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Genetic programming and floating boom performance

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ABSTRACT

In this paper the performance of floating booms under waves and currents is investigated by means of genetic programming (GP). This artificial intelligence (AI) technique is used to establish a mathematical expression of the significant effective draft, an essential parameter in predicting the containment capability of floating booms, and more specifically the occurrence of drainage failure. Obtained by applying GP to a comprehensive dataset of wave–current flume experiments, the expression makes the relationships among the relevant variables explicit – an advantage relative to other AI techniques such as artificial neural networks (ANN). The expression was selected as the most adequate to represent this physical problem from various expressions generated in two different stages in which dimensional and dimensionless variables were considered as input and output variables respectively. The most representative expressions obtained in both stages are presented and compared taking into account their goodness-of-fit, physical meaning, coherence and complexity. In addition, the adjustment with the experimental data obtained with these expressions is also discussed and compared with a previously developed ANN model.

1. Introduction

Floating booms are widely used for controlling oil spills. They are key to the most usual oil spill response method, mechanical containment and recovery (Ventikos et al., 2004; Oebius, 1999). With this method, oil spills are contained by floating booms and subsequently removed from the water surface by means of skimmers.

Oil spills can have different causes, e.g., maritime transport or oil platform accidents, oil leaks at port terminals, etc. (Vanem et al., 2008). The improvements in safety measures in the last decades have resulted in a reduction in both the number of tanker accidents involving oil spills and their importance in terms of oil volume spilled (Burgherr, 2007). However, it is certain that the possibility of new oil spills cannot be ruled out, especially in certain areas (Vieites et al., 2004).

When an oil spill happens it is essential that it should be contained as soon as possible with the objective of protecting coastal and marine ecosystems from environmental damage. The efficiency of the containment operation depends on the ability of floating booms to fulfill their role. Their containment capability is usually satisfactory in port basins or estuaries sheltered from the action of currents, waves and winds, but often insufficient in unsheltered waters. Under these conditions the efficiency of floating booms can be drastically reduced, and different modes of failure can occur (Amini et al., 2008).

One of the most important containment failures is the drainage failure. This mode of failure (Fig. 1) occurs when the contaminant escapes underneath the boom due to an insufficient effective draft (D_e) which represents the boom draft available at a certain time. The effective draft depends on the boom motions induced by the action of waves, currents and winds and the free surface displacements. Owing to this fact, it is essential to have available tools for predicting the performance of floating booms under these actions in terms of effective draft to prevent drainage failure.

Drainage failure on floating booms was previously investigated considering different approaches. A large majority of research works dealing with this subject studied this failure by means of fixed physical or numerical models without taking into account the boom motions despite their importance, (Fang and Wong, 2000; Lau and Moir, 1979; Moloney, 1996; Wilkinson, 1972). In these works, the geometries of the models were usually very simple, for example, a vertical plate, and the only action considered was generally the current. Wave action and their effect on the effective draft due the induced boom motions were taking into account so far in just a few researches. Numerical models were developed based on potential-flow assumption to analyze the reduction on the effective draft due to the relative vertical displacements between the boom model and the free surface (Cho and Cho, 1995; Lee and Kang, 1997). However, it is well known that the response of a boom under waves is not limited to vertical displacements due to the vertical motion of the free surface, roll motions induced by dynamic effects of waves and currents can be also very important, being a potential cause of considerable reductions on the

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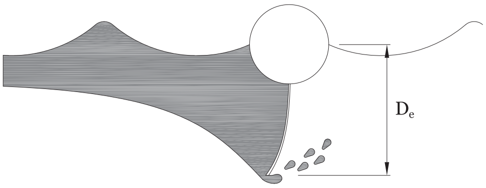

Fig. 1. Schematic of drainage failure including effective boom draft.

available effective draft. So far, only a few research studies have investigated the performance of floating booms considering the influence of both motions, vertical and roll motion, on the effective draft (Kim et al., 1998; Castro et al., 2010).

In this work, the performance of floating booms in terms of effective draft is investigated using a new approach based on genetic programming (GP). This technique of artificial intelligence (AI) was previously applied with very good results in other Civil Engineering fields (Pérez et al., 2012, 2010). GP can provide mathematical expressions to explain the fundamentals of a certain physical problem, making explicit the relationships between the variables involved. In this particular case, this approach was used to obtain a mathematical expression to predict a representative value of effective draft that will be expected for a certain boom design under a given combination of wave and current conditions.

This expression was extracted using GP from experimental data obtained from an extensive laboratory campaign in which the performance of seven floating boom designs was investigated using physical models at a 1:10 scale in a laboratory flume (Castro et al., 2010). The models, consisting on three typical elements: a cylindrical float, a vertical skirt and a weight acting as ballast, were allowed to move freely in presence of both waves and currents, as move the prototypes. In order to determine the time evolution of the effective draft during the tests, a Computer Vision System was used to record the free surface position and the motions of the boom models in a nonintrusive manner (Iglesias et al., 2009a). The boom performance in each test was characterized using a statistic of the effective draft time records, the significant effective draft, which will be the target variable for the GP.

GP was applied to obtain mathematical expressions in two different stages. In the stage #1, the variables considered as inputs and output were the original dimensional parameters related to the fundamental characteristics of both boom design and wave and current conditions. Instead, in the stage #2, the variables selected were dimensionless parameters developed in a previous work (Iglesias et al., 2010a) in which another AI technique, artificial neural networks (ANN), widely used in Naval and Maritime Engineering problems (Castro et al., 2014, 2011; Hashemi et al., 2010; López and Iglesias, 2014, 2013; Iglesias et al., 2010b, 2009b, 2009c, 2008; Ok et al., 2007) was applied to investigate the floating boom performance.

The most significant expressions produced by the GP in both stages are presented and commented considering different factors: goodness-of-fit, complexity, physical meaning, coherence, etc. Moreover, the goodness-of-fit results obtained with these expressions are compared with those corresponding to the ANN model, discussing the pros and cons of both powerful AI methods. Finally, the GP expression that emerged as the most appropriate is proposed for predicting the performance of floating booms in terms of significant effective draft.

2. Materials and methods

2.1. Experimental data

The experimental data used in this work were obtained from a previous laboratory campaign in which a large number of physical tests involving seven boom models subjected to different wave and current conditions were conducted. These tests are briefly described in this section. Further information regarding the laboratory campaign can be found in Castro et al. (2010).

Tests were conducted in the laboratory flume of the University of Santiago de Compostela. The flume is 20 m long and 0.65 m wide, with a maximum water depth of 0.8 m. A piston-type paddle equipped with a system for absorbing reflected waves and a reversible pumping system permit to generate different wave and current conditions respectively. In addition, at the end of the flume, an artificial beach consisting on a porous ramp with a 1:15 slope serves to dissipate wave energy, minimizing wave reflection.

Seven model booms representing different boom geometries and buoyancy–weight ratios at a 1:10 scale were tested. The models consisted on a cylindrical float with a diameter of 8.0 cm made in polystyrene to provide buoyancy and a vertical skirt made on PVC with two possible lengths: 8.0 cm or 12.0 cm (Fig. 2). In addition, ballast was added to the models by attaching a variable number of stainless steel sheets to the end of the skirt, simulating different values of buoyancy–weight ratio (B/W). In this manner, the models presented different values of initial draft (D_0) and buoyancy–weight ratio (B/W) that allow studying their effects on the boom performance.

The boom model was held in this longitudinal position in the flume by means of four mooring lines (Fig. 3), two lines on each side of the model connected to the float, permitting to the model to move vertically and rotate freely with the waves.

A water depth of 0.55 m was used during the tests. The free surface displacements were measured by means of wave gauges located at five positions along the longitudinal axis of the flume. Both regular and irregular wave conditions were tested. However, taking into account that the number of irregular tests was lower than the corresponding to the regular tests, only the data obtained from regular tests were considered in this work to develop the GP models, in a similar way as it was done with the ANN model.

Regular tests provide a dataset comprised by 210 data, of which 189 were combinations of various wave and current conditions and the remaining 21 corresponded to tests under current alone (no waves). The data covered all possible combinations of the seven model booms with four values of prototype wave heights (0 m, 0.25 m, 0.5 m and 1.0 m), wave periods (4 s, 6 s and 8 s) and current velocities (0 ms^{-1}, 0.26 ms^{-1} and 0.52 ms^{-1}).

The model motions (heave and roll) and the free surface elevation adjacent to the model were measured in a nonintrusive manner by means of a Computer Vision System based on the analysis of digital images. This system, developed ad hoc for the laboratory campaign, uses a set of processing algorithms to extract information from images recorded with a digital video camera, providing the information needed to determine the effective boom draft at each time step during the tests (Fig. 4).

For each test, the effective draft is calculated using the following expression:

$$D_{e.i} = (D_0 + d_0)\cos\,\theta_i - d_i \tag{1}$$

where the subindex i denotes the time step number, $D_{e,i}$ is the effective draft, D_0 is the initial draft, d_0 is the vertical distance between the cylinder axis and the free surface at rest (Fig. 5), and

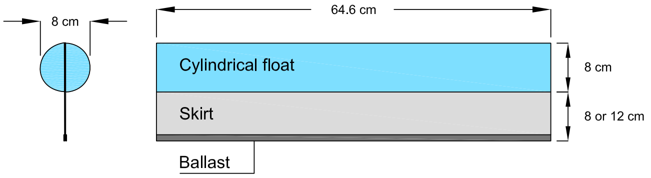

Fig. 2. Geometrical parameters of floating boom models (model values).