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Studying the effects of clay percent, the shear strength of cohesive sediments and flow hydraulic on the deepest equilibrium scour using an inductive approach GMDH

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Abstract: In this study, using self-organizing systems of Group method of data handling (GMDH), the highest depth of scour around bridge piers in bed of sticky soils is estimated. GMDH network is developed by back propagation algorithm. To train GMDH algorithm with the above-mentioned method, quadratic polynomial is used in the structure of GMDH. Parameters affecting scour depth include the initial moisture content of cohesive sediments bed, clay percent of the sediments, flow Froude number, and shear strength of the sediments of the bed. These parameters are also specified as algorithm input variables. Assessment of GMDH gives accurate approximation of scouring in the bed of cohesive soils compared with empirical relationships based on regression model evaluation.
Key words: *Local scour,Bridge piers,Cohesive soil,Group method of data handling(GMDH)*

Introduction

Generally, scouring is the erosion of the bed and the banks of the rivers and streams due to water flow(1). The difference of the level of the eroded bed compared to the initial bed is called the scour depth(2). Local scour depth estimation has been one of the key issues in the design of hydraulic structures in the rivers and waterways by civil engineers. Lack of attention to this issue may cause irreparable fatalities and financial damages(3). Most of the studies are conducted on local scour of bridge piers. Research on pier scour has been continuing since 60 years ago Laursen and Toch and Shen were among the first researchers who offered scour pier empirical relationships based on soil physical properties and geometric structure(4). Breusers et al found that the time required for development of equilibrium scour depth might be limited(5). This is mostly due to hydraulic conditions of clear water upstream(6). Kothyari studied the effects of the size of deposits with non-uniform and uniform particle sizes, clear water hydraulic conditions, and live bed on local scour around bridge piers. They concluded that by increase in the standard deviation of grain size, protective layer on the soil reduces scour depth(7). Chiew and Melville concluded that 50 to 80 percent of equilibrium scour depth that develops at 10 percent of equilibrium time depends on the velocity of the flow approaching the pier(8). Chang conducted studies on bridge pier local scour in steady and unsteady flow conditions(9). In this study, sediments with uniform and non-uniform grain sizes were used. They were able to offer a method for calculating the bridge pier scouring in non-uniform flows by analyzing experimental data(10).
In recent decades, various methods of artificial intelligence such as artificial neural networks (ANNs), adaptive neuro-fuzzy inference system (ANFIS), genetic programming (GP), linear genetic programming (LGP), support vector machine (SVM) and data mining algorithms have been used to estimate scour depth around hydraulic structures(11).
The results of using these intelligent methods showed that these methods could be a substitute for the relevant empirical equations. Recent studies have shown that the approximation of artificial intelligence

methods in comparison with empirical relations and regression is higher in precision. Therefore, in this study, GMDH is used, for the first time, to estimate the depth of scour around bridge piers. The results of this method will be compared with the related empirical relations and regression.

2. GMDH method

Ivakhnenko used GMDH algorithm to analyze systems with high degrees of complexity for first time. Ivakhnenko proposed model has an input, middle, and output layers. Regarding the structure, this algorithm is similar to artificial neural networks and data-mining algorithms with the exception that the number of layers and neurons are determined using a predetermined standard. GMDH algorithm has been widely used in solving various problems of Engineering Sciences(12).

Problem-solving mechanism using the mentioned algorithm is that in the first layer, the neurons are generated by combining input parameters and in the second layer, they bind to previous top neurons. Choosing top neurons that have the best characteristic is done based on external criteria that can assess the errors in each neuron. In GMDH model, to create a second degree polynomials in the first layer neurons, binary combinations of input parameters are considered. If the number of GMDH networks has P input parameter, the number of neurons of the first layer is equal to $L=\binom{2}{P}$. Moreover, to produce middle layer neurons, paired combination of neurons of previous top layers are considered (13).

In each layer of GMDH network, one can use a different value for the threshold criterion. The duty of threshold criterion in each layer is filtering out or disabling neurons that have less credibility and transferring only those neurons that have a better performance than the threshold to the next layer. More explanation about the training mechanism of this proposed model has been proposed in the reference.(12)

3. The analysis of input data required for modeling scour

Based on research in the field of scour in cohesive soils, soil parameters such as initial moisture content, soil density, the percent of cohesive clay soil, and shear strength of cohesive soils in saturated and unsaturated modes influence the calculation of scour depth (8). In this study, the experimental data of researchers such as Rambabu and Debnath and Chaudhuri and Najafzadeh and Barani are used. Thus, the following function could be used to predict scour in the context of cohesive soils:

$$d_s = f(\rho, \mu, U, d_{50}, y, g, D, IWC, C_p, S) \qquad (1)$$

Where ρ، y، g، d_{50}، D، μ، IWC، C_p، U ، S and, d_s are respectively, the density of water, flow depth, gravity, median particle diameter of bottom sediments pier, pier diameter, absolute viscosity of the fluid, the initial moisture content, density, average speed upstream, the shear strength of cohesive soils, and the highest scour depth(14).

The range of changes of the mentioned parameters is given in Table 1 below.

Table 1: The range of changes in the parameters affecting scour depth around bridge piers in the context of cohesive soil

y	0.3-0.6m
D	50-120(mm)
d_{50}	0.037-0.00808(mm)
S	1.88-35.6(Kpa)
IWC	10.7%-45.92%
C_p	20%-100%
ρ	1000(kg/m^3)
d_s	7.3-224(mm)
U	0.141-0.8187(m/s)
g	10(m/s^2)
μ	0.001(Pa.S)

By making the above relations dimensionless, dimensionless parameters of scouring of the bed of cohesive soils are obtained as follows:

$$d_s / D = f(R_{ep}, d_{50} / D, Fr_p, y / D, IWC, C_p, S / \rho U^2) \quad (2)$$

$$Fr_p = U / \sqrt{g.D} \quad (3)$$

Where Frp is Froude number depending on the diameter of the diameter of bridge pier.In this study, to reduce the number of dimensionless parameters in Relation (15), by combining the parameters y/D and Frp, Froude number depending on water depth is obtained.

Moreover, if the flow around bridge pier is in a state of full chaos, Reynolds number does not have any effect on depth of scour (16). Based on the research by Atma and Chievo, whenever the dimensionless parameter d_{50} / D is smaller than 50, it will not have a significant effect on depth of scour. Thus, by eliminating the two parameters, Relation (2) can be written as follows:

$$d_s / D = f(Fr, IWC, C_p, S / \rho U^2) \quad (4)$$

Out of 95 series of laboratory data collected, about 75 and 25 percent of data are used for training and testing of GMDH network.

4. Development GMDH Model

In this study, GMDH model is trained using the least square method. The training error was 0.034. GMDH model consists of three layers, in which there are six neurons are in the first layer, 3 in the hidden layer, and one neuron in the output layer.

Performance of the models developed by the statistical parameters is measured by indices such as correlation, the highest absolute error, minimum mean square error, average difference between calculated and observed values (BIAS), and the dispersion index. Relations related to the statistical parameters used are provided in the references (14).

Statistics show that GMDH algorithm has high correlation coefficient (R^2 = 0.92) in the training. Error parameters show that BIAS error is zero and it can be concluded that GMDH proposed model has had successful performance during the training phase of the input. In the testing, the values of R^2, RMSE and SI obtained are almost equal to training stage. Moreover, BIAS and MAPE values are determining parameters to test the training and testing stages accuracy. BIAS and MAPE values for testing are respectively -0.045 and 0.74.

According to the statistical parameters, it can be said that GMDH method has acceptable accuracy in scour depth in testing phase. The error parameters results are provided in Table 2.

Table 2: The performance of the model in training and testing

Method	Training	Test
R	0.92	0.91
RMSE	0.183	0.184
MAPE	0.26	0.74
BIAS	0.00	-0.045
SI	0.218	0.22

In order to compare the results of GMDH model with experimental models, several empirical relationship are used (Table 3). The results of the comparisons showed that Relationship (12) has more errors (R^2 = 0.86, RMSE = 67.3, MAPE = 298.4, BIAS = -59.03, SI = 81.64) than the other empirical relationships. Moreover, this relationship has only two dimensionless parameters of Froude number and shear stress of the bed from four parameters used in the modeling of scour. In other words, the Reynolds number in full chaos flow conditions has no effect on depth of scour around bridge piers. Table 4 shows that the empirical relations (13) and (10) have fewer errors compared with Relation (8) that is mostly due to parameters such as initial moisture content, clay percent, and shear strength substrate of the materials of the bed. Calibration of relations (13) to (10) is conducted in five ranges of IWC and C_p.

The results showed that these empirical relations have fewer errors (R = 0.88, RMSE = 0.19, MAPE = 0.6, BIAS = 0.012, SI = 0.2) than other relations. Empirical relationships are limited to the range of measured parameters in the laboratory and

cannot well predict the physical behavior of pier scouring if the bed of cohesive soils. Figure 1 shows quality assessment of GMDH model for testing stage.

Table 3: Available empirical relationships to estimate the depth of scour around bridge pier in bed of cohesive soils

Relationship number	Researcher	Empirical relationship
8	Rambabu et al. (2003)	$d_s / D = Fr^{0.641} R_{ep}^{0.64} (S / \rho_s gy)^{-0.976}$
9	Molinas, and Hosny (1999)	$d_s/D = 0.0288 IWC^{1.14} (350/IWC^2 - Fr)^{0.6}$
10	Najafzadeh and Barani (2014)	$d_s/y = 5565.05 (S/\rho_s gy)^{0.83} C_p^{-2.179} Fr^{2.306}$
11	Debnath and Chaudhuri (2010, 2012)	$d_s / D = 2.05 (U / \sqrt{g.D})^{1.72} C_p^{-1.29} (S / \rho U^2)^{-0.37}$ C_p=20%–85% & IWC=20%–23.22%
12	Debnath and Chaudhuri (2010, 2012)	$d_s/D = 3.64 (U/\sqrt{g.D})^{0.22} C_p^{-1.01} (S/\rho U^2)^{-0.69}$ C_p=20%–50% & IWC=27.95%–33.55%
13	Debnath and Chaudhuri (2010, 2012)	$d_s/D = 20.52 (U/\sqrt{g.D})^{1.28} C_p^{0.19} (S/\rho U^2)^{-0.89}$ C_p=50%–100% & IWC=27.95%–33.55%
14	Debnath and Chaudhuri (2010, 2012)	$d_s / D = 3.32 (U / \sqrt{g.D})^{0.72} C_p^{-0.62} IWC^{0.36} (S / \rho U^2)^{-0.29}$ C_p=20%–70% & IWC=33.60%–45.92%
15	Debnath and Chaudhuri (2010, 2012)	$d_s/D = 8 (U/\sqrt{g.D})^{0.61} C_p^{0.58} IWC^{1.24} (S/\rho U^2)^{-0.19}$ C_p=70%–100% & IWC=33.60%–45.92%

Table 4: Statistical analysis of experimental relations

R	RMSE	MAPE	BIAS	SI	Relationship number	Method
0.91	0.18	0.74	-0.045	0.22	--	GMDH
0.86	67.3	298.4	-59.035	81.64	(8)	Rambabu et al. (2003)
0.6	0.67	3.44	0.193	1.042	(9)	Molinas, and Hosny (1999)
0.68	0.8	3.7	0.725	0.97	(10)	Najafzadeh and Barani (2014)
0.88	0.19	0.76	0.016	0.2	(11)-(15)	Debnath and Chaudhuri (2010, 2012)

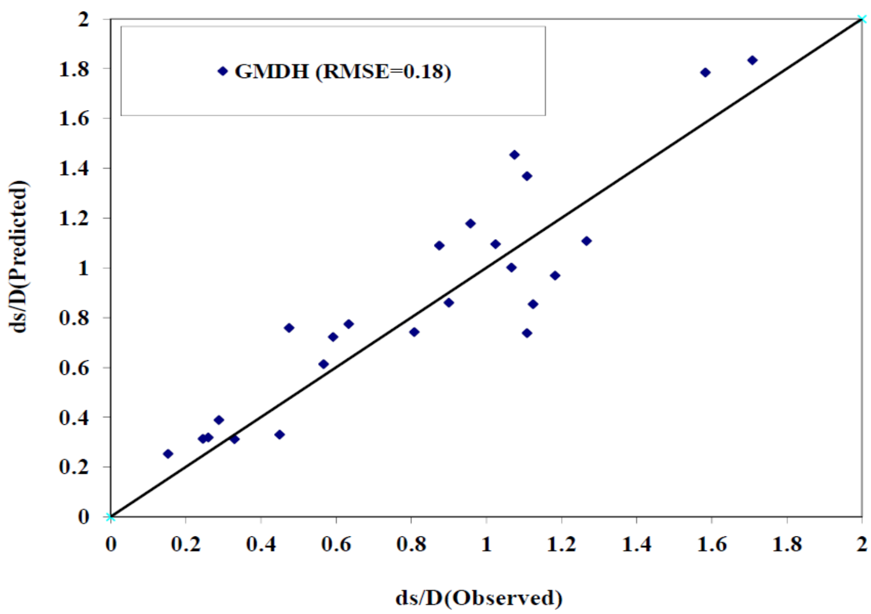

Figure 1: Comparison between observed and calculated scour pier in the context of cohesive soils obtained by GMDH model in testing stage

To determine the effect of each input parameter of GMDH network on bridge-pier scour depth, sensitivity analysis is done on GMDH model. For sensitivity analysis, every time, one of the input parameters of the network is eliminated and by having four inputs and one output, scour modeling is done. The statistical parameters of error are recalculated after executing any network.

Sensitivity analysis results showed that the parameters (R = 0.7, RMSE = 0.528, MAPE = 1.36, BIAS = 0.267, SI = 0.77) C_p and the ratio without shear resistance (R = 0.89 RMSE = 0.22, MAPE = 0.93, BIAS = 0.004, SI = 0.251) have the maximum to minimum effect on depth of scour around bridge piers, respectively. According to the assessment of the statistical parameters obtained from the sensitivity analysis, Froude number is second in importance. Moreover, after Froude number, the dimensionless parameter of initial moisture content R, RMSE, and MAPE with respectively 0.86, 0.24, and 1.11 have the highest effect on depth of scour. The overall results of the sensitivity analysis are given in Table 5.

Table 5: The statistical results of the sensitivity analysis

Functions	R	RMSE	MAPE	BIAS	SI
$d_s / D = f(S / \rho U^2, C_p, IWC)$	0.71	0.37	1.73	-0.163	0.4
$d_s / D = f(S / \rho U^2, C_p, Fr)$	0.86	0.24	1.11	-0.04	0.324
$d_s / D = f(IWC, C_p, Fr)$	0.89	0.22	0.93	0.004	0.251
$d_s / D = f(S / \rho U^2, Fr, IWC)$	0.7	0.528	1.36	0.267	0.77

5. Conclusion

In this study, scour around bridge piers was estimated using GMDH self-organizing algorithm. Using dimensional analysis, four independent dimensionless variables are considered for modeling of local scour of the bridge piers in cohesive soils. Conclusion of the results of the study is presented as follows:

- Statistical parameters showed that GMDH model has good performance in estimating the depth of bed scour of the bridge piers in cohesive soils both in training and testing stages.

- Comparison of the results of the proposed GMDH algorithm with empirical relationships Rambabu et al. (2003), Molinas, and Hosny (1999), Najafzadeh et al. (2013), and Debnath and Chaudhuri (2010, 2012) showed that the empirical relationship by Rambabu et al. (2003) have significant errors (MAPE = 298.4) compared to the other models.

- Great error in relation by Rambabu et al. (2003) is because this relationship has been obtained in laboratory conditions in saturated soil and other relations are true for unsaturated conditions of cohesive soils.

- Sensitivity analysis showed that the parameters of clay of cohesive soils have the greatest impact on bridge pier scouring in cohesive soil bed.

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