Fourth Australia - New Zealand
Conference on Geomechanics,
Perth, 14-18 May 1984

Rock for Breakwater Construction in Western Australia — Its Availability and Influence on Design

R.P. MATHER
Supervising Geologist, Engineering & Environmental Geology Branch, Geological Survey of Western Australia

SUMMARY Small-boat harbours protected by rubble-mound breakwaters are currently being built along the exposed western and southern coasts of Western Australia. The properties that rocks must have to be suitable for armour blocks on breakwaters are discussed. Particular reference is made to the special problems produced by the remoteness of heavy armour material from the sites of sixty seven per cent of breakwaters recently built or being considered in Western Australia. Fuller geotechnical investigations for quarries are warranted in these circumstances.

1 INTRODUCTION

There is a growing need in Western Australia for small-boat harbours - for both the fishing industry and recreational boating - along about 2 000 km of exposed coastline facing west and south. South of Exmouth, natural harbours are rare, and in fact do not exist in many areas where safe anchorages are needed. It is a State Government policy to build artificial small-boat harbours at selected sites along the coast from Exmouth to Esperance.

2 HARBOUR AND BREAKWATER TYPES

These harbours are generally created behind breakwaters by enclosing an area of the sea as was done at Port Denison. However, if site conditions are favourable, harbours may also be created by excavating inland, as at Carnarvon. Some form of breakwater is still required to protect the entrance. So far, rubble-mound breakwaters have been built. These are constructed from rock armour blocks over a core of smaller sized material.

The limiting factor that determines such a breakwater's ability to resist a wave of a given height is the specific gravity of the rock used for its armour. Blocks of rock in excess of 10 t cannot usually be economically quarried, carted, or emplaced. In general, this means that the maximum wave height that can be resisted by 10 t armour blocks of rocks is 4-5 m (Fig. 1). For rubble-mound breakwaters using such blocks, 4-5 m waves mark the upper limit of performance without failure.

So far, 10 t blocks have been adequate for the provision of small-boat harbours in Western Australia. In locations where wave heights may exceed 4-5 m, alternative types of structures must be considered - for example the use of double breakwaters as at Townsville (Bremner and others, 1981), the use of man made armour units such as dolosse, tribars or tetrapods as at Botany Bay, or construction methods using caissons as in Japan.

3 BREAKWATER CONSTRUCTION MATERIAL

3.1 Requirement

A review of the design and construction of a number of recent Public Works Department breakwaters shows that 2-10 t armour blocks of igneous and metamorphic rocks of specific gravity 2.5-2.7, represent about 10-20% of the total material required. The balance is made up of the lower classes of armour blocks, core, and fill material, which may be and often are of lower specific gravity.

It is important to note that, as the specific gravity of the rock of an armour block decreases, the weight of the block required to resist the same size of wave increases. This is shown in Figure 1. For example, to resist a 3 m wave breaking on the head of a breakwater, a 4 t block of diorite of specific gravity 2.7, or a 9 t block of limestone of specific gravity 2.2 is required.

3.2 Availability

Figure 2 shows the distribution of 12 small boat harbours, recently built or under consideration, where some form of breakwater is required. Also shown is the distribution of igneous and metamorphic rocks, whose specific gravity is greater than 2.5, and which may be suitable for armour blocks. It can be seen that in 67% of cases, these rocks are not in immediate proximity to the harbour sites. In these cases, the selection of economically satisfactory quarry sites usually requires extensive geotechnical investigations. Also, flexibility during both design and construction stages is necessary to make the best use of available material and provide economically feasible breakwaters.

3.3 Suitability and Yield

Table I shows the relationship between dimensions and mass of cubes of rock with specific gravities of 2.2 and 2.7. It should be noted that both the 4 t block of diorite, which has a specific gravity of about 2.7 and side of 1.15 m, and the 9 t block of limestone, which has a specific gravity of 2.2 and side of 1.6 m, can withstand the same sized waves.

In looking for a quarry site for armour blocks of a given mass, the spacing of natural breaks, usually joints, must exceed at least the length of the side of a theoretical cube of the given mass (Table I), if satisfactory yields are to be obtained.

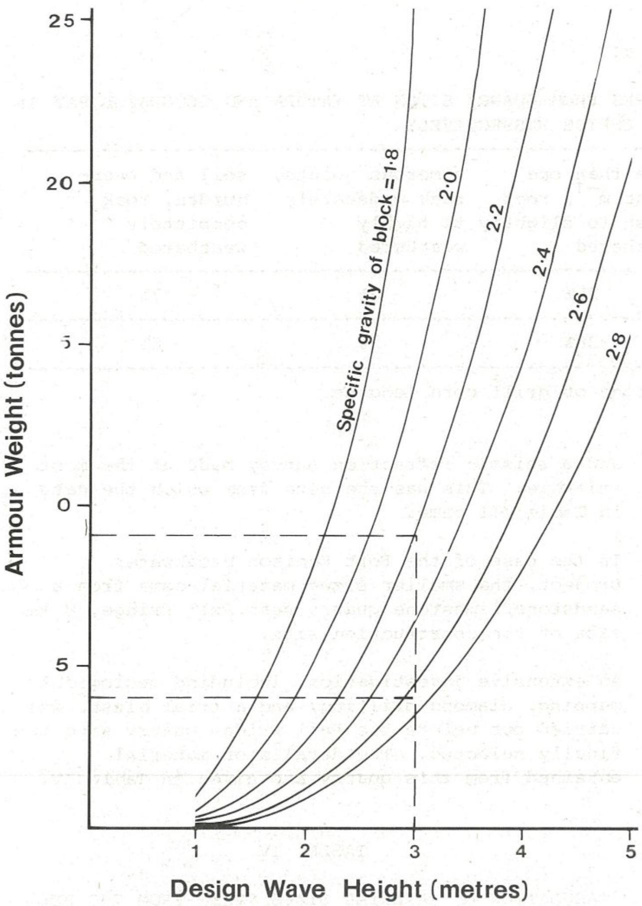

Figure 1 Relationship between the weight of an armour block and the height of the wave it will resist, (for blocks of different specific gravities in the case of a breaking wave on the head of a breakwater with side slopes of 1:1.5.)

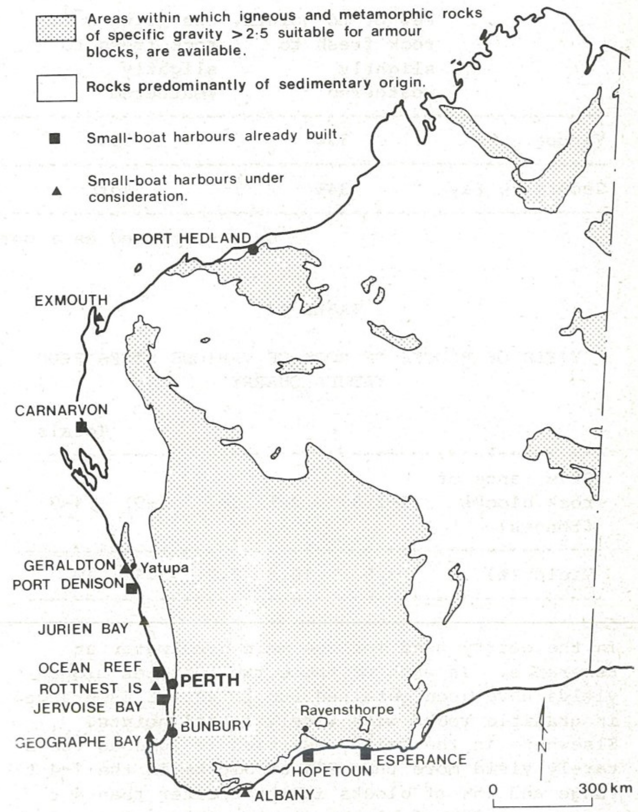

Figure 2 Locations of small-boat harbours in Western Australia and the broad distribution of igneous and metamorphic rocks of specific gravity greater than 2.5.

For rocks of low specific gravity, especially the limestone along the coast, their strength, even when fresh, is often an additional limiting factor that makes it difficult to achieve a satisfactory yield of large blocks. It has long been recognised from experience with limestone blocks used for armour, that, in spite of a careful approach to investigation and testing, the ultimate criterion of suitability is whether a particular block can be placed intact on the breakwater. If it can, then it will be satisfactory providing it meets the mass specification for a rock of its specific gravity.

The quarry at Yatupa (granulite - specific gravity 2.7) 50 km north of the Port Denison project site, supplied heavy armour blocks for the two breakwaters. It had a yield of 10% of blocks in the range 1-9 t. The details are given in Table II.

A yield such as this is considered satisfactory in normal cases because, as mentioned in section 3.1, it falls within the approximate percentage of armour required for rubble-mound breakwaters.

From experience in Western Australia, it also represents about the maximum recovery that could be expected from a quarry in crystalline rocks of high specific gravity and normal jointing. Exceptions have been noted in parts of the Roelands quarry, about 20 km east of Bunbury, and

TABLE I

RELATIONSHIP BETWEEN LENGTH OF SIDE AND MASS FOR ROCK CUBES OF SPECIFIC GRAVITIES OF 2.2 AND 2.7

Length of side of rock cube (metres)	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8
Mass of cube for rock of specific gravity 2.2 (tonnes)	0.8	1.1	1.6	2.2	2.9	3.8	4.8	6.0	7.4	9.0	11.8	12.8
Mass of cube for rock of specific gravity 2.7 (tonnes)	0.9	1.4	2.0	2.7	3.6	4.7	5.9	7.4	9.1	11.1	13.2	15.7

TABLE III

JOINT FREQUENCY AND ROCK WEATHERING DATA FROM DRILL CORES FROM QUARRY SITES AT YATUPA AND GEOGRAPHE BAY IN GRANULITE AND GRANITE GNEISS RESPECTIVELY

	Few or no joints, rock fresh to slightly weathered	one joint m^{-1}, rock fresh to slightly weathered	more than one joint m^{-1}, rock fresh to slightly weathered	numerous joints, rock moderately to highly weathered	soil and overburden, rock completely weathered
Yatupa	33%	35%	25%	0%	7%
Geographe Bay	34%	15%	38%	7%	6%

Data expressed as a percentage of drill core lengths

TABLE II

YIELD OF BLOCKS OF ROCK OF VARIOUS SIZES FROM YATUPA QUARRY

					Totals
Size range of rock blocks (tonnes)	1-2(3)	2-5	3-7	5-9	1-9
Yield (%)	3.5	10.3	2.2	3.1	19.1

in the quarry used for the main breakwater at Esperance. In each of these two quarries higher yields have been obtained (up to 40% at Esperance) in granitic rocks with widely spaced joints. Elsewhere in the world, quarries in igneous rocks rarely yield more than 20% of blocks in the 1-4 t range and 15% of blocks in the greater than 4 t range - or 35% of blocks greater than 1 t.

However, at Yatupa and some other places in Western Australia where quarries for armour blocks were remote from the breakwater sites, it was uneconomical to use the other 80% or so of the quarry production because of the long haul distance.

A summary of joint-frequency data from relevant drill cores of rock obtained in the vicinity of Yatupa showed that 35% of the drill core had rock with a joint frequency of 1 joint m^{-1} and 33% had few or no joints.

Fuller details are given in Table III, which also compares the Yatupa data with that from a quarry drilled in granite gneiss for a breakwater, proposed but not built, at Geographe Bay.

To obtain rock of the quality found at Yatupa, many locations, mostly closer to the breakwater site, were investigated; but the rock at these other locations was found to be too closely jointed, too weathered, or to have a specific gravity that was too low. A full geotechnical investigation of the type carried out for quarry selection for the Port Denison harbour project is essential, especially when a haul distance of 50 km to the breakwater construction site has to be justified. The full investigation is further justified when it is known in advance, as mentioned above, that any extra material of sizes too small for heavy armour resulting from a yield lower than expected, can not be economically used in the breakwater.

At Geographe Bay, granite gneiss was well exposed in the vicinity of the breakwater sites under consideration. Three quarry sites were drilled, and a seismic refraction survey made at the most suitable. This was the site from which the data in Table III came.

In the case of the Port Denison breakwater project, the smaller sized material came from a sandstone/limestone quarry near Pell Bridge, 8 km east of the construction site.

An extensive investigation, including geological mapping, diamond drilling, and a trial blast, was carried out before the Pell Bridge quarry site was finally selected. The details of material obtained from this quarry are given in Table IV.

TABLE IV

TABULATION OF MATERIAL SIZES TAKEN FROM THE PELL BRIDGE QUARRY FOR THE PORT DENISON BREAKWATERS

core	C3, clean sand and rubble	1 200 m^3
	C2, 0-2 t blocks, 50% > 0.5 t and quarry fines to exceed 20%	22 500 m^3
	C1, 0-2 t blocks, 50% > 0.5 t and quarry fines (up to 150 mm) not to exceed 20%	36 200 m^3
armour	A6, 0.5-2 t blocks, 50% > 1.5 t	1 300 t
	A5, 2-4 t blocks, 50% > 3 t	16 200 t
	A4, 4-8 t blocks, 50% > 6 t	25 000 t

4 HOPETOUN BREAKWATER PROJECT

4.1 Introduction

Reference has already been made to data from this project, but it is considered appropriate to conclude the paper with a brief outline of a case history to demonstrate the main geotechnical points already referred to.

4.2 Site Conditions

Although granitic rock crops out at sea level at the site and provides a suitable foundation on which to build a breakwater, it is not available in suitable fresh form above sea level within about 40 km of the site.

4.3 Original Requirements

Initial schemes were based on providing a 2.5 m deep berth and a jinker ramp for fishing boats behind a breakwater. This would have meant that large sections of the breakwater would have been subjected to a 3 m breaking wave. As mentioned in section 3.1, this would mean that a diorite block of 4 t or a limestone block of 9 t would be required as heavy armour. Details of the requirement are given in Table V.

TABLE V

QUANTITIES OF MATERIAL REQUIRED FOR THE SCHEME ORIGINALLY PROPOSED FOR THE HOPETOUN BREAKWATER

Material type	Quantities of materials	
	Breakwater, ramp and berth only	Breakwater, ramp car park & berth
Core	22 000 m^3	19 000 m^3
Sand/rubble fill	nil	26 000 m^3
Class II armour 0.5 t diorite or 1 t limestone	11 500 t	15 000 t
Class I armour 4 t diorite	6 500 t	6 500 t

4.4 Materials Search

4.4.1 General

Thirteen locations within a 45 km radius of Hopetoun were inspected. Of these, 3 were in crystalline rocks (granitic rocks, quartz diorite, and dolerite) of specific gravity 2.6 - 2.8; 5 were in limestone of specific gravity 2.0 - 2.2; 3 were in quartzite (Barren Beds) of specific gravity 2.6; and 2 were in laterite of variable specific gravity.

It was considered that an existing quarry (in quartz diorite intruded by dolerite dykes) near Ravensthorpe was the closest source of rock suitable for Class 1 armour, and that 2 limestone occurrences containing excavations and cliff faces exposing the rock, situated respectively 4 km and 8 km from Hopetoun were the most likely sources for the provision of material of the smaller categories.

4.4.2 Investigation of selected sites

Site No. 1 is 6 km southeast of Ravensthorpe and 42 km from Hopetoun. The quarry had been developed in a northwest direction along a series of dolerite dykes intruded into quartz diorite. A drill hole into the dolerite showed joints spaced 0.3 m apart. The quarry faces showed quartz diorite with joints spaced up to 1 m or more apart, giving rise to blocks of rock generally up to 1 m in size but in some cases up to 2 m. Many blocks of rock were less than 0.3 m in size. The quartz diorite was not drilled.

Site No. 2 is 4 km from Hopetoun near the Golf Club. A series of rock-faces 2-3 m high had been excavated in Tamala Limestone over a distance of about 140 m around the contour of a scrub-covered hill. The core from 3 drill holes in the area showed that none of the rock would be suitable for armour blocks, and that only 27% of the rock would be suitable for the smaller categories.

Site No. 3 is 8 km west of Hopetoun, near Culham Inlet. Steep rock-faces in Tamala Limestone occurred in 3 main localities along about 250 m of foreshore. It could be seen that the limestone overlay granitic rocks to the north. The core from 2 drill holes east of the rock-faces showed that none of the rock would be suitable for armour blocks and that only 25% of the rock would be suitable for the smaller classes. The core from 3 drill holes through the limestone into the granitic rocks showed poor quality rock.

4.4.3 Conclusions from the investigation

It was inferred that the dolerite dykes from Site No. 1 were unsuitable for armour blocks, but that 3 t blocks could be obtained from the quartz diorite into which the dolerite was intruded.

Site No. 2 was recommended over Site No. 3 because it had marginally better rock and was closer to Hopetoun. Doubt was expressed about the availability of blocks greater than 1 t from Sites 2 and 3.

4.5 Modified Requirement

In view of the available quarry materials, the breakwater was modified so that only a small section would be subjected to a 3 m breaking wave. The berth had to be sited in shallower water than originally planned, only giving clearance to R.L. minus 1.8 m. This imposes operational restrictions as the large fishing boats cannot use the berth at low tide. An alterntive was proposed that utilized the surplus material from the limestone quarry as fill to form a parking area on the breakwater. Design rock quantities are shown in Table VI.

TABLE VI

QUANTITIES OF MATERIAL IN THE TWO SCHEMES, WITH AND WITHOUT A CAR PARK, PUT TO TENDER

Material type	Quantities of Materials	
	Breakwater and ramp only	Breakwater, ramp and car park
Core	17 500 m^3	19 300 m^3
Fill	5 700 m^3	20 000 m^3
Class III armour 0.7 t limestone or 0.4 t diorite	7 600 m^3	7 700 m^3
Class II armour 2 t diorite	1 400 t	1 400 t
Class I armour 4 t diorite	2 100 t	2 100 t

4.6 Final Results

The tendered prices were such that the scheme with the parking area was adopted and built. There was very little cost saving in not including a car park. The tenders assessed double handling and stockpiling of excess fill material at much the same cost as moving it about 5 km to the breakwater.

The materials provided by quarries at Sites 1 and 2 are shown in Table VII. Some modification of size ranges within Classes I-II was allowed the contractor at the time of construction.

TABLE VII

QUANTITIES OF MATERIAL ACTUALLY PROVIDED FROM EACH OF QUARRIES NOS 1 AND 2 FOR THE SCHEME WITH CAR PARK

Material type	Quantities of materials Quarry No.1 quartz diorite	Quarry No.2 limestone	TOTAL
Core Quarry material up to 1.0 t	9 500 m^3	16 000 m^3	25 500 m^3
Fill	nil	27 500 m^3	27 500 m^3
Class III armour 0.2-0.5 t diorite 50% >0.3 t or 0.3-1.0 t limestone 50% >0.6 t	5 500 m^3	2 200 m^3	7 700 m^3
Class II armour 50% > 2 t or 2-4 t limestone 50% >3 t	2 300 t	nil	* 2 300 t
Class I armour 2-5 t diorite 50% > 3.5 t	1 300 t	nil	* 1 300 t

* These figures are estimates. At the time of writing construction of the breakwater had not been completed.

5 CONCLUSIONS

Rocks suitable for use as heavy armour are remote from 67% of breakwaters recently built or under consideration in Western Australia.

This means that more extensive geotechnical investigation must be carried out to ensure the availability of suitable materials for construction than would be required if satisfactory rocks were available close to a site. Not only is it harder to locate the most suitable rock in the wider area of search, but the degree of confidence in the rock quality and expected yield from a remote quarry must be higher than for a local one because the economical penalty of failure is higher. Economic considerations often make it necessary to modify the design of a breakwater to suit the available material.

6 ACKNOWLEDGEMENTS

Appreciation is expressed to the Director of the Geological Survey of Western Australia and to the Director of Engineering, Public Works Department of Western Australia for permission to publish this paper. The paper could not have been written without the help of engineers from the Harbours and Rivers Branch of the P.W.D. whose assistance is gratefully acknowledged.

7 REFERENCES

BREMNER, W., FOSTER, D.N., MILLER, C.A., and WALLACE, B.C. (1981). The design concept of dual breakwaters and its application to Townsville Harbour, Queensland, Australia. Civil Engg. Trans. I.E. Aust. vol. CE23, No.4, Nov. pp.283-288.

P.I.A.N.C. (Permanent International Assoc. of Navigation Congress) (1980). Final Report, Third International Commission for the study of waves. Supp. to Bull. No.36, vol.II.