of internal pressures which may cause considerable disturbance to the structure. Systematic tests, made during the study of the Mers-el-Kebir naval base, have shown that an impervious revetment could be lifted almost bodily by internal pressures, even when the revetment is constructed of 400-ton blocks. In addition, a permeable revetment is desirable in order to absorb incidental swell and thus reduce wave overtoppind and reflection. These two occurrences may constitute a considerable drawback to navigation and use of the harbor. Besides, waves overtopping a structure may attack its more or less unprotected inner slope and, in this way, cause a part of or even the whole structure to collapse. A new block must therefore permit construction of a pervious facing and the perviousness obtained must not be reduced or eliminated by subsequent alterations which may be

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caused by sea action against the structure. This condition, therefore, eliminates blocks which may provide a continuous facing; and consequently, the ideal block should have as few large plane surfaces as possible.

ROU GHNESS

It is desirable for a marine structure revetment to have a rough surface so that it can dissipate the energy of incidental waves and slow down the water masses which tend to rise along the facing and to pass over the structure. The "friction" of water against the mound is thus increased. On the other hand, it is of advantage to increase "internal friction" of the mound by promoting the interlocking of the blocks of which it is made. These results can be obtained with blocks having projections which will ensure both a rough external facing and satisfactory interlocking of the blocks.

RESISTANCE

Finally the block must have maximum resistance, and therefore, the study was passed on to one of the laboratory's experts on the resistance of materials. It seemed difficult to satisfy all of these conditions. However, after various preliminary studies the outline took shape: a sort of sea monster with four tentacles which was patented under the name "tetrapod" (Fig. 1).

Hydraulic tests were made to check the properties of the new block and perfect its design; in this respect one of the essential points was to find the most suitable proportion between the length of the four prongs and the size of the body: the prongs could not be too short because the blocks would then not interlock properly and the revetment would be less stable, they could not be too long because then they would be too fragile. The correct design was finally established.

Once these general proportions were found, further details were settled by considering not only the resistance and hydraulic problems but also the ease of manufacture of the tetrapod casting forms. The result was to give prongs the shape of a truncated cone, of which the angle was determined so as to favor the wedging effect during the first settling movements they make after they are placed into position. The tetrapod with four equidistant prongs gives, to our knowledge, the best combination of those qualities required for a block used to protect marine structures.

A revetment constructed of tetrapods is pervious, and therefore, on the one hand there is no risk whatever of under-pressure, and on the other, wave energy is satisfactorily absorbed and overtopping is reduced. In addition the block projections provide the revetment with the required roughness.

But before deciding that the tetrapod was the perfect answer, the block in its final shape was again the subject of other experiments. Tests of resistance were made. Sample blocks of several weights were

cast in concrete, reinforced or not, and of several mixes, and then tested for resistance to shocks (Fig. 2). Then followed systematic scale model tests on the behavior of the blocks when they undergo prolonged attack by the sea. The tetrapod came through all of these tests in a completely satisfactory manner and it was shown to have some great advantages over other blocks in current use; i.e.,

- a. The same degree of stability can be achieved with smaller unit weights and steeper facings;
- b. The structures can be built lower because overtopping is reduced;
- c. Maintenance and repairs are relatively easy as is the case of pell-mell construction.

Once these advantages of the tetrapod were established on scale models, it was deemed possible to use them in actual construction.

USE OF TETRAPODS

There are obviously several ways in which tetrapods may be used for building new structures, or for strengthening and repairing existing ones. In each case where tetrapods are used it is necessary to make a special study, and just as it should be done for any large marine project, it is often helpful to make a scale model study, as this will give the best solution from both technical and economical points of view.

Nevertheless, by referring to experience acquired from many scale model studies, it is possible to specify the most frequently recommended and particularly favorable designs. In fact, two of these are in the majority: the "mound" and the "double layer". A mound of tetrapods is generally used when a vertical structure is to be protected by placing against its seaward face a fill of natural or artificial rocks having a sufficient weight to resist wave action (Fig. 3).

This fill must satisfy several requirements:

- a. It protects the wall against any direct wave attack which may endanger its stability;
- b. It reduces overtopping;
- c. It reduces wave reflections.

If the water at the structure is not too deep, it is often desirable to design this protection in the form of a mound composed completely of tetrapods. This type of construction provides the maximum use of the tetrapods properties, i.e., high stability is obtained, although the seaward slope is very steep (about 1:1). Despite this slope, the mounds have low reflection coefficients because they are pervious and round. To avoid "slaps" against the upper part of the wall,



Fig. 1. A tetrapod



Fig. 2. A four-ton tetrapod after a 3 ft. fall.

a slight berm is often provided at the upper part of the tetrapod nound. The berm obviously increases the volume of the mound a small amount.

When large water depths are reached, the mound, whose volume increases roughly as the square of the depth, would become too expensive if it was made entirely of tetrapods. The alternative is therefore a core of natural rocks and a revetment of tetrapods. The best design of this revetment is the "double layer" previously mentioned. The part of the core laying directly under the facing should be constructed of rocks having a unit weight not less than 1/10 of that of the tetrapods in order that these rocks may not pass through the gaps. This foundation cannot, as a rule, have a slope as steep as 1:1, because this would be destroyed by any sea disturbance occurring before the tetrapods are placed into position. Thus it is necessary to give a gentler slope to the facing; this will increase the volume, and consequently the expense, but as against this, the method will allow tetrapods to be replaced by small, less expensive natural rocks and will finally result in an economy in comparison to a complete mound of tetrapods. On such a foundation the double layer is built as follows:

- a. A first layer of tetrapods is laid down so that three prongs rest on the mound with the fourth pointing outward. This disposition is not strict but simply indicates the general orientation of the tetrapods in the first layer.
- b. The second layer is then laid down pointing in the opposite direction to the first, i.e., with one prong directed inward. Tetrapods in the second layer have a natural tendency to settle in this manner, but they are, of course, still less regularly placed than the first because these rest on a relatively plane foundation.
- c. When the second layer has been laid down, there is a rather compact revetment which has few recesses open for additional tetrapods. Thus it is difficult to add a few more tetrapods, which would in any case be useless or even harmful. Scale model tests have shown that such additional tetrapods are the first to be torn away by wave action when this reaches the limit of resistance of the facing.

Therefore, the only way to increase the thickness of the revetment would be by constructing a second "double layer". But then the first becomes useless and it is not advisable to use such a method because the upper "double layer" will then restanaless even and more expensive base than that made of small rocks.

The "double layer" revetment therefore constitutes a well adapted constructional method. It has even better stability than a mound of tetrapods. This can be explained by the fact that tetrapods in a mound are placed quite haphazardly, while those in the "double layer", although largely laid down at random, nevertheless have a general rational organization; because of this tetrapods on the surface offer the smallest possible hold to lifting forces and have the maximum points of contact



Fig. 3. Comparative study between a tetrapod mound and classic blocks used for protecting structures.



Fig. 4. Study in a wave channel for a revetment made of a double layer of tetrapods.

with those in the second layer.

When the double layer is used, thickness of the revetment varies with the unit weight of the tetrapods (Table 1). For a given revetment surface, the required quantity of these blocks at a determined unit weight is almost constant. As a first approximation, the percentage of space in a mound of tetrapods is approximately 50 percent or a little higher. The quantity of tetrapods required to fill a given volume can thus be calculated both easily and quickly.

Table 1

| * Unit weight _T | 50 | 40 | 32 | 25 | 20 | 16 | 12.5 | 8 | 4 | 2 | l | 0.5 | 0.25 |
|------------------------------------|------|------|------|------|------|-------------|------|--------|------|---------------|------|------|------|
| Volume m ³ | 20 | 16 | 12.5 | 10 | 8 | 6 .3 | 5 | 3.2 | 1.6 | 0.8 | 0.4 | 0.2 | 0.1 |
| Height of tetrapod mm | 4155 | 3860 | 3550 | 3300 | 3060 | 2830 | 2620 | 2 26 0 | 1790 | 1 4 20 | 1130 | 900 | 710 |
| Thickness of double layer mm | 5600 | 5200 | 4900 | 4500 | 4100 | 3800 | 3500 | 3000 | 2400 | 1900 | 1500 | 1200 | 950 |
| Quantity on 100 m ² | 14 | 16 | 19 | 22 | 26 | 30 | 35 | 47 | 74 | 120 | 190 | 300 | 470 |

Characteristics for use of tetrapods in double layers

Density of concrete = 2.5

 $T_{(tonne)} = 0.984 \text{ long ton} = 1.102 \text{ U.S. ton}$ m³ = 35.314 cm s⁴

= 35.314 cu. ft.; mm = 0.039 inch; $m^2 = 10.764$ sq. ft.

In very deep water it is not necessary to construct a protection of tetrapods down to the sea-bed. In such cases, the toe of the facing rests on a rock footing built up to a certain level (Fig. 4). This level obviously depends on the amplitude of waves which attack the structure concerned and on the unit weight of the rocks available. Another equally important question is to establish the height above sea level to which the tetrapod protection must be built. This height also depends on the wave amplitude and on the amount of overtopping which can be allowed.

Systematic studies are now in progress and it will soon be possible to give rapidly a rough estimate for any project. However, it will always be of value to make a scale model study of a projected structure in order to find the most economical and the most technically satisfactory solution.

In particular, the most important question is to decide the proper unit weight for tetrapods so that they can resist waves of a certain amplitude with a given slope. The Neyrpic Hydraulics Laboratory has



Fig. 5.

made a series of tests to find the necessary rules for determination of the unit weights necessary. These tests do not as yet cover all possible cases because a really complete series of tests is very long and expensive to conduct. The results obtained to date nevertheless allow useful conclusions in a great many problems. Graphs plotted from these tests (Fig. 5) provide a good approximation for proposed projects and enable possible special studies to be greatly curtailed.

CONCLUSION

Several structures using tetrapods already have been built, or are in the course of construction. Tetrapods have produced the results expected of them and experience has shown that they have the qualities anticipated. For instance, the first structure for which tetrapods were used, the sea-water intake for the Roches Noires thermic power station at Casablanca, North Africa, has withstood four hard winters. The 15-ton tetrapods protectin; the pier-heads have not moved, although they are exposed to formidable Atlantic waves; when photographs taken at two or three years interval are examined, all the blocks above low water mark are seen to be in their original position.

In all the cases studied to date, tetrapods have proved themselves more efficient and economical than ordinary rectangular or cubic blocks. They have undoubtedly enabled marine construction engineers to widen their field of activity, because the tetrapod offers a new answer to the problem of protecting structures in the sea.

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