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Estimation of scour around submarine pipelines with Artificial Neural Network

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ABSTRACT

The process of scour around submarine pipelines laid on mobile beds is complicated due to physical processes arising from the triple interaction of waves/currents, beds and pipelines. This paper presents Artificial Neural Network (ANN) models for predicting the scour depth beneath submarine pipelines for different storm conditions. The storm conditions are considered for both regular and irregular wave attacks. The developed models use the Feed Forward Back Propagation (FFBP) Artificial Neural Network (ANN) technique. The training, validation and testing data are selected from appropriate experimental data collected in this study. Various estimation models were developed using both deep water wave parameters and local wave parameters. Alternative ANN models with different inputs and neuron numbers were evaluated by determining the best models using a trial and error approach. The estimation results show good agreement with measurements.

1. Introduction

Pipelines are widely used for transporting liquids and gases. Pipelines laid on erodible seabeds in coastal areas are exposed to wave and current action. The interaction between submarine pipelines, the erodible bed and the flow from waves and currents creates complicated flow patterns. Gaps will develop under a pipeline installed on an initially flat plane bed due to scour caused by the complicated flow pattern. The scour spreads along the length of the pipeline. The scour holes have limited length. When the free span of the pipeline is long enough, the pipeline sags into its scour hole and it may experience resonant flow-induced oscillations that in turn may lead to the structural failure of the pipeline. Therefore, accurate estimation of the equilibrium scour depth is very important in the design of submarine pipelines.

The scour process around a pipeline occurs in three stages. The onset of scour is basically related to the seepage flow in the sand beneath the pipeline, which is driven by the pressure difference between the upstream and downstream sides of the pipe. Piping occurs when the seepage flow exceeds a critical limit, ejecting sediment and water downstream of the pipeline. The onset of scouring process is followed by the stage called tunnel erosion. During this stage, a substantial amount of water is diverted to the formed gap leading to very large velocities in the gap and presumably resulting in very large shear stress on the bed just below the pipeline. The large increase in the bed shear stress below the pipeline results in a tremendous increase in sediment transport. This scour process is called the tunnel erosion. The tunnel erosion is followed by the stage called lee-wake erosion. The scour at the stage of the lee-wake erosion is governed by the vortex shedding [40].

The scour depth around submarine pipelines under the action of both steady currents and waves has been investigated experimentally by Kjeldsen et al. [17], Littlejons [25], Herbich [10], Bijker and Leeuweistein [4], Lucassen [26], Leeuweistein et al. [21], Herbich et al. [11], Bijker [3], İbrahim and Nalluri [12], Mao [28], Kristiansen [19], Kristiansen and Torum [20], Sumer and Fredsøe [38,39], Klomp [18], Çevik and Yüksel [5], and Mousavi et al. [33]. Kiziloz et al. [16] implemented experiments for developing analytical equations to predict the scour depth under pipelines influenced by irregular wave attacks.

Numerical methods have been also developed to simulate the scour around submarine pipelines by Chao and Hennesy [6], Liang and Cheng [23,24].

Myrhaug et al. [35] provided an approach to estimate the scour depth below pipelines in shoals under the action of non-breaking and breaking random waves. They combined the scour depth formula presented by Çevik and Yüksel [5] and the wave height distribution including shoaling and breaking waves by Mendez

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et al. [31] who assumed a stationary Gaussian narrow-band random process. Yasa [41] developed a model by using data set of other researchers' to predict scour depth by multiple regression analysis in both live bed and clear water conditions.

Sumer and Fredsøe [38] found that the relative scour depth (S/D) correlated remarkably well with the Keulegan–Carpenter (KC) number. Specifically, the relative scour depth increases with increasing KC number. S/D was expressed as

$$\frac{S}{D} = 0.1\sqrt{\mathrm{KC}} \tag{1}$$

in which S is the equilibrium scour depth and D is the pipe diameter

They concluded that the main parameter that determines the equilibrium scour depth in a live-bed situation, the sediment transport prevails over the entire bed, is the KC number under wave conditions. The KC number is defined by

$$\mathrm{KC} = \frac{u_m T}{D} \tag{2}$$

where u_m is the maximum water particle velocity on the bed in the absence of the pipe, T is the wave period and D is the pipe diameter. They also stated that the scour depth weakly depends on the Reynolds number in the range $10^3 < \mathrm{Re} < 10^5$.

Sumer and Fredsøe [39] also studied the influence of irregular waves on scour using the JONSWAP wave spectrum. They proposed the following equation for the scour depth in the case of irregular waves:

$$\frac{S}{D} = 0.1\sqrt{\mathrm{KC}} = 0.1\sqrt{\frac{U_m T_p}{D}} \tag{3}$$

where T_p is the peak period and U_m is defined by

$$U_m = \sqrt{2\sigma_u} \tag{4}$$

in which σ_u is the standard deviation of the orbital velocity u at the bed.

Scour below submarine pipelines for normal incidence regular waves were studied experimentally by Çevik and Yüksel [5]. They conducted tests for both a horizontal bed and 1/5 and 1/10 sloping beds in a shoaling region. They proposed the following expression (Eq. (5)) for the equilibrium scour depth in terms of Keulegan–Carpenter (KC) number for both sloping (1/5 and 1/10) and horizontal beds.

$$S/D = 0.11\mathrm{KC}^{0.45} \tag{5}$$

Additionally to the above, Çevik and Yüksel [5] proposed another empirical formula for regular waves with a high correlation coefficient, equal to $R = 0.90$ for the equilibrium scour depth below submarine pipelines for both sloping (1/5, 1/10) and horizontal bed as follows:

$$\frac{S}{D} = 0.042U_{RP}^{0.41} \tag{6}$$

where U_{RP} is the modified Ursell parameter obtained by the Ursell parameter (U_R) and the relative wave height (H/D):

$$U_{RP} = U_R\left(\frac{H}{D}\right)^2 = \frac{H^3L^2}{d^3D^2} \tag{7}$$

U_{RP} includes the local wave height (H), the local wave length (L), the local water depth (d) and the pipe diameter (D).

Kızılöz et al.[16] carried out an experimental study to develop analytical expressions for estimating the scour depth under pipelines under the action of irregular waves. Eq. (6) given by Çevik and Yüksel [5] was developed for regular waves. To use this formula under irregular wave conditions representative wave parameters of irregular waves that cause the same scour depth as a regular wave attack had to be defined. They tried to propose the representative wave parameters. More specifically [16] obtained the relative scour depth (S/D) equations in terms of the modified Ursell parameter considering two wave characteristic pairs; i.e. H_s–T_m and H_{rms}–T_p, where H_s is the significant wave height, T_p is the period of the maximum value of the wave energy spectrum ($1/f_p$), H_{rms} is the root-mean-square wave height, representing the total energy of the whole wave height distribution, and T_m is the spectral mean wave period. These pairs were identified as the representative wave parameter pairs to be used in characterizing an irregular sea state that causes the same scour depth as that caused by a regular wave.

$$\frac{S}{D} = 0.055\left(\frac{H_s^3L_m^2}{d^3D^2}\right)^{0.353} = 0.055U_{RP}^{0.353} \tag{8}$$

$$\frac{S}{D} = 0.062\left(\frac{H_{\mathrm{rms}}^3L_p^2}{d^3D^2}\right)^{0.328} = 0.062U_{RP}^{0.328} \tag{9}$$

In recent years Artificial Neural Networks (ANNs), Genetic Programming (GP) and Fuzzy Inference Systems (FIS) have been used to predict the equilibrium scour depth around piles or pipes (e.g., [14]). These techniques have also been used in other marine and coastal engineering studies such as nearshore processes and coastal modeling [37,7], wind-wave estimation (e.g., [9,13,42,27]), ecological system analysis in coastal waters [34,8], and current velocity forecasting in straits [1].

Kazeminezhad et al. [14] studied the wave-induced equilibrium scour depth around submarine pipelines using the experimental data from Pu et al. [36], Sumer and Fredsøe [38], and Mousavi et al. [33] by ANN approach. Kazeminezhad et al. [14] tried to determine the non-dimensional effective parameters on equilibrium scour depth. The correlation between independent parameters (e.g., KC number) and the dependent parameter (non-dimensional scour depth) was determined. ANN models with different input parameters including the gap to diameter ratio (e/D), the Keulegan–Carpenter number (KC), the pipe Reynolds number (Re), the Shields number (θ), the sediment Reynolds number (Re_s) and the boundary layer Reynolds number (Re_0) were trained and evaluated to determine the best prediction model. The results showed that the model including the e/D, KC, Re, θ, Re_s, and Re_0 parameters in input layers is the most accurate one.

ANN is a powerful utility for input-output mapping if there is sufficient data available. The use of an ANN model is intended to reduce the effect of uncertainties in deterministic models that are based on empirical expressions. As the ANN models rely heavily on the input data, the resultant models are only applicable within the region of the training data set.

The purpose of this study is to investigate the performance of Feed Forward Back Propagation (FFBP) ANN models for prediction of local scour depth around fixed submarine pipelines exposed to lateral regular and irregular waves considering different input parameter combinations. In addition to this, representative wave parameters of irregular waves corresponding to regular wave parameters for the combined regular and irregular waves' model were also obtained again by the help of FFBP ANN technique.

2. Source of experimental data

The data used in this paper were obtained from the experimental study which was previously published by Kızılöz et al.[16]. In Kızılöz et al. [16], the experiments were carried out in the wave flume at the Hydraulic and Coastal-Harbor Engineering Laboratory of Yıldız Technical University. The wave flume is 1 m wide, 1 m deep and 20 m long where 16 m of it has glass sidewalls and this part includes the sections of shoaling and the test area. The channel is equipped with piston type wave maker which can generate