CHAPTER 102

COST-EFFECTIVENESS OF D-ARMOR BREAKWATER

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ABSTRACT

The cost-effectiveness of conventional and D-armor breakwaters are compared. Initial cost and capitalized anticipated damage during the lifetime of the structure are the basic elements to be considered in the economic optimization problem. A four level structural response function and a linear initial construction cost estimation are used to define the economic function. An exponential approximation to the return period of the design wave storm with an uncertainty factor is used to estimate the economic impact of the wave climate uncertainty. Finally, the adaptative design concept is introduced considering the advantages of designing for repairing and monitoring breakwaters after construction.

INTRODUCTION

During the last two decades, a variety of large mound breakwaters have failed in many regions of the world. The Working Group PIANC-PTCII (1985) analyzed more than 160 mound breakwaters all over the world. 28% of the large breakwaters (depth> 10 m., and H_s> 6.5 m.), and 60% of the very large breakwaters (depth> 12 m., and H_s> 8.5 m.) reported, were damaged after or during construction. Most of them were built with special concrete armor units. The position of mound breakwaters worldwide may be worse, because some of the most famous breakwater failures were not analyzed in the report (see Farrow, 1988). Some breakwaters like Sines (Portugal) at 50 m. depth were totally destroyed; other breakwaters like Bilbao (Spain) were partially damaged forcing expensive reparation and reinforcement works. These experiences generated a worldwide lack of confidence in the optimistic extrapolation of the design techniques of the sixties to new deep water conditions. The last decade has been characterized by the critiques

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and controversy among different designers, constructors, researchers, and laboratories about the collapse of the old design techniques and the necessity of a significantly improved updated methodology to design mound breakwaters. We are now in a transitional phase between a traditional design methodology with a weak scientific and technical support, and a variety of new methodologies with weak real experimental support.

The cost-effective optimization of rubblemound cross sections requires an estimation of a variety of economic factors during the structural life cycle: initial construction cost, maintenance cost, economic losses due to the functional performance, capitalized costs to cover structural damages, and economic losses associated with total failure. Medina(1992a) presented a new design of a rubblemound breakwater cross section named the "D-armor breakwater", which showed similar resistance in the laboratory to the initiation of damage than conventional design but a significant increase of resistance to total failure. The characteristics of the D-armor design appears to be cost-efficient to face high uncertainties of the design wave conditions at the construction site. In this paper, a comparative analysis of the cost-efficiency of conventional and D-armor cross sections is presented. The D-armor breakwater shows a higher cost-effectiveness when uncertainty of design wave conditions and economic losses due to breakwater destruction increase.

A continuous effort has been developed towards a better understanding of the structural and hydrodynamic factors affecting the stability of rubble-mound breakwaters. There are two main goals of the research effort: a) New calculation procedures for a more reliable and accurate estimation of the structural response during the lifetime to optimize the designs; and b) New designs to reduce the construction cost, maintenance and risk of failure in its lifetime.

The design waves of a variety of maritime projects can only be estimated assuming large uncertainties. On the other hand, there are still significant differences in the calculation procedures proposed by different authors to estimate the structural response of conventional breakwaters for given wave conditions (see Medina, 1992a). Additionally, a number of concrete armor unit designs have been proposed and used in conventional cross sections. However, some of the most costly failures involved the use of special concrete armor units (Sines, San Ciprián, Tripoli, Arzew, Giona Tauro, etc.). Finally, some new breakwater cross sections are being proposed to reduce construction cost or to increase armor resistance. However, some failures have been reported recently (St. Paul berm breakwater) with only a few unconventional breakwaters actually built. This paper focuses the attention on the economic evaluation problem associated to breakwater cross sections.

A variety of alternative designs to the conventional rubblemound breakwater cross section have been proposed. The S-shape and berm type breakwaters are the most popular unconventional designs. In spite of the limited number of prototypes built according to these new designs. There is an increased number of laboratory results which indicate some of their advantages. However, the current practice for the design and construction of mound breakwaters is conservative. The frequent breakwater failures, the unknown risks associated with designs that lack experimental verification, and a general aversion to risk of most decision makers, may explain the general opposition of designers to adopt radical changes in the classic mound breakwater cross section. This paper describes the economic comparative analysis of conventional and the D-armor breakwater concept that could be extended to other breakwater designs. The general goal is to provide an objective evaluation of the economic niche of each design concept. The D-armor breakwater seems to be a robust solution to face large uncertainties associated with long term wave actions at a construction site.

D-ARMOR: A ROBUST DESIGN

Fig. 1 shows the cross sections corresponding to the Conventional (SPM, 1984), S-Shape (Ergin et al., 1989), and D-armor breakwater (Medina, 1992a). This paper compares the cost-effectiveness of D-armor and conventional mound breakwaters; the D-armor section reshapes to an efficient S-shape armor near the total failure point, and appears to be a reasonable first step towards a convenient evolution from the old conventional breakwater to more efficient designs.

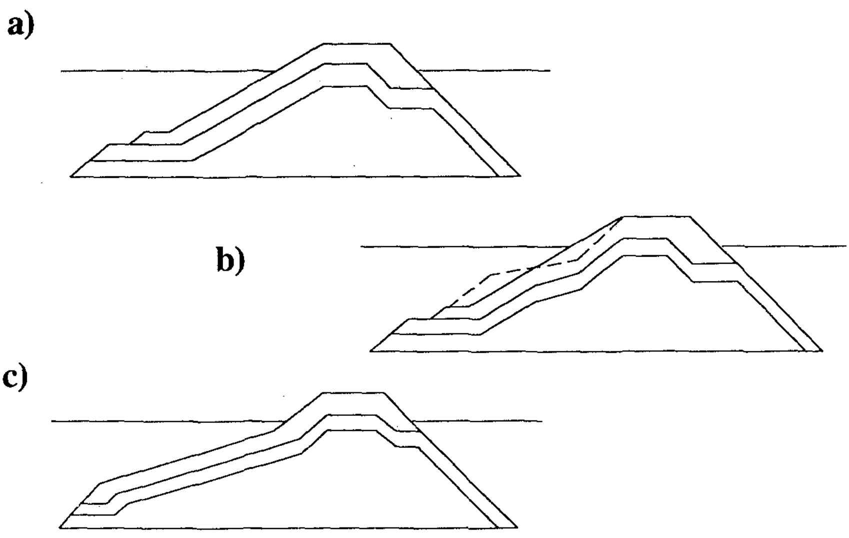

Figure 1.- Rubble-Mound Breakwater Cross Sections: a)Conventional; b)D-Armor; and c)S-Shape.

The D-armor model showed a similar initiation of damage, but a significant higher resistant capacity to total failure. Using the definition of armor damage proposed by Medina(1992a), for a structure with as much as 50% more armor erosion capability before total failure, it may be reasonable to consider a "initiation of damage" range as the identifiable damage below the extra active armor area of the D-armor section. Fig. 2 shows the failure functions corresponding to conventional and D-armor breakwater with a 2/3 reduction in the armor weight to equalize the total failure point. On the other hand, the failure function suggested by SPM(1984) for rough quarrystones fits the line

$$\frac{H_{10}}{H_d} = \left[\frac{D}{1.6}\right]^{\frac{1}{5}} \qquad (1)$$

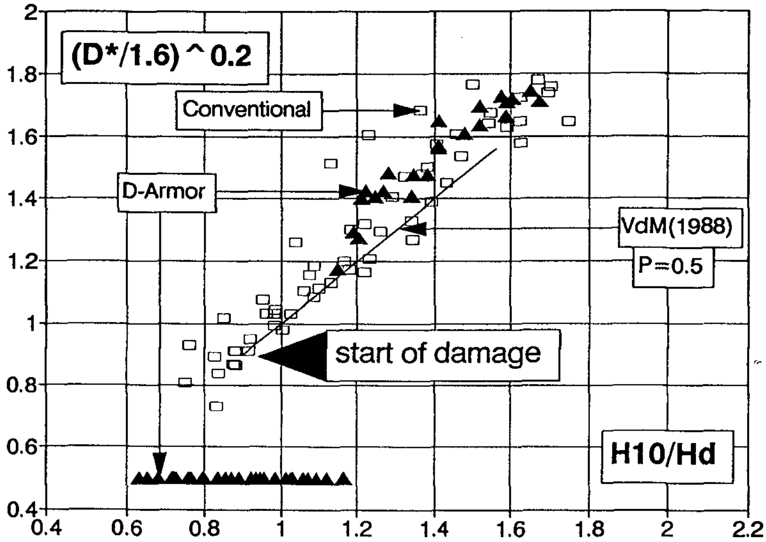

Figure 2.- Equalized Failure Functions of D-Armor and Conventional Breakwaters.

The sensitivity analysis included in the methodologies proposed by Medina(1989, 1992b) for the optimization of rubblemound breakwater cross sectional designs, increases the cost-efficiency of the resistant capacity to total failure, and the flexible structural response to wave attack shown by D-armor. On the contrary, a cost-efficient breakwater design, having brittle structural response, requires a reliable estimation of design wave conditions during its lifetime. From a structural point of view, the D-armor breakwater is similar to a conventional design with a significant increase of the armor thickness in the area where the mean water level crosses the external armor profile of uniform slope. Figs. 1-a and 1-b show the cross sections corresponding to the conventional and D-armor breakwaters.

Before damage, the external profile is the same; however, when armor erosion increases, the D-armor design progressively transforms to an S-shape breakwater (see Fig. 1-c). Because of this characteristic, the structural performance is similar to the conventional breakwater at low levels of armor erosion, but the reshaping process significantly increases the resistance capacity as an S-shape breakwater. Therefore, the D-armor design has the large structural response flexibility required to face the high levels of uncertainty usually associated with the design wave storms. Contrary to the conventional or S-shape breakwaters, the D-armor breakwater is designed to reshape significantly during its lifetime.

From the economic point of view, the structural response of conventional and D-armor breakwaters may be classified in four levels: (I) No armor movement, (II) Identifiable but acceptable armor movement (no repair needed), (III) Partial damages (repair needed but no port disruption), and (IV) Total failure (port disruption and breakwater reconstruction needed). Table 1 shows the $H_{10}/H_{D=0}$ limits defining the structural response of conventional and D-armor breakwaters.

RESPONSE	Conventional	D-Armor
I - II	0.87	0.87
II - III	1.00	1.25
III - IV	1.65	1.89

Table 1.- $H_{10}/H_{D=0}$ Corresponding to the Threshold Levels Between Different Structural Response Stages.

Most breakwaters are built at a construction site where the long term wave climate or the maximum water depth (MSL to sea bed) can only be estimated with large uncertainties. In those cases, low risk and economically-efficient solutions demand robust designs with a flexible structural response having a wide margin between initiation of damage and total destruction. To face large uncertainties in wave action, economic optimization leads to very conservative and expensive designs for brittle structural responses, and to less expensive and safer designs for flexible structural responses. In those conditions, the D-Armor breakwater seems to be a reasonable first step for a safe migration from the inefficient conventional breakwater to new structural and cost-efficient designs. It appears to have about the same construction cost at prototype scale, with higher stability and structural flexibility, making it appropriate to face high uncertainties in the design wave conditions at the construction site. Therefore, it seems to be a reasonable economically-efficient alternative to the conventional design in both deep and shallow waters.

BREAKWATER COST-EFFECTIVENESS

Three decades ago, Van der Kreeke and Paape(1964) proposed a methodology to optimize breakwaters, considering initial construction cost and capitalized anticipated damage. The optimum design was dependent on the lifetime, the failure function and the long term wave climate. Mol et al.(1983) analyzed the failure of the breakwater at Port Sines (Portugal) and found the uncertainty of the wave climate to be an important factor to be taken into consideration when designing large breakwaters. A similar conclusion was found by C.E.L.(1983), demonstrating the impact of the uncertainty of long term wave climate on the cost of breakwaters in deep water conditions. Recently, Burchart(1991) reviewed design innovations and research contributions, remarking the importance of the procedures for estimating the uncertainties associated with wave data sets, extrapolation from short data samples and lack of knowledge of the long term distributions.

The uncertainty of the long term wave climate, not taken into account in breakwater design, has been found to be responsible of major breakwater failures in the past decades. The estimation of the wave climate uncertainty and the use of safety coefficients, is a first step towards a better rationalization of the optimum breakwater design problem. More elaborate probabilistic methods, considering estimated uncertainties of the principal wave climate parameters, are the natural evolution of the methods for optimization the breakwater design. During the next decades a significant effort will be made worldwide to reduce the uncertainty of the long term wave climate. Therefore, right now it is necessary to use methods and breakwater designs to face large uncertainties in deep waters.

The cost-effectiveness of alternative breakwater cross sections have to take into account not only estimated initial cost and risk to failure during the lifetime, but also the estimated uncertainty of the principal wave climate variables and the procedures to take advantage of monitoring programs for updating the estimated anticipated capitalized damage during the lifetime. The cost-effectiveness of structures with brittle response in deep waters is critically dependent on the reliability and uncertainty of long term wave climate. On the contrary, the structures with a flexible response are not so critical to a precise description of wave climate. Furthermore, an adequate monitoring program after construction can provide valuable information for a precise evaluation of risk during the lifetime, including additional works of repair and reinforcement.

If it is not possible to minimize the uncertainties of the wave climate which critically affects the risk of failure during the lifetime, it is reasonable to face those uncertainties with robust designs and reinforcement strategies based on adequate monitoring programs. The first years after construction may be the best one to one scale test, since most failures of most breakwaters occurs during this period. An adequate design and monitoring program may be useful to limit the risk of failure and to optimize the breakwater design.

Initial Construction Cost

The initial construction cost of a breakwater depends critically on the technological and geological conditions. Although the model tests referred to rubblemound breakwaters of quarrystone, it will be assumed that the failure functions are also a reasonable first approximation for large mound breakwaters with robust concrete armor units. Some of the largest mound breakwaters with robust concrete armor units (cubic o parallelopipedic blocks) are built on the Spanish coast. Two typical Spanish breakwaters are selected to define a reasonable initial construction cost function: 1)"Dique del Este" in the Mediterranean Port of Valencia, and 2)"Dique de Zierbana" in the Atlantic Port of Bilbao.

Del Moral and Berenguer(1980) published the optimization methodology applied to the "Dique del Este" of the Port of Valencia. The water depth was about 14 m and the $\mathbf{H_{s100}} \approx 8.5$ m. The authors proposed several cross sections following the Irribarren's design criteria for different design wave conditions ($\mathbf{H_{sd}}$). Because both monetary and wave climate parameters have different meaning in different countries and years, the costs have been made dimensionless by the cost corresponding to the design for one hundred year return period. The design wave storm have been made dimensionless by that corresponding to one the hundred year return period. In the case of Valencia, the following linear function was fitted:

$$C_0(H_{sd}) \approx C_0(H_{s100})\left[1 + 1.1\left(\frac{H_{sd} - H_{s100}}{H_{s100}}\right)\right] \tag{2}$$

where $\mathbf{C_0(H_{sd})}$ is the initial construction cost for a design significant wave height of $\mathbf{H_{sd}}$, and $\mathbf{H_{s100}}$ is the significant wave height for one hundred year return period. In the Cantabric Sea open to the Atlantic Ocean, Uzcanga and González(1992) defined pre-designs for the "Dique de Zierbana" in the Port of Bilbao. The water depth was about 25 m. and the $\mathbf{H_{s100}} \approx 12$ m.. The function that fitted the cost estimation provided by the authors was:

$$C_0(H_{sd}) \approx C_0(H_{s100})\left[1 + 1.5\left(\frac{H_{sd} - H_{s100}}{H_{s100}}\right)\right] \tag{3}$$

Fig. 3 shows the dimensionless initial construction cost functions for the cases of Valencia and Bilbao. In the following, the initial construction cost of Bilbao will be used for the economic analysis of conventional and D-armor breakwaters. The economic function used to analyze the cost-effectiveness will be based on the initial construction cost function and the long term wave climate function containing an uncertainty factor. With these two basic elements, the economic problem will be reduced to define an economic function with the capitalized anticipated damages due to damages and risk to failure during the lifetime.

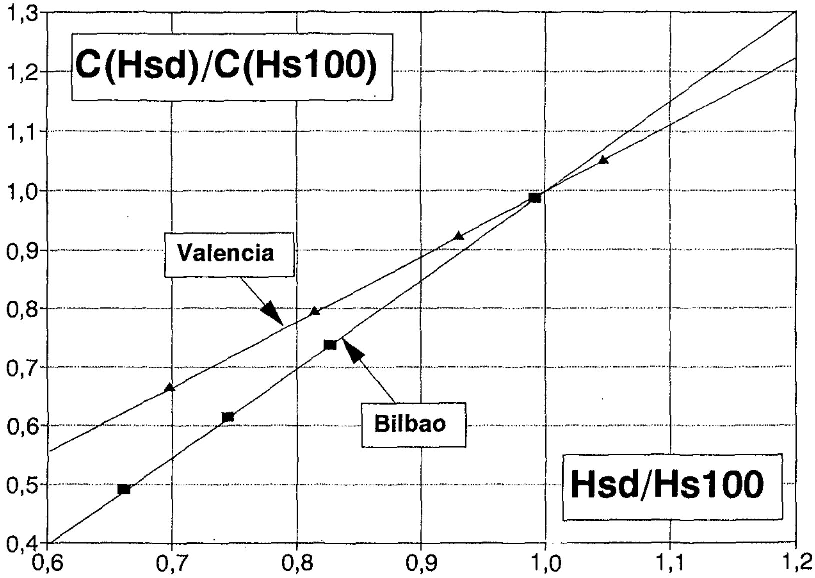

Figure 3.- Dimensionless Initial Construction Cost Functions Corresponding to Mound Breakwaters Built in Valencia and Bilbao.

Wave Climate

There are a variety of statistical methods for estimating the long term wave climate to be considered in breakwater design. However, both data and methods have an evolution in time changing the "best" estimation to be considered in design. As an example, Copeiro(1978) published a long term wave climate for Bilbao which may be approximated by the following exponential approximation for the return period: $\mathbf{R \approx exp(H_s\text{-}7.5)}$. Some years later, the Spanish Ministry of Public Works published a recommended manual for maritime design (ROM 0.3-91) with a long term wave climate for Bilbao which may be approximated by: $\mathbf{R \approx exp(H_s\text{-}6.8)}$. In the future, it is reasonable to assume that both methods and data will contribute to modify the recommended long term wave climate for different locations.

In a specific location, in a given year, only an approximation to the real long term wave climate will be available, if that long term wave climate really exists. In addition to the number of sources of risk and uncertainty affecting the long term wave climate of a specific location, some doubts still remain about the interannual stationarity of the wave climate. Therefore, a reasonable way to take into consideration the global uncertainty in the long term wave climate, is to define a model for the return period affected by an uncertainty factor, β. The higher the β, the higher uncertainty on the estimated return period for the given location is considered: If $\beta=0$, no uncertainty is considered for the wave climate.

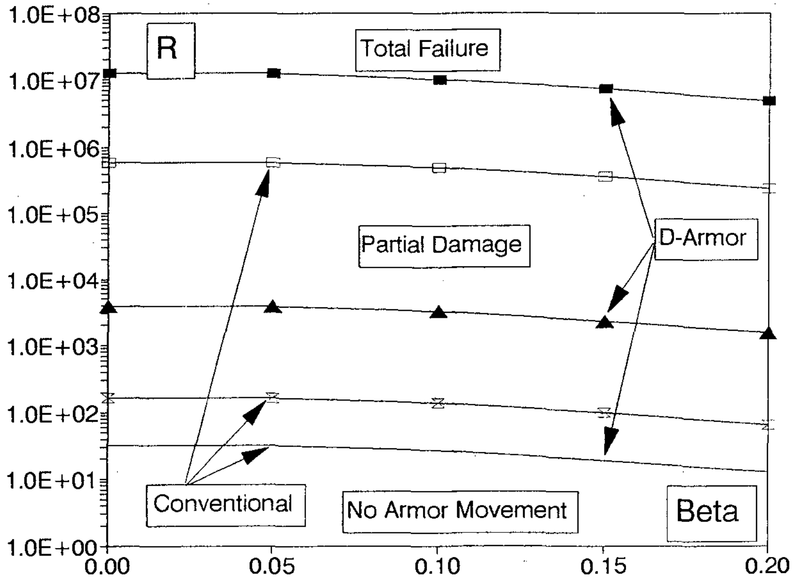

Figure 4.- Return Periods of Conventional and D-Armor Responses.

Taking as a basis an exponential approximation of the return period with a reasonable parameter, say **R ≈ exp(H_s-7.5)**, an ensemble of possible scenarios with different return period functions may be considered. Eq. 4a shows the family of return period functions to be considered and Eq. 4b the return periods to be considered depending on the uncertainty factor.

$$R_i\,(H_s) \approx \exp(H_s - 7.5 + \beta\,\omega_i H_{s100}) \tag{4a}$$

$$R(H_s,\beta) = \frac{1}{E\left[\dfrac{1}{R_i}\right]} \;;\; E[\omega_i \cdot \omega_{i+k}] = 0\,,\, k \neq 0\,;\, \sigma_\omega^2 = 1 \tag{4b}$$

Eqs. 4a,b defines a one-parameter exponential function for the return period in which the parameter is considered a Gaussian random variable with a mean given by usual wave climate estimations and a standard deviation, $\sigma(\beta w_i)=\beta$, given by qualitative assessment considering all sources of risk and uncertainty involved in the designing process. Figure 4 shows the return periods corresponding to the structural response limits shown in Table 1 for conventional and D-armor breakwaters.

Economic Function

Using the design guidelines of Iribarren, Del Moral and Berenguer(1980) proposed a number of economic ratios that were considered in the economic evaluation of the Valencia breakwater. The most important ratios were: 1)Cost of the conventional armor $\approx$ 45% cost of the conventional breakwater, 2)Value of properties defended by the breakwater $\approx$ 400% cost of the breakwater, 3)Cost of partial repair $\approx$ three times the initial construction cost, and 4)Cost of total reconstruction $\approx$ twice the initial construction cost. In addition, comparing the volume of armor stones used by Medina(1992a) in the conventional and D-armor breakwater, two additional ratios may be used in the economic function: 5)Cost of D-armor $\approx$ 50% cost of the conventional breakwater, and 6)Cost of the D-armor breakwater $\approx$ 105% cost of the conventional breakwater.

In this paper, the economic function of both conventional and D-armor breakwaters are based on the economic ratios given above, the initial construction cost given by Eq. 3, the structural responses given by Eq. 1 and Table 1, the long term wave climate given by Eqs. 4a,b and the following anticipated capitalized formula to cover risk of failure

$$C_L(H_{sd}) = C_0(H_{sd}) + ac\left[\frac{(1+i)^L - 1}{i(1+i)^L}\right] \tag{5}$$

in which **L** is the lifetime of the structure, **ac** is the annual cost to cover the risk of failure, $\mathbf{C_0}$ is the initial construction cost (including maintenance and monitoring in lifetime), $\mathbf{C_L}$ is the total cost (including repair and risk of failure), and **i** is the interest rate. The first component of Eq. 5 is an increasing function with the design significant wave height, because a larger and more expensive breakwater is required to resist a stronger design wave storm. On the contrary, the second component of Eq. 5 is a decreasing function, because the risk to failure decreases when the design significant wave height increases. Eq. 5 have a minimum value which corresponds to the optimum economic design point; however, the optimum design point depends on the selection of β, **i**, and **L**, which are based on engineering judgement. Fig. 5 shows the economic functions (**L**=100 and **i**=5%) of conventional and D-armor breakwater for different values of β. The total cost has been normalized by the initial construction cost of the conventional breakwater for the one hundred year return period significant wave height, $\mathbf{C_0(H_{s100})}$. The design wave height, H_d, is related with the design significant wave height by $\mathbf{H_d} = 1.27\ \mathbf{H_{sd}}$, which corresponds to the H_{10} of the design storm.

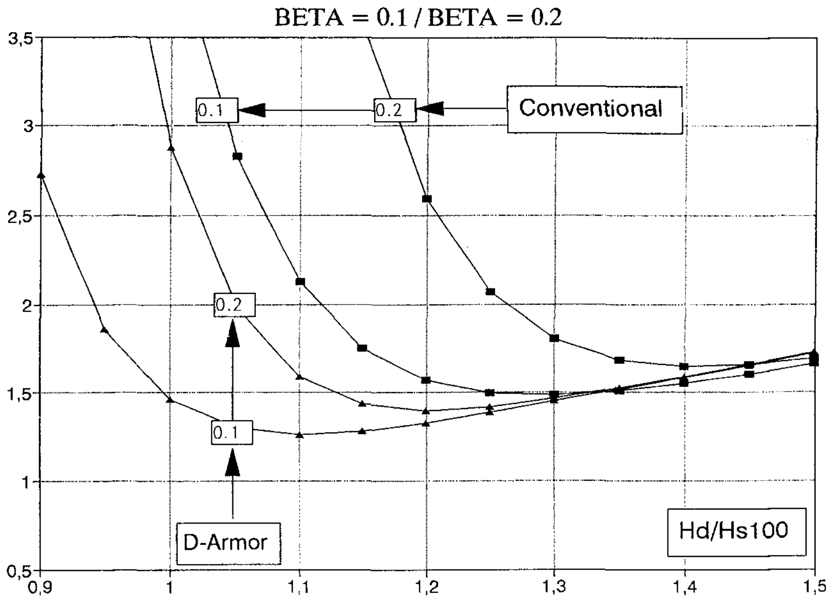

Figure 5.- Dimensionless Total Cost of Conventional and D-Armor Breakwaters (L=100, i=5%).

The optima points with minima costs shown in Fig. 5 are sensitive to the subjective selection of **L**, **i** and β. Therefore, the economic description of the conventional and D-armor alternatives would require not only the economic functions, but also a sensitivity analysis of the factors decided on the basis of judgement, specially β. A preliminary qualitative analysis of the economic functions shown in Fig. 5, shows an increase in the total cost for both the D-armor and conventional breakwaters when β increases. However, D-armor is more efficient because its economic function for $\beta=0.2$ (high uncertainty) is similar to the economic function of conventional breakwater when $\beta=0.0$ (no uncertainty).

UNCERTAINTY AND ADAPTATIVE DESIGNS

According to Medina et al.(1994), most breakwater failures occurred during construction or within a few years after construction. It is obvious that the construction phase and the few years after construction, offers a unique opportunity for a reliable estimation of the risk of failure during the lifetime. An adequate monitoring program may provide a reliable basis for a decision of re-design or structural reinforcement or repair program during the lifetime. Robust designs with flexible structural responses, like those shown in Table 1, are appropriate to put a limit on the risk to total failure during the monitoring phase. On the basis of robust designs, adaptative designs could be considered in advance to take full advantage of the information obtained during the monitoring phase after construction.

The adaptative design concept may be associated with designing for repairs. In other words, if it seems impossible to design for no damage during the lifetime, the best alternative is to design for having damage during the first years after construction. If the damage actually occurs, a structure designed to be repaired will have to be repaired. In addition, a reliable estimation of risk of failure will have been obtained during the monitoring phase during and after construction until partial damages were reported. If no damage is observed after construction, the reliable estimation of risk of failure during the lifetime obtained from the monitoring phase, will provide the guarantee that a supposed underdesigned breakwater is safe enough for the given lifetime. The economic advantage of the adaptative design concept is so evident than some engineering design strategies applied in practice may be considered in this category.

Two adaptative design alternatives were evaluated on the basis of the D-armor cross section, which was found to be robust enough to be appropriate for testing the new concept. Figs. 6 show the cross sections of the conventional and the two D-armor sections with short and long berm. The sections were very efficient in economic terms with 1.5:1 slope and less armor stone than the conventional breakwater. In order to analyze the structural performance of the two adaptative D-armor designs of Figs. 6, series of 2-D experiments were conducted at the UPV wave flume (30x1.2x1.2 m), divided in two parts to test simultaneously a conventional and a D-armor cross section with berm. A transparent glass divider was used for the verification of the same wave attack on the two cross sections during the experiments. Seven minutes of random wave generation of PM using the DSA-FFT method produced between 200 and 300 waves depending on the **Ir** value of the run. An Iribarren's number for random waves defined as $\mathbf{Ir}=[\tan\beta]/[2\pi H_{m0}/gT_{02}^2]^{0.5}$ was constant for all the runs of each test; two different values of **Ir** were used for each test (**Ir**= 2.5, 3.0). Starting from the zero-damage design wave height, $H_{10}=H_d=12$ cm, the wave height was increased 10% each run ($H_{10}=H_d\,[1.1]^k$; $k=1,2,\ldots 7$). After the seventh run, the sections were re-built to a 2/1 slope, to continue the experiment until total failure of the armor layer.

The berm were found to be reasonably stable, but the behavior of the armors were different than expected in the pre-design phase. The section with short berm showed more resistance to total failure than the section with long berm. After the reinforcement, neither the section with short berm nor the section with long berm show a significant increase of the resistance to total failure shown by the D-armor breakwater with a 2/1 slope (Medina, 1992a). On the contrary, the conventional breakwater increased the resistance to failure after the reinforcement. Additionally, the volume of armor stones required to reinforce the conventional breakwater was significantly lower than the volume required for the sections with berm. Therefore, the preliminary analysis of results, of the experiments on the two adaptative designs shown in Figs. 6, suggests than both the conventional and the original D-armor breakwater with no berm may be a better adaptative design alternative than those shown in Figs. 6.

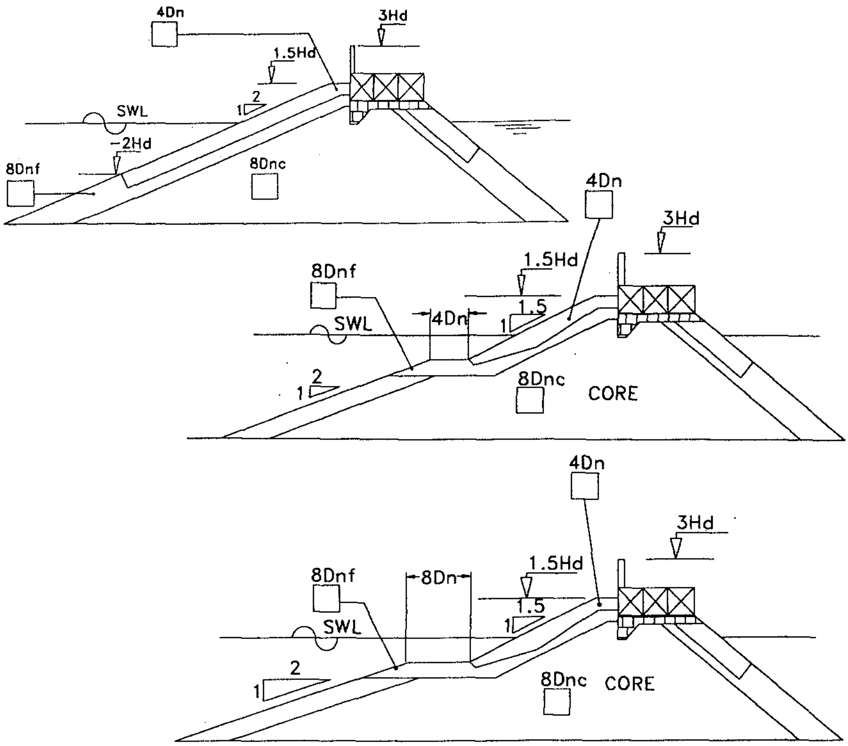

Figure 6.- **Breakwater Cross Sections: a)Conventional, b)D-Armor with Short Berm, and c)D-Armor with Long Berm.**

CONCLUSIONS

The cost-effectiveness of conventional and D-armor breakwaters are compared considering different uncertainty levels on the wave climate. In deep water conditions, robust designs with flexible structural responses, monitoring programs and adaptative design strategies after construction, appears to be the rational elements for economic optimization of breakwater design.

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