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Review

Fuzzy logic approach to conventional rubble mound structures design

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ABSTRACT

Stability of rock slopes are usually evaluated by empirical formulae, none of which deal with uncertainties. In fact, stability number and damage level are closely related random variables and their relationship can best be modeled by methods that explicitly take uncertainty into account as vagueness, ambiguities, and imprecision. Fuzzy logic (FL) approach is one of these methods that can deal with nonlinear, complex and uncertain systems. In this paper, the use of non-traditional FL technique is employed as a means to develop efficient predictive model for designing conventional rubble mound structures. A total of 579 experimental small and large scale test data from Van der Meer are used for calibration and verification. FL model results are compared with empirical Van der Meer model in addition to the artificial neural network (ANN) model of Mase et al. It is shown that one can forecast the stability number of conventional rubble mound structures with more significant accuracy by the FL approach than previous models.

1. Introduction

Extensive research has been conducted on design of breakwater armor layer stability all over the world for a long time. Most of the design formulae have been developed based on physical model tests under monochromatic waves. Hudson (1958) following the pioneering work of Iribarren (1938) determined the parameters affecting the armor layer stability and obtained the well-known empirical formula for predicting the weight of an individual armor unit in the cover layer of rubble mound structures using dimensional analysis. The formula has been widely used because of its simplicity. However, it does not take into account many effective factors such as wave period, number of waves attacking structure, porosity of underlayer material, and damage level. In 1980s, the number of testing facilities which have ability to generate random waves became so large that the necessity of new design formulas became evident. Van der Meer (1988) investigated the influence of several relevant parameters. Based on the earlier work of Thompson and Shuttler (1976) an extensive series of irregular wave model tests were carried out by Van der Meer (1988). These studies made a breakthrough in the design of conventional rubble mound breakwater because the new stability model was based on irregular waves. His method has been accepted throughout the engineering community due to its explicit inclusion of wave period, structure permeability, storm duration and damage for a single design storm. Mase, Sakamoto, and Sakai (1995) developed two ANN models to forecast the stability number and damage level, using randomly chosen 100 experimental data out of 579 data set of Van der Meer (1988). The parameters included several important wave–structure characteristics, such as the stability number, damage level, number of waves impinging the structure, dimensionless water depth, d/H_s, at the toe of the structure, surf similarity parameter, permeability of structure and spectral shape parameter. It was found that the ANN method produced better estimates of the damage level with smaller bias than those obtained from the application of the Van der Meer's empirical formula. However, the estimated stability numbers became lower than Van der Meer's empirical model. Kim and Park (2005) proposed several ANN models to predict stability number and compared their results with that of Van der Meer and Mase et al., by using 641 data of Van der Meer (1988), including data with low crested structures. To date, it is worth to note that, when design of conventional rubble mound structures are taken into consideration, only Van der Meer's stability equation performed the best under irregular wave conditions. However, distribution of measured and predicted values around the perfect model line (45° line) can not be negligible (see Fig. 2), which is an indication of uncertainty of the mutual wave–breakwater interaction inherent in the dynamic system. Due to the uncertainty of the predicted stability numbers there would be substantial increases in the construction cost.

It is, therefore, required to develop a model that expilicitly takes uncertainty into account. It seems that there is no study on the application of FL in predicting stability number. Contrary to all the previous works, herein a fuzzy algorithm is proposed for representing the stability number and damage level relationship in the form of a set of IF-THEN rules rather than mathematical equations.

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The model is calibrated and tested using 579 measured data of Van der Meer (1988) and then compared with the empirical model of Van der Meer (1988) and ANN model of Mase et al. (1995). The algorithm developed in this study can be applied in any part of the world within the conditions tested by Van der Meer (1988).

2. Models in conventional rubble mound breakwater design

2.1. Van der Meer's approach in comparison with the Hudson's method

Using Thompson and Shuttler's riprap stability data and data from his own experiments, Van der Meer (1988) developed an empirical stability model, which included wave period, so-called structure permeability, storm duration, damage parameter and breaking wave conditions.

Van der Meer formulae, developed with data from the laboratory test results carried out with irregular sea states, can take into account the damage level, permeability of structure and number of waves. His formulae for the stability number was given by,

$$N_S = 6.2S^{0.2}P^{0.18}N_z^{-0.1}\xi_m^{-0.5} \quad \text{Plunging waves}: \xi_m < \xi_{mc}, \tag{1}$$

$$N_S = 1.0S^{0.2}P^{-0.13}N_z^{-0.1}\sqrt{\cot\alpha}\,\xi_m^P \quad \text{Surging waves}: \xi_m > \xi_{mc}, \tag{2}$$

where P = Permeability coefficient; N_z = Number of waves; α = Slope angle; and N_S is the stability number defined as

$$N_S = \frac{H_S}{\Delta D_{n50}}$$

in which H_S = Significant wave hight in front of breakwater; D_{n50} = Equivalent cube length of median rock; $\Delta = (\rho_s/\rho_w) - 1$; where ρ_s = Mass density of rocks; and finally ρ_w = Mass density of water. Herein, ξ_m is the surf similarity parameter defined as

$$\varepsilon_m = \frac{\tan\alpha}{\sqrt{2\pi H_S/gT_m^2}}$$

in which T_m = Mean wave period. Transition condition of surf similarity parameter occurs as

$$\xi_{mc} = (6.2P^{0.31}(\tan\alpha)^{0.5})^{1/(P+0.5)}.$$

In Eqs. (1) and (2), S is the damage parameter defined as the quotient between the average eroded area in the breakwater's sections, A_e and the square of the armour stone size, D_{n50}^2 as

$$S = \frac{A_e}{D_{n50}^2}.$$

The permeability parameter P in Eqs. (1) and (2) is defined in terms of the armour, sublayers and core rubble gradations (see Fig. 3.25 in Van der Meer, 1988). The suggested values of P range from 0.1 for a relatively impermeable core to 0.6 for a homogeneous rock structure. It must be noticed that P values are only assumed by curve-fitting procedure and not related to the actual core permeability.

He then validated the developed formula against Hudson's (1958) approach. The verification of the proposed model is achieved through the comparison of the scatter diagrams of each empirical equation proposed by him with scatter diagram of empirical equation by Hudson (1958) by using his test data (see Figs. 3.26, 3.27 and 3.28 in Van der Meer, 1988). His study demonstrated that Van der Meer's empirical model can be used to estimate the stability number with a superiour performance to that of Hudson.

2.2. Mase et al.'s approach (1995)

They constructed two ANN models, each of which is trained with the randomly selected 100 data out of 579 data of Van der Meer (1988), in order to forecast the stability number and damage level, respectively. In their ANN models seven parameters, namely, permeability of structure, surf similarity parameter, damage level, stability number, number of waves, spectral shape, and depth to significant hight ratio at the toe of the structure, are used to build the structure. The proposed models are tested with the data set of Van der Meer (1988) and Smith et al. (1992), which cover 579 and 30 data values, respectively. Correlation coefficient of each model is calculated and used as an evaluation criterion to compare their results with the empirical model of Van der Meer (1988). As a result, their approach to estimate damage level is shown to improve significantly upon the Van der Meer's model. However, the estimations of stability numbers are a little bit lower compared to Van der Meer's formula (see Figs. 2 and 3). Consequently, only Van der Meer's stability model, in the confines of the test data conducted by him, can predict stability numbers more accurately than Hudson (1958) and Mase et al.'s (1995) models.

3. Evaluation of previous breakwater stability models

Breakwaters are high-priced structures, and hence predicting stability numbers are of vital importance. Uncertainties in the dynamic system surely increase construction costs (Kim & Park, 2005). Significant cost savings can be achieved by predicting stability number more close to the real conditions. Therefore, an advanced prediction model for the stability number is a prerequisite. Scatter diagram of observed and predicted stability numbers by the empirical formula of Van der Meer with 45° straight line shows that there is a remarkable scatter due to uncertainties (see Fig. 2). By utilizing 579 experimental data of Van der Meer, forecasting accuracy of Van der Meer's empirical model is obtained with coefficient of determination, R^2, 89.5%.

The accuracy of the stability model can be achieved better by addressing the following assumptions implied in the empirical model of Van der Meer.

1. Most of the studies in the area of breakwater design do not consider scatter diagram of input versus output, but a direct application of the regression analysis is employed to derive the relevant equation. Van der Meer (1988) used regression analysis to model stability number from the various related factors such as number of attacking waves, damage level, surf similarity parameter, permeability of the structure, and slope angle. However, this analysis includes strict assumptions such as normal distribution and constant variance (Sen & Altunkaynak, 2006). In these applications, the underlying assumptions of regression analysis are violated. Hence, the widely used regression technique cannot take into account, or solve, uncertainty concerning the measured data and the relations between the system components in wave–breakwater interaction, without considering dynamic response of the complex system. It is clear from the Fig. 1 that measured damage level (Van der Meer, 1988) do not fit the normal probability plot. This implies that the system dynamic is already restricted by a deterministic expression of Van der Meer. Van der Meer (1988) admits that one of the reasons in the spreading of stability results could be due to curve-fitting procedure. In order to characterize the process behaviour, it is indispensable to propose alternative approaches involving dynamic behaviour of the system such as FL methodology.
2. As stated by Van der Meer (1988), almost all structural parameters have an influence on the complicated dynamic system. Most of the formulations are derived by ignoring some of the factors affecting the structures. Each one of these factors contributes to the relationship between stability number and