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

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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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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:

\[ g_m(x_1, x_2, \ldots, x_n) = h_m(x_1, x_2, \ldots, x_n) \]

where \( g_m(x_1, x_2, \ldots, x_n) \) refer to the values of the variables involved, \( g_m(x_1, x_2, \ldots, x_n) \) is the safety margin and \( h_m(x_1, x_2, \ldots, x_n) \) and \( h_m(x_1, x_2, \ldots, x_n) \) 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 \( g_m \leq 0 \). Then, the probability \( P_{lm} \) of failure mode \( m \) in a given period becomes:

\[ P_{lm} = \int_{g_m(x_1, x_2, \ldots, x_n) \leq 0} f(x_1, x_2, \ldots, x_n) dx_1 dx_2 \ldots dx_n, \]

where \( f(x_1, x_2, \ldots, x_n) \) is the joint probability density function of the variables.

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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:

\[
\begin{align*}
\text{Safe} : & \quad S = \left\{ \left( x_1, x_2, \ldots, x_n \right) \mid g_m(x_1, x_2, \ldots, x_n) > 0 \right\}, \quad m \in M \\
\text{Failure} : & \quad F = \left\{ \left( x_1, x_2, \ldots, x_n \right) \mid g_m(x_1, x_2, \ldots, x_n) \leq 0 \right\}
\end{align*}
\]  

(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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