Coastal Engineering 121 (2017) 107–118

Contents lists available at ScienceDirect

Coastal Engineering

journal homepage: www.elsevier.com/locate/coastaleng

Prediction of non-breaking wave induced scour depth at the trunk section of breakwaters using Genetic Programming and Artificial Neural Networks

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ARTICLE INFO

Keywords:
Scour
Non-breaking waves
Genetic Programming (GP)
Artificial Neural Networks (ANNs)
Breakwater
Uncertainty assessment

ABSTRACT

Scour may act as a threat to coastal structures stability and reduce their functionality. Thus, protection against scour can guarantee these structures' intended performance, which can be achieved by the accurate prediction of the maximum scour depth. Since the hydrodynamics of scour is very complex, existing formulas cannot produce good predictions. Therefore, in this paper, Genetic Programming (GP) and Artificial Neural Networks (ANNs) have been used to predict the maximum scour depth at breakwaters due to non-breaking waves (S_{max}/H_{nb}). The models have been built using the relative water depth at the toe (h_{toe}/L_{nb}), the Shields parameter (θ), the non-breaking wave steepness (H_{nb}/L_{nb}), and the reflection coefficient (Cr), where in the case of irregular waves, H_{nb}=H_{rms}, T_{nb}=T_{peak} and L_{nb} is the wavelength associated with the peak period (L_{nb}=L_p). 95 experimental datasets gathered from published literature on small-scale experiments have been used to develop the GP and ANNs models. The results indicate that the developed models perform significantly better than the empirical formulas derived from the mentioned experiments. The GP model is to be preferred, because it performed marginally better than the ANNs model and also produced an accurate and physically-sound equation for the prediction of the maximum scour depth. Furthermore, the average percentage change (APC) of input parameters in the GP and ANNs models shows that the maximum scour depth dependence on the reflection coefficient is larger than that of other input parameters.

1. Introduction

Coastal structures such as breakwaters are constructed to protect harbors and vessels from wave attacks. Proper and optimum initial design of these structures can eliminate the main construction problems, such as the structure instability, which could cause significant unforeseen expenditure. Therefore, optimizing the design of coastal structures is fundamental.

Scour, which may act as a threat to the stability and functionality of marine structures, is one of the main reasons for the failure of coastal [11,17,23,31] and offshore (e.g. [21,22] structures. Therefore, protecting structures against scour is critical in the construction of well-functioning man made harbors. To do this, the accurate prediction of maximum scour depth at coastal structures has inevitable importance. Although several studies have been conducted on scour at coastal structures, the complexity of onshore hydrodynamic and complex interaction between incoming waves, bed sediments and structure has impeded the accurate maximum scour depth prediction. Scour at breakwaters or seawalls (vertical or inclined) can be categorized into two main classes: scour at the head of coastal structures; and scour at the trunk section of coastal structures (due to breaking or non-breaking waves). Since the present paper focuses on predicting of the maximum scour depth at breakwaters due to non-breaking waves (hereafter S_{max}), only the non-breaking wave-induced scour depth at the trunk section of coastal structures has been discussed here. It is noted that S_{max} is the ultimate value of scour depth when the equilibrium bottom profile is reached and it is independent of time.

Scour at inclined and vertical breakwaters due to non-breaking

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http://dx.doi.org/10.1016/j.coastaleng.2016.12.008
Received 19 August 2016; Received in revised form 3 December 2016; Accepted 29 December 2016
0378-3839/

waves was investigated in several studies based on small-scale experiments. Sawaragi [28] and Baquerizo and Losada [5] investigated the relation between the wave reflection and the equilibrium scour depth at a rubble-mound breakwater and suggested that the scour depth becomes larger with the increase of the reflection coefficient (Cr). Similarly, using small-scale experiments, Oumeraci [23] studied the effect of breakwater slope on $S_{\max}$ and suggested that the maximum scour depth in front of a vertical breakwater is larger than that at sloped breakwaters. Furthermore, he indicated that the key mechanism for scour due to non-breaking waves is the action of standing waves (fully or partially), which leads to a steady streaming pattern. Carter et al. [6] investigated the regular and irregular wave-induced scour depth at vertical breakwaters, and showed that the scour and deposition pattern in front of the vertical breakwaters emerges in the form of alternating scour and deposition developing parallel to the shoreline. This finding has also been obtained by Baquerizo and Losada [5].

Soft computing approaches like Artificial Neural Networks (ANNs) and Genetic Programming (GP) have been successfully employed for the prediction of scour depth in various fields of coastal engineering, such as the estimation of scour depth below free overfall spillways [27], the estimation of scour around submarine pipelines [14], the prediction of scour depth under live-bed conditions at river confluences [4], the prediction of scour depth in bridges [1], the prediction of scour at a bridge abutment [2], the determination of the most important parameters on scour at coastal structures [33]; [25], the study of scour below submerged pipeline [3]. Regarding the mentioned studies, GP and ANNs can predict scour depth at coastal structures with high precision, and, to the best knowledge of the authors, these approaches have not been implemented in the prediction of the $S_{\max}$. Therefore, ANNs and GP have been used in this study as robust and promising tools. Furthermore, GP is capable of producing physically-sound and accurate solutions in the form of mathematical equations. Using this capability of GP, a new formula was developed for the prediction of $S_{\max}$.

This study is structured as follows: Section 2 shows the overview of scour governing parameters; Section 3 presents ANNs and GP concepts. The modeling approach and the data at the basis of the analyses are reported in Section 3; the results and discussions are given in Section 4; the sensitivity analysis is given in Section 5 and finally Section 6 contains this study summary and the conclusion.

2. Scour governing variables and formulas

Scour at the trunk section of breakwaters due to non-breaking waves depends on three classes of parameters: the wave characteristics, the sediment properties and the breakwater configuration. Several small-scale experimental studies are available that provide useful information about the governing parameters of scour at breakwaters. Among the most important experimental studies that also led to empirical formulas to predict scour depth we find the following.

Xie [32] examined the scouring profile of a bed consisting of fine and coarse sediments at a vertical breakwater. Xie's [32] experiments were performed using four different sediment diameters d_{50}=0.106, 0.150, 0.200, and 0.780 mm, d_{50} being the mean diameter of bed sediments. The fall velocities (V_s) associated with d_{50}=0.106, 0.150, 0.200, and 0.780 mm are V_s= 0.7, 1.5, 2.2, and 11 cm/s., respectively. He showed that the scour profile is utterly different for fine and coarse sediments depending on the waves' characteristics. In the case of fine material (suspension mode of sand transport), the bed sediments move in suspension from the node towards the antinode, while in the case of relatively coarse sand (bedload inception), the sediments transport are governed by the bed shear and scour occurs halfway between the node and the antinode, and deposition at the node, this finding is in line with De best et al. [7] results. Xie proposed the following threshold for bedload inception:

$$\frac{U_{\max} - U_{cr}}{V_s} \le 16.5 \tag{1}$$

where U_{max} is the maximum value of the orbital velocity at the bed, U_{cr} is the critical velocity for initiation of the bed sediments motion and V_s is the sand grain fall velocity. The bed sediments are transported in suspension mode (fine sediments) when $U_{\max} - U_{cr}/V_s > 16.5$.

Based on the results of mobile-bed flume experiments, Xie [32] proposed Eq. (2) for the prediction of the maximum scour depth at vertical breakwaters:

$$\frac{S_{\max}}{H_{nb}} = \frac{C}{\left(\sinh \frac{2\pi h}{L_{nb}}\right)^{1.35}} \tag{2}$$

where $S_{\max}$ is the maximum scour depth (the ultimate value of scour depth when the equilibrium bottom profile is reached), H_{nb} is the non-breaking wave height (both regular and irregular waves analysed), h is the still water depth in deepwater and L_{nb} is the non-breaking wave length (regular or irregular), and $C = 0.3$ (suspension mode of sand transport) for fine sediments and $C = 0.4$ (bedload mode of sand transport) for coarse sediments. In the following the subscript "nb" means "non-breaking" and it is employed to clarify that this study focuses on the scour induced by non-breaking waves. In the case of random waves or irregular waves, H_{nb}=H_{rms}, T_{nb}=T_{peak} and L_{nb} is the wavelength associated with the peak period (L_{nb}= L_p).

Eq. (2) was proposed to describe the action of fully standing waves condition, thus the effect of the structural configuration, such as the breakwater slope, was not accounted for. Although this formula is very limited in application, it was the basis for subsequent investigations. To amend Xie's [32] formula deficiencies, Sumer and Fredsøe [29] conducted some wave flume small-scale experimental studies on scour at rubble-mound and vertical breakwaters. They concluded that the wave reflection is the most important phenomenon accounting for the effects of breakwater slope and structural configuration, and, thus, suggested the following empirical equation to predict the maximum scour depth at a vertical or a rubble-mound breakwater:

$$\frac{S_{\max}}{H_{nb}} = \frac{0.3 - 1.77\exp(-\frac{\alpha}{15})}{\left(\sinh \frac{2\pi h}{L_{nb}}\right)^{1.35}} \tag{3}$$

where α is the breakwater slope in the range of 30–90°. Eq. (3) includes the effect of the breakwater slope, while the effects of structural configuration, breakwater submergence and permeability, sediments properties and bed slope were not accounted for.

Lee and Mizutani [16] investigated the scour at vertical submerged breakwaters. In agreement with Sumer and Fredsøes' [29] findings, they introduced the reflection coefficient as the main parameter affecting the scour depth. Their proposed formula is as follows:

$$\frac{S_{\max}}{H_{nb}} = \frac{0.06}{(1 - Cr)\left(\sinh \frac{2\pi h}{L_{nb}}\right)^{2.04}} \tag{4}$$

where Cr is the reflection coefficient.

This equation accounts for the structural configuration, the relative water depth at the toe of the breakwater and the wave height. However, it cannot be used to predict the scour depth for fully standing waves since it diverges when $Cr = 1$. Furthermore, it does not give account of the sediment-waves interactions, since sediment properties do not appear in (4).

The aforementioned studies experimentally investigated the non-breaking wave-induced scour at breakwaters and developed regression-based empirical formulas to predict $S_{\max}$. However, the proposed equations do not include the effects of all important parameters for scouring; also they do not have adequate accuracy and wide applicability in predicting $S_{\max}$. Hence, developing accurate and robust