Int. J. MAr. Sci. Eng., 4(2), 57-64, Summer & Autumn 2014
ISSN 2251-6743


# Materials performance assessment of protective layer of rubble mound breakwaters, southern coast of Iran

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Received 10 June 2014; Revised 1 September 2014; Accepted 12 September 2014

**ABSTRACT:** This study aims to examine the performance of the rock materials in the protective layer of rubble-mound breakwaters in southern Iran, from Rostami Port in Bushehr Province to Beris Port in Sistan and Baluchestan Province. Field inspections were carried out on a great number of rubble-mound breakwaters built in the Persian Gulf and Oman Sea coastal regions to study the protective layer of these breakwaters under ambient conditions as well as to detect the damage caused by factors affecting the failure of the used materials. Subsequently, samples were taken from these rock materials, the specimens were tested in accordance with various quality assessment criteria, and the results were compared with those obtained from international standard tests. The obtained results showed that in most cases, the physical and chemical properties of the local rock materials did not meet standard requirements. As such, these materials are not recommended for use in the construction of breakwaters. In practice, however, these rocks exhibit an acceptable performance in certain cases depending on the position of each rock group in the structure of the breakwater. For this reason, design, construction, and structural considerations can somehow influence the performance of these rock materials in the respective marine structures.

**Keywords**: *Rubble-mound breakwater; Breakwater protective layer; Rock armor erosion and durability/endurance; Rock (identification) test; Breakwater failure mechanisms*

## INTRODUCTION

Large-scale investments on offshore structures on the coasts of the country indicate the importance of research on the optimization of projects and selection of appropriate materials for the construction and maintenance of these structures.

Due to the high volume of materials used in the protective layer of rubble mound breakwaters, rock is usually one of the most useful and the most important materials used in these structures to reduce costs and the risk of failure. The need for identifying rock materials and their durability in offshore structures becomes clear after taking a look at the list of structures destroyed due to the use of inappropriate rocks materials. Failure and accidents in large rubble mound breakwaters in the coast of the Atlantic Ocean and the Mediterranean Sea such as Sines Port in Portugal, Port of Tripoli in Libya and Giolatauro in Italy prove this (Burcharth, 1987). There are also reports on damage to offshore structures made of rocks in Iran, especially rubble mound breakwaters. The destruction of the eastern arm of the fishing breakwater of Rostami Port, Port Magham breakwater and shipyard pool breakwater in the Port of Bandar Abbas was mainly due to the use of nondurable rock materials (Hosseini, 2006).

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Several factors control the degradation of natural materials. Accordingly, it is very difficult to predict the behavior of natural materials during the exploitation. A good method for detecting the degradation of rock materials is to review existing structures in each region made of rock materials (Poole *et al*., 1983). The performance of the protective layer of a breakwater is directly dependent on the degradation of rock material used in this layer (Clark, 1988). Rock degradation can be evaluated by field observations or experimental data (CIRIA/CUR, 2000). Physical processes including abrasion, roundness, scaling, large fractures or a combination of them are the main causes of degradation of rock materials in offshore structures (Dibb *et al*., 1983).

Numerous studies have been conducted to evaluate the performance of rock materials in offshore structures.

Jalali investigated the importance of the durability of rock materials in the stability of rubble mound breakwaters in detail. He provided a criterion for the acceptance or rejection of igneous rocks of Gachin Salt Dome as the main supplier for rock materials used in Bandar Abbas shipyard pool (Jalali, 1990).

Nikoodel examined 21 rock samples from Gachin and Angooran salt domes in Hormozgan province used for the construction of Shahid Rajaei and Persian Gulf shipyard breakwaters (Nikoodel, 1990).

Nasehi examined rock samples of Chabahar rubble mound breakwaters. In addition to comparing the performance of rock samples, a criterion was proposed for scoring the rock materials (Nasehi, 1997).

Hosseini examined the geological features of biodegradable rocks as well as the performance of cap rocks and proposed revision of the acceptance criterion for such rocks (Hosseini, 2006).

Despite very useful and valuable studies carried out in Iran, a specific rock type or a specific region of the southern coast of Iran has been examined in most studies. Therefore, the results cannot be used for all types of rocks across the southern coast of Iran.

The aim of the present study was to examine rubble mound breakwaters on the southern coast of Iran to evaluate the performance of the protective layer in terms of structure, hydraulics and materials. In the case of breakwater failure, the type of failure and its cause would be determined and solutions would be proposed to eliminate or reduce the failures. On the other hand, the samples of rock materials used in the protective layer of breakwaters are evaluated by quality evaluation tests to determine the acceptance or rejection of rock specifications from the perspective of existing standards.

## MATERIALS AND METHODS

The early stage of the investigation includes gathering information about the condition of the breakwaters, design parameters, mines used, design and construction. Traveling to the region to assess the breakwaters, a report on the failure modes, failure causes and the quality of materials was prepared for each breakwater.

Rock blocks were selected as samples from longitudinal sections including the head and the arc-shaped part and the main arm as well as various cross sections including submerged, tidal and uptidal zones (Fig. 1).

At least one sample was taken of all the different types of rocks in each breakwater. Table 1 shows sampling mode and the number of samples taken from each breakwater.

Several cores were prepared in the laboratory from each block sample. Various physical, mechanical and durability evaluation tests including water absorption, density and porosity, point load index, Los Angeles abrasion, aggregate impact, and magnesium sulphate soundness were performed base on ASTM and ISRM (Amrican society for testing materials, 1996; International Society for Rock Mechanics,1980). Table 2 shows the tests and the number of block samples used in each test.

The results of tests conducted on rock samples were analyzed and compared with those obtained by other researchers and those in related regulations to determine the durability of the protective layer of rubble mound breakwaters on the southern coast of Iran. Based on field observations, the role of rock durability in the stability of the structure is studied to evaluate the performance of rock materials to select the suitable rock type.

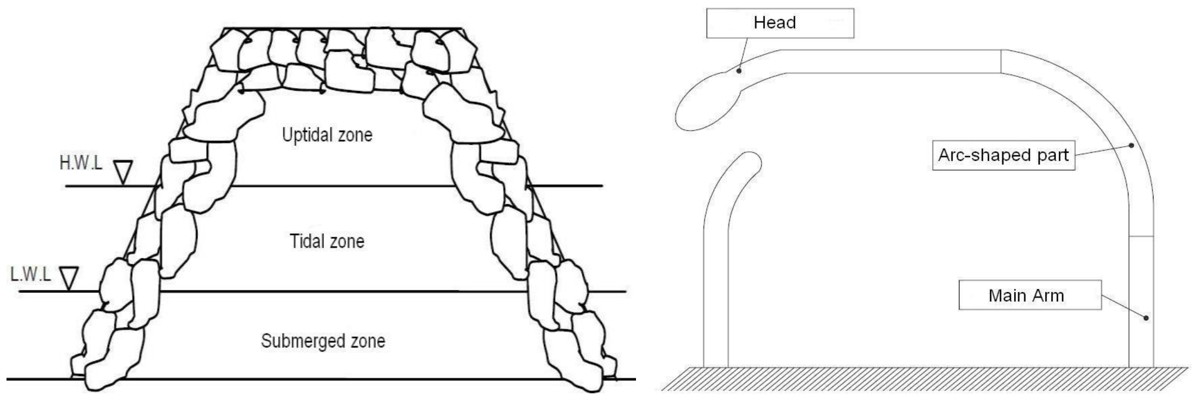


Fig. 1: In plan sampling zone of the breakwater (right), cross sectional sampling zones of the breakwater (left)

Table 1: Sampling of the breakwaters on the southern coast

| Breakwate r | In plan | Cross sectional | Number of |
|---|---|---|---|
| Rostami | Head | UpTidal | 4 |
| | | Tidal | 4 |
| | | Submerged | 3 |
| Ameri | Head | UpTidal | 2 |
| | | Tidal | 3 |
| | | Submerged | 2 |
| | Arc-shaped | UpTidal | 2 |
| | | Tidal | 3 |
| Kangan | Head | UpTidal | 2 |
| | | Tidal | 3 |
| | | Submerged | 2 |
| | Arc-shaped | UpTidal | 2 |
| | | Tidal | 3 |
| Siraf | Head | UpTidal | 2 |
| | | Tidal | 3 |
| | | Submerged | 2 |
| | Arc-shaped | UpTidal | 2 |
| | | Tidal | 3 |
| | Main Arm | UpTidal | 1 |
| | | Tidal | 1 |
| Shirinu | Head | UpTidal | 2 |
| | | Tidal | 3 |
| | | Submerged | 2 |
| | Arc-shaped | UpTidal | 2 |
| | | Tidal | 3 |
| | Main Arm | Tidal | 2 |
| Nakhl Taqi | Head | UpTidal | 2 |
| | | Tidal | 3 |
| | | Submerged | 2 |
| | Arc-shaped | UpTidal | 2 |

| Breakwater | In plan | Cross sectional | Number of samples |
|---|---|---|---|
| Hoseyniyeh | Head | UpTidal | 2 |
| | | Tidal | 3 |
| | | Submerged | 2 |
| | Arc-shaped | UpTidal | 2 |
| | | Tidal | 3 |
| | Main Arm | Tidal | 2 |
| Bostaneh | Head | UpTidal | 2 |
| | | Submerged | 3 |
| | Arc-shaped | UpTidal | 3 |
| | | Tidal | 3 |
| Kong | Head | UpTidal | 2 |
| | | Tidal | 3 |
| | Arc-shaped | Submerged | 2 |
| | Main Arm | UpTidal | 2 |
| | | Tidal | 3 |
| Gooksar | Head | UpTidal | 4 |
| | | Tidal | 4 |
| | | Submerged | 2 |
| Konarak | Head | UpTidal | 2 |
| | | Tidal | 3 |
| | Arc-shaped | Tidal | 3 |
| | | Submerged | 3 |
| Tis | Head | UpTidal | 2 |
| | | Tidal | 3 |
| | | Submerged | 2 |
| | Arc-shaped | Tidal | 3 |
| | Main Arm | Tidal | 2 |
| Beheshti | Head | UpTidal | 2 |
| | | Tidal | 3 |
| | | Submerged | 1 |

| Breakwater | In plan | Cross sectional | Number of samples |
|---|---|---|---|
| | | Tidal | 3 |
| Basaidu | Head | Submerged | 3 |
| | Arc-shaped | UpTidal | 2 |
| | | Tidal | 3 |
| | | Submerged | 2 |
| Salakh | Head | UpTidal | 2 |
| | | Submerged | 3 |
| | Arc-shaped | UpTidal | 3 |
| | | Tidal | 3 |
| Lengeh | Head | UpTidal | 2 |
| | | Tidal | 3 |
| | | Submerged | 3 |
| | Arc-shaped | Tidal | 3 |
| | | Submerged | 2 |
| | Arc-shaped | UpTidal | 2 |
| | | Tidal | 3 |
| | | Submerged | 2 |
| Kalantari | Head | UpTidal | 2 |
| | | Tidal | 3 |
| | Main Arm | UpTidal | 2 |
| | | Tidal | 3 |
| Beris | Head | UpTidal | 2 |
| | | Tidal | 2 |
| | | Submerged | 2 |
| | Arc-shaped | UpTidal | 2 |
| | | Tidal | 2 |
| | | Submerged | 2 |

Table 2: The number and types of tests carried out on each rock sample

| Test type \ Rock type | Test | Igneous rocks | Calcareous rocks | Sandstone rocks | Cap rocks | Total |
|---|---|---|---|---|---|---|
| Physical properties | Water absorption | 29 | 94 | 14 | 76 | 213 |
| | Porosity | 29 | 94 | 14 | 76 | 213 |
| | Density | 29 | 94 | 14 | 76 | 213 |
| Strength | Point load index | 23 | 72 | 9 | 58 | 162 |
| Mechanical durability | Aggregate impact | 18 | 46 | 9 | 47 | 120 |
| | Los Angeles abrasion | 10 | 32 | 8 | 22 | 72 |
| Chemical durability | Weight loss (5 | 15 | 34 | 7 | 26 | 82 |

## RESULTS AND DISCUSSION

In this section, the results of the tests on the rock materials used in the construction of the southern coastal breakwaters are compared with different evaluation criteria proposed by researchers or regulations to determine valid rocks.

Different criteria have been proposed for evaluating the protective layer of rubble mound breakwaters. Table 3 shows the acceptable range for the rocks used in the protective layer of rubble mound breakwaters from the perspective of different regulations and standards Most criteria divide rocks into two categories including acceptable and unacceptable rocks. The criteria provided by Nikoodel and CUR are used for the classification of rocks.

Comparing the results of the quality evaluation test with above criteria, only very resistant igneous rocks and limestone are acceptable for the protective layer. Most rocks used in the construction of southern breakwaters, *i.e.* cap rocks are placed in the poor or unusable group. Table 4 classifies the rock samples based on the existing assessment criteria.

As shown in Table 4, more than 96% of cap rocks in the southern breakwaters are unacceptable on average based on existing selection criteria.

Fig.s 2, 3 and 4 show the frequency of calcareous-sandstone, cap rocks and igneous rocks, respectively, according to CUR and Nikoodel criteria.

Table 3: The most important selection criteria for the rock materials of the protective layer from the perspective of different regulations

| Reference | | Density (t/m3) | Water absorption (%) | Los Angeles abrasion at 500 rpm (%) | Aggregate impact (%) | Magnesium sulphate soundness in 5 cycles |
|---|---|---|---|---|---|---|
| Wakeling, 1977 | | > 2.6 | < 3 | - | < 30 | < 18 |
| Poole *et al.*,1983 | | > 2.6 | < 2.5 | - | < 16 | < 12 |
| British Standard, 1989 | | > 2.6 | < 3 | < 18 | < 30 | < 18 |
| CEM, 2005 | | > 2.6 | <1.2 | < 25 | - | < 2 |
| Jalali, 1990 | | > 3.55 | < 3 | < 18 | < 12 | - |
| CUR, 2000 | Excellent | > 2.99 | < 0.5 | - | - | < 2 |
| | Good | 2.6-2.9 | 0.5-2 | - | - | 2-12 |
| | Moderate | 2.3-2.6 | 2-6 | - | - | 12-30 |
| | Poor | < 2.3 | > 6 | - | - | > 30 |
| Nikoodel, 1990 | Very high | >2.7 | < 1 | < 10 | < 10 | < 1 |
| | High | 2.5-2.7 | 1-2.5 | 10-14 | 10-13 | 1-2 |
| | Moderate | 2.3-2.5 | 2.5-4 | 14-18 | 13-15 | 2-3 |
| | Low | 2.1-2.3 | 4-6 | 18-24 | 15-18 | 3-5 |
| | Very low | < 2.1 | > 6 | > 24 | > 18 | > 5 |

Table 4: Classification of rock samples based on existing criteria

| Criterion | Igneous rocks | | Calcareous - Sandstone rocks | | Cap rocks | |
|---|---|---|---|---|---|---|
| | Acceptable (%) | Unacceptable (%) | Acceptable (%) | Unacceptable (%) | Acceptable (%) | Unacceptable (%) |
| Wakeling | **76** | **24** | **43** | **57** | **12** | **88** |
| Poole *et al.* | **69** | **31** | **22** | **78** | **4** | **96** |
| British Standard | **49** | **51** | **11** | **89** | **2** | **98** |
| CEM | **94** | **4** | **22** | **78** | **2** | **98** |
| Jalali | **79** | **19** | **12** | **88** | **2** | **98** |

As shown in Fig. 2, 13.5, 52, 30.5 and 4 % of calcareous-sandstone samples are placed in poor, moderate, good and excellent categories, respectively, based on CUR criterion. Based on Nikoodel criterion, the frequency of limestone samples shows a declining trend from very low to very high scores so that about 45% of the samples received a very low score while less than 5% of them received a very high score.

According to Fig. 3, 18.5, 78.5 and 3% of cap rock samples are placed in the poor, average and good categories, respectively, based on the CUR criterion. More than 98% of the cap rock samples obtain a low score and less than 2% have a moderate, high and very high scores based on the Nikoodel criterion**.**

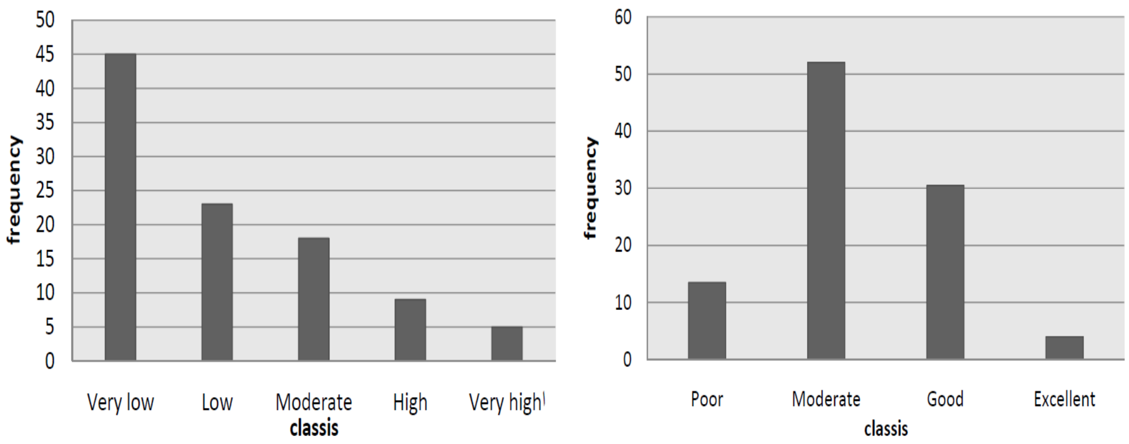


Fig. 2: Calcareous-sandstone sample classification based on CUR (right) and Nikoodel (left) criteria

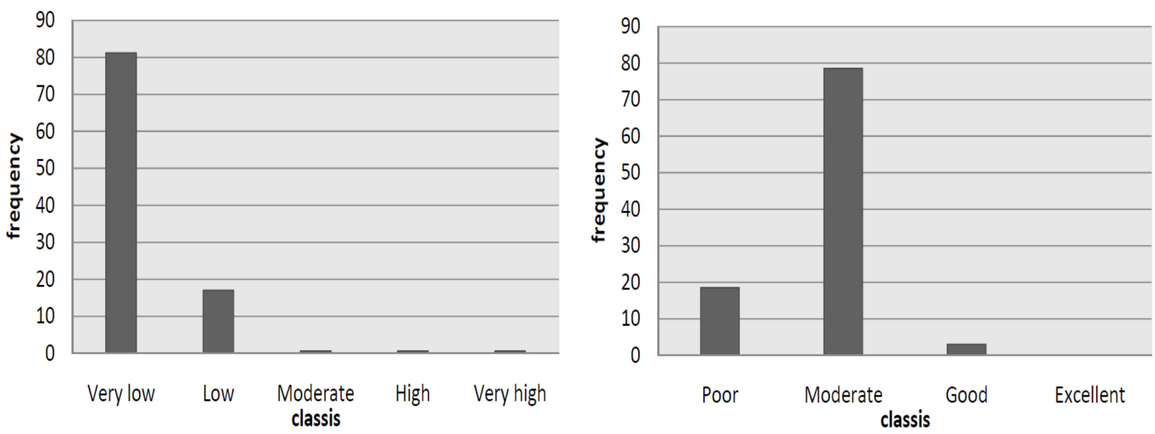


Fig. 3: Cap rocks sample classification based on CUR (right) and Nikoodel (left) criteria

As seen in Fig. 4, 99% of the igneous samples are placed in the good to excellent categories based on the CUR criterion. Based on the Nikoodel criterion, about 89% of the igneous samples obtain a high and very high score and 11% gain a moderate score. None of the samples is placed in the category of low and very low scores.

## CONCLUSION

This study compared the test results of assessing the quality of rock samples used in the construction of breakwaters with the international standard evaluation criteria. According to the results, most rocks used in the southern coastal structures do not achieve a quorum in terms of quality and therefore are not suitable for this purpose. However, field observations and the acceptable service of breakwaters constructed with such materials during the lifetime of the structure convinced us that these criteria alone are not sufficient to assess the quality of rocks. A new criterion can be developed for evaluating these rocks based on the results of this study and similar studies using past experiences in the field of breakwater design on the basis of actual performance of rock materials.

At the same time, factors such as the rock structure and its location on the structure can affect the performance of rock materials.

The performance of cap rocks is strongly influenced by the size of fossil particles and cemented materials between the particles. In the uptidal zone, fine-grained cap rocks experience less erosion than coarse-grained rocks.

The performance of sandstones is strongly influenced by their physical characteristics. The erosion of rocks with higher density is lower at lower water absorption, porosity and weight loss in sulfate. The rocks in the uptidal zone are highly erodible and thus are scaled. The rocks with good physical characteristics in tidal and flood zones are suitable for the protective layer of breakwaters.

Igneous rocks are the most appropriate rocks for constructing the protective layer of breakwaters. The performance of igneous rocks is influenced by initial cracks that may exist in the rock. In the case where there are many cracks in the rock, the erosion rate increases in the tidal and flood zones. In the uptidal zone, igneous rocks show a good performance in all conditions.

In addition to the physical characteristics, the performance of limestone is mainly affected by the constituent particles of the rock. Erosion of limestone in the uptidal zone and crown occurs through weathering and scaling. Limestone shows a poor performance in tidal and flood zones. Such rocks are experiencing erosion and rounding in the tidal zone. The strength of limestone decreases in flood zones.

Physical weathering and imposed loads showed the significant degradation effects on rock materials over the operation time. However, chemical weathering processes should not be ignored, because such processes deteriorate rock materials, especially in climatic conditions in the study area.

Secondary cracks in the rock fragments caused by the production and extraction of rocks is an important factor in non-durability and degradation of rocks used in the construction of breakwaters. Thus, proper extraction, transportation and placement is essential to prevent secondary cracks.

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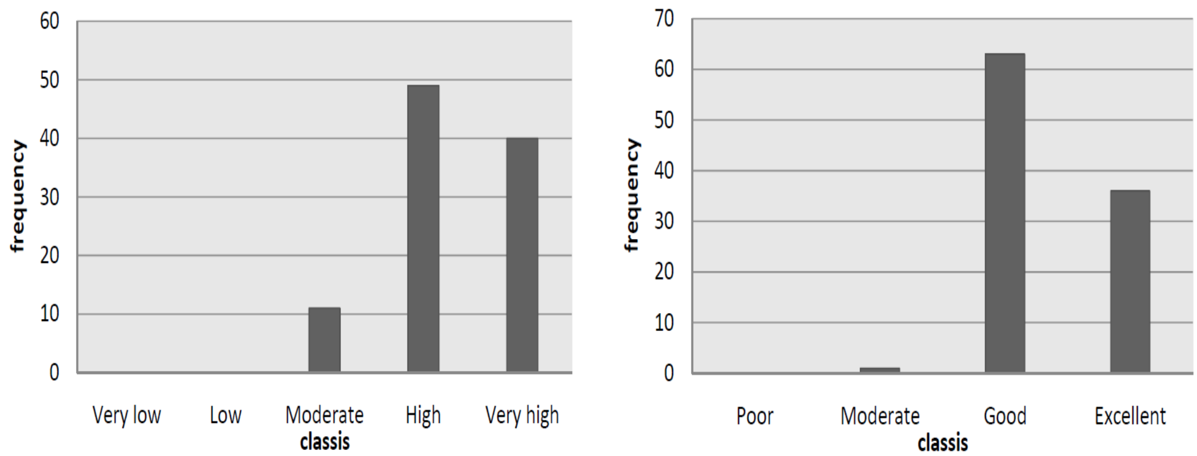


Fig. 4: Igneous rocks sample classification based on CUR (right) and Nikoodel (left) criteria

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**How to cite this article: (Harvard style)**

*Atabak, P.; Allahyaribeik, S.; Azarsina, F., (2014). Materials performance assessment of protective layer of rubble mound breakwaters, southern coast of Iran. Int. J. Mar. Sci. Eng., 4 (2), 57-64.*