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Neuro-fuzzy GMDH systems based evolutionary algorithms to predict scour pile groups in clear water conditions

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ABSTRACT

In this paper, neuro-fuzzy based group method of data handling (NF-GMDH) as an adaptive learning network was utilized to predict the local scour depth at pile groups under clear-water conditions. The NF-GMDH network was developed using particle swarm optimization (PSO) and gravitational search algorithm (GSA). Effective parameters on the scour depth include bed sediment size, geometric properties, piles spacing, arrangements of pile group, and flow characteristics in upstream of group piles and critical flow condition due to initiation of particles' motion on bed surface. Nine dimensional parameters were considered to define a functional relationship between input and output variables. The NF-GMDH models were carried out using datasets collected from the literature. The efficiency of training stages for both NF-GMDH-PSO and NF-GMDH-GSA models was investigated. Testing results for the NF-GMDH networks were compared with the empirical equations. The NF-GMDH-PSO network produced more efficient performance (R=0.95 and RMSE=0.035) for scour depth prediction compared with the NF-GMDH-GSA model (R=0.94 and RMSE=0.036). The NF-GMDH models indicated quite higher accuracy of scour prediction, compared with the empirical equations (R=0.44 and RMSE=0.127). Also, the sensitivity analysis indicated that pier diameter was the most significant parameter on scour depth.

1. Introduction

Pile groups are extensively utilized to provide stability of marine structures. These structures are imbedded in the coastal environments and deep rivers. Also, pile groups are considered as submerged piles because these may be exposed to floods with high level. This factor leads to scour process in the pile foundations due to the existence of currents and waves. The scouring at pile groups reduces the stability of such structures and their failure may be unavoidable. Hence, scour depth prediction at pile groups has attracted considerable attention for its safe design and maintenance. An accurate prediction of scour depth is difficult because three-dimensional flow at around pile foundations is a complicated process.

Experimental investigations of scour depth around a pile have been carried out comprehensively for various flow conditions (e.g., Melville and Sutherland, 1988; Breusers and Raudkivi, 1991; Dey et al., 1995, 2008; Melville and Coleman, 2000). In contrast, scour studies of pile groups are restricted (Hannah, 1978; Vittal et al., 1994; Salim and Jones, 1996; Ataie-Ashtiani and Beheshti, 2006; Ataie-Ashtiani et al., 2010; Amini et al., 2012). From experimental studies, it is seen that formulating mathematical approaches cannot present the scour depth with suitable accuracy.

Occasionally, the scour depth at pile foundations is predicted using empirical equations yielded for simple piers. It is clear that pile groups are assumed as an equivalent solid pile group. Also, it can be lead to obtaining inaccurate scour depth prediction. Hence, knowledge of exiting conventional methods for predicting scour depth at pile groups in clear water is essential to be improved. Empirical equations are limited to the range of experimental database. In case of pile groups scour due to clear water condition, one of the considerable drawbacks related to the use of database is the lack of datasets' availability (Ataie-Ashtiani and Beheshti, 2006; Ataie-Ashtiani et al., 2010; Amini et al., 2012; Ferraro et al., 2013). Therefore, empirical equations in terms of traditional methods do not have a high generalization capacity to be applied for the determination of scour depth for marine structures in coastal environments.

In the recent decade, artificial intelligence (AI) approaches such as artificial neural networks (ANNs), adaptive neuro-fuzzy inference system (ANFIS), support vector machine (SVM), and model tree (MT) have been applied to predict local scour depth at group piers under waves and currents (Bateni and Jeng, 2007; Zounemat-Kermani et al., 2009; Etemad-Shahidi and Ghaemi, 2011; Ghazanfari-Hashemi et al.,

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2011; Ghaemi et al., 2013). Bateni and Jeng (2007) evaluated the local scour depth at group piles under waves using the ANFIS model. Zounemat-Kermani et al. (2009) predicted the scour depth around pile groups due to clear water conditions using the ANNs and ANFIS models. They proposed two ANNs in forms of feed forward back propagation (FFBP-NN) and radial basis function (RBF-NN) neural networks. From their methods, it was found that the FFBP-NN model provides better prediction, compared to the ANFIS, RBF-NN, and empirical equations. In addition, local scour depth at group piles under waves and currents was estimated using the data mining approaches in terms of the SVM and MT models (Kambekar and Deo, 2003; Bateni and Jeng, 2007; Zounemat-Kermani et al., 2009; Etemad-Shahidi and Ghaemi, 2011; Ghazanfari-Hashemi et al., 2011; Ghaemi et al., 2013). These applications indicated that predictive methods can present good validations with low error for measured datasets compared with empirical equations.

Among the various intelligence methods, the GMDH network is known as the self-organized approach that solves various problems in non-linear systems with large complexity (Hwang, 2006; Amanifard et al., 2008). Recently, alternative GMDH networks were utilized to predict the scour depth around hydraulic structures (Najafzadeh and Barani, 2011; Najafzadeh and Azamathulla, 2013b; Najafzadeh et al., 2013a, 2013b, 2013c, 2013d, 2014). From these applications, performing the GMDH networks produced relatively more accurate prediction than those yielded using conventional regression-based equations and other soft computing tools. The GMDH approach has been used to identify the behavior of non-linear systems such as forecasting of mobile communication, explosive cutting process, tool life testing in gun drilling, constructing optimal educational test, control engineering, marketing, economics and engineering geology (Astakhov and Glitsky, 2005; Hwang, 2006; Witczak et al., 2006; Amanifard et al., 2008; Srinivasan, 2008; Jamali et al., 2009; Abdel-Aal and El-alfy, 2009; Mehrara et al., 2009; Kalantary et al., 2009).

In the past two decades, Nagasaka et al. (1995) proposed multi-stage fuzzy decision rule as neuro-fuzzy GMDH algorithm to model grinding characteristics. Also, Takashi et al. (1998) applied the orthogonal and successive projection approach for learning the NF-GMDH network. Hwang (2006) utilized the NF-GMDH model to forecast the unreliable mobile communication. The NF-GMDH model was configured through the least square training method. From his study, it was found to be excellent for solution of the forecasting problems. The neuro-fuzzy GMDH networks were used to identify physical insights of complicated problems in computer sciences. For instance, the NF-GMDH model was developed efficiently using self-organizing neuro-fuzzy multilayered classifiers (SONeFMUC) (Mitrakis et al., 2008; Mitrakis and Theocharis, 2012). Application of the SONeFMUC approach demonstrated suitable accuracy of performances in comparison with other well-known classification methods. Also, the NF-GMDH models based evolutionary algorithms were applied for fault diagnosis of hydraulic systems and prediction of scour depth at downstream of sluice gates and pile groups due to waves (Najafzadeh and Azamathulla (2013a); Najafzadeh and Azamathulla, 2013b; Najafzadeh and Lim, 2015; Mozaffari et al., 2014). One of the useful features of neuro-fuzzy GMDH networks is analytical equations, which can be obtained using partial descriptions based on multi-stage fuzzy rule decision (Hwang, 2006). In fact, the NF-GMDH model has not been applied yet for prediction of local scour depth at group piles under currents.

In this study, structure of the NF-GMDH model, which is organized automatically using the heuristic self-organization method, is applied in topology design of the GMDH network. In this way, a computer program is developed to improve the NF-GMDH network using PSO and GSA algorithms for scour depth prediction at pile groups due to clear water. Efficiency of the NF-GMDH models for training and testing stages is evaluated in terms of statistical error parameters. The performances of the proposed NF-GMDH models are compared with empirical equations.

2. Review on local scour investigations at pile foundations under clear water

Complex mechanism of the scour process at pile groups is basically different from that of scour around a single pile. Effective parameters on the pile groups scour are comprehensively various in comparison with a single pile scour. A few investigators have studied scour at pile groups due to clear-water conditions.

A survey on the scour at pile groups indicates that Hannah (1978) initiated studies in this area. He investigated scour depth at pile groups with different configurations including two-piles, side-by-side, and tandem. Vittal et al. (1994) attempted to reduce scour depth at solid circular piers using a group of three small piers. They investigated the best orientation of a pier group for the scour reduction. From their work, it was found that scour prediction due to a full pier group is about 40%. Salim and Jones (1996) conducted local scour experiments at different conditions including the spacing, skew angles, patterns and exposure of a pile cap in the flow field. They presented a hybrid approach based on the Hec-18 equation (Richardson et al., 2003) and Donguang et al. (1994) datasets. Coleman (2005) carried out experiments of clear-water local scour at complex piers. He proposed a new methodology to predict the scour depth regarding the existing formulations at a uniform complex pier. Also, Ataie-Ashtiani and Beheshti (2006) studied pile groups scour in clear-water conditions. They presented a correction factor to predict the scour depth based on their datasets and previous laboratory works. Through their investigation, it was found that scour depth prediction based proposed correlation factor provided good agreement with experimental datasets. Beheshti and Ataie-Ashtiani (2010) carried out an experimental setup for perceiving the three-dimensional flow fields around a complex pier. One of the remarkable observations was production of strong downward flow from flow at downstream and near the top of pile cap. Ataie-Ashtiani et al. (2010) proposed a simple and practical methodology to predict local scour depth at compound piers using the improved FHWA (Hec-18) method. Amini et al. (2012) performed clear-water scour experiments for both submerged and un-submerged pile groups. They proposed a new method to predict local scour depth for shallow water conditions. In addition, Ferraro et al. (2013) studied the influences of pile cap thickness on the temporal evolution of the maximum scour depth and the development of equilibrium conditions. They found that observed maximum scour depth increased with increase of a thicker pile cap.

3. Analysis of presenting the data for scour modeling

Prior to laboratory studies on scour depth at pile groups due to clear-water and live-bed conditions, the scour depth depends on the pile geometry, piles arrangement, characteristics of flow condition, and physical properties of the bed material (e.g., Vittal et al., 1994; Salim and Jones, 1996; Ataie-Ashtiani and Beheshti, 2006; Ataie-Ashtiani et al., 2010; Amini et al., 2012; Ferraro et al., 2013; Gaudio et al., 2013). In this way, the relationship function between scour depth and effective parameters can be expressed as follows:

$$d_s = f(U, U_c, d_{50}, y, D, S_m, S_n, m, n, \rho, \rho_s, \mu, g) \quad (1)$$

where d_s, U, U_c, d_{50}, y, D, S_m, S_n, m, n, ρ, ρ_s, μ, and g are the scour depth, average flow velocity, critical flow velocity due to initiation