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Coastal Engineering 53 (2006) 1 – 25

Coastal Engineering
An International Journal for Coastal, Harbour and Offshore Engineers

www.elsevier.com/locate/coastaleng

An optimal engineering design method with failure rate constraints and sensitivity analysis. Application to composite breakwaters

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Received 6 December 2002; received in revised form 28 April 2005; accepted 13 September 2005
Available online 21 November 2005

Abstract

The paper introduces a new approach to composite breakwater design based on minimizing initial/construction costs subject to yearly failure rate bounds for all failure modes, and presents a technique for sensitivity analysis. The solution of the resulting optimization problem becomes complex because the evaluation of failure rates involves one optimization problem per failure mode (FORM), so that a decomposition method is used to solve the problem. In addition, a sensitivity analysis is performed, which makes it possible to determine how the cost and yearly failure rates of the optimal solution are affected by small changes in the input data values. The proposed method is illustrated by its application to the design of a composite wall under breaking and non-breaking wave conditions. The storms are assumed to be stochastic processes characterized by their maximum significant wave heights, their maximum wave heights and the associated zero-up-crossing mean periods.
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Keywords: Cost optimization; Failure probability; Modes of failure; Stochastic process; Reliability analysis; Safety factors

1. Introduction

The phases that an engineering structure undergoes are: construction, service life and dismantling. In addition, maintenance and repair take place during the service lifetime. During each of these phases, the structure and the environment undergo a continuous sequence of outcomes, the consequences of which have to be considered in the project. The objective of the design is to verify that the structure satisfies the project requirements during these phases in terms of acceptable failure rates and cost (see Losada, 1990 and ROM, 2001).

Since repair depends on the modes of failure and their occurrence frequencies, these must be defined. A mode describes the form or mechanism in which the failure of the structure or one of its elements occurs. Each mode of failure is defined by a corresponding limit state equation as, for example:

$$g_{\mathrm{m}}(x_1,x_2,\ldots,x_n) = h_{\mathrm{sm}}(x_1,x_2,\ldots,x_n) - h_{\mathrm{fm}}(x_1,x_2,\ldots,x_n);\ m\in M, \qquad (1)$$

where $(x_1, x_2, \ldots, x_n)$ refer to the values of the variables involved, $g_{\mathrm{m}}(x_1, x_2, \ldots, x_n)$ is the safety margin and $h_{\mathrm{sm}}(x_1, x_2, \ldots, x_n)$ and $h_{\mathrm{fm}}(x_1, x_2, \ldots, x_n)$ are two opposing magnitudes (such as stabilizing and mobilizing forces, strengths and stresses, etc.) that tend to prevent and produce the associated mode of failure, respectively, and M is the set of all failure modes.

In this paper it is supposed that failure occurs during storms that are assumed to be stochastic processes of random intensity, and that failure occurs when the critical variables (extreme wave heights and periods) satisfy $g_m \le 0$. Then, the probability P_{fm} of failure mode m in a given period becomes:

$$P_{\mathrm{fm}} = \int_{g_m(x_1,x_2,\ldots,x_n)\le 0} f_{X_1,X_2,\ldots,X_n}(x_1,x_2,\ldots,x_n)\,dx_1 dx_2\ldots dx_n, \qquad (2)$$

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doi:10.1016/j.coastaleng.2005.09.016

where $f_{X1,\,X2,\,\ldots,\,Xn}\,(x_1,\,x_2,\,\ldots,\,x_n)$ is the joint probability density function of all variables involved in the problem. With this information, and the consideration of all storms that may occur in a year, the different yearly failure rates for all failure modes can be estimated.

If the design variables lead to admissible failure rates, i.e., below given upper bounds, the design is said to be safe. The main advantage of probabilistic based design is that the reliability of the structure can be evaluated. However, they are very sensitive to tail assumptions (behavior of the random variables for extreme values) (see Galambos, 1987; Castillo, 1988), and in some cases, as, for example, vertical wall stability, run-up, overtopping, geotechnical stability, etc., the dependence structure and the statistical distributions of the variables involved are difficult to define.

Over the last few years, design methods have been improved by applying optimization techniques. The main advantage is that these techniques lead to optimal design and automation, i.e., the values of the design variables are provided by the optimization procedure (the optimal values) and not fixed by the engineer. Designer concerns are the constraints to be imposed on the problem and the objective function to be optimized.

Some authors consider the construction cost (Castillo et al., 2003a,b,c,d, 2004) or the total cost (construction, maintenance and repairs) as the design criteria (Van Dantzig, 1956; Voortman et al., 1998; Enevoldsen, 1991; Enevoldsen and Sorensen, 1993, 1994; Mínguez et al., in press). As one of the main purposes of the different maritime structures is to protect harbor areas from being flooded by large waves, and because they can be used in very different conditions where the consequences of a partial or complete failure are also very different, the accepted corresponding probability of failure varies considerably. However, people should not allow engineers and politicians to make their decisions based only on economic criteria. Human life, quality and service reliability, and perhaps other criteria must be considered. In fact, some constraints on the yearly failure probability rate should be imposed. The evaluation of composite breakwater reliability implies solving as many optimization problems as failure modes. Thus, use of optimization programs is not straightforward.

In some cases (see Nielsen and Burcharth, 1983) cost evaluations take into account the occurrence of failures, but taking into account the actual sequence of failures is difficult. Large storms produce at most one single failure of each type (mode) or combinations of them, because even though several of its waves (the largest) are able to produce failure, once destroyed, the breakwater cannot be destroyed again before its repair, which will take place once the storm has finished.[1] An evaluation of the number of failures must take into consideration that several dangerous sea waves normally occur during the same storm, but produce at most one failure of each type. This implies that the natural event to predict the number of failures is the storm occurrence.

In addition to requiring optimal solutions to problems, some interest is shown by people in knowing how sensitive the solutions to data values are. A sensitivity analysis provides excellent information on the extent to which a small change in the parameters or assumptions (data) modifies the resulting design (geometric dimensions, costs, reliabilities, etc.). This will be useful to: (a) the designer in order to know how sensitive the design is to the assumptions, (b) the construction engineer to know to what extent changes in the unit prices and other data modify the cost and reliabilities, and (c) the code designer to know, for example, how much a lowering of the failure rate bounds increases the cost.

Though in the literature there are efficient one-level and two-level optimization techniques for reliability-based optimization problems, see e.g. Kuschel and Rackwitz (1997, 2000), Sorensen et al. (1994b), one needs methods able to deal with failure rates and sensitivity analysis.

The aims of this paper are: (a) to introduce a new approach of composite breakwater design based on minimizing initial/construction cost subject to yearly failure rate bounds for all failure modes, and (b) to present a technique for sensitivity analysis.

The paper is structured as follows. In Section 2 the probabilistic design is described. In Section 3 the proposed method for optimal design is presented. Section 4 illustrates the proposed method by an example application dealing with the design of a composite breakwater. Section 5 is devoted to the discussion of the statistical assumptions. Section 6 presents a numerical example. Finally, Section 7 gives some conclusions.

2. The probabilistic design problem: safe and failure domains

In the design and reliability analysis of a maritime structure, there are some random variables $(X_1,\ldots,X_n)$ involved. They include geometric variables, material properties, loads, etc. In this paper, without loss of generality, we make no distinction between random and deterministic variables. So, it is assumed that all variables involved are random, and deterministic variables are only particular cases of them. They belong to an n-dimensional space, which, for each mode of failure, can be divided into two domains, the safe and the failure domains:

$$\left.\begin{array}{ll}\text{Safe}: & \mathcal{S}\equiv\{(x_1,x_2,\ldots,x_n)\}|g_m(x_1,x_2,\ldots,x_n)>0\}\\ \text{Failure}: & \mathcal{F}\equiv\{(x_1,x_2,\ldots,x_n)\}|g_m(x_1,x_2,\ldots,x_n)\leq 0\}\end{array}\right\};m\in M \tag{3}$$

where M is the set of all modes of failure m.

It is important to distinguish between design values of the random variables X_i, and their actual values x_i $(i=1,2,\ldots,n)$. The design values are those values selected by the engineer at the design stage for the geometric variables (dimensions), the material properties (strengths, stiffness, etc.), that do not necessarily correspond with those in the real work. Thus, in this paper the design values are assumed to be the means or

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[1] The case of the sliding of a caisson, which can occur many times bit by bit during a single big storm for the sake of simplicity is assumed to occur here in one go.

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