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Intelligent design of retaining wall structures under dynamic conditions

Haiqing Yang [1], Mohammadreza Koopialipoor [2], Danial Jahed Armaghani [*3],
Behrouz Gordan [4], Majid Khorami [5] and M.M. Tahir [6]

[1] *School of Civil Engineering, Chongqing University, Chongqing, China 400045*
[2] *Faculty of Civil and Environmental Engineering, Amirkabir University of Technology, 15914, Tehran, Iran*
[3] *Institute of Research and Development, Duy Tan University, Da Nang 550000, Vietnam*
[4] *Department of Geotechnics and Transportation, Faculty of Civil Engineering, Universiti Teknologi Malaysia (UTM), 81310 Skudai, Johor, Malaysia*
[5] *Universidad UTE, Facultad de Arquitectura y Urbanismo, Quito, Ecuador*
[6] *UTM Construction Research Centre, Institute for Smart Infrastructure and Innovative Construction (ISIIC), School of Civil Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia*

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Abstract. The investigation of retaining wall structures behavior under dynamic loads is considered as one of important parts for designing such structures. Generally, the performance of these structures is under the influence of the environment conditions and their geometry. The aim of this research is to design retaining wall structures based on smart and optimal systems. The use of accuracy and speed to assess the structures under different conditions is one of the important parts sought by designers. Therefore, optimal and smart systems are able to have better addressing these problems. Using numerical and coding methods, this research investigates the retaining wall structure design under different dynamic conditions. More than 9500 models were constructed and considered for modelling design. These designs include height and thickness of the wall, soil density, rock density, soil friction angle, and peak ground acceleration (PGA) variables. Accordingly, a neural network system was developed to establish an appropriate relationship between data to obtain safety factor (SF) of retaining walls under different seismic conditions. Different parameters were analyzed and the effect of each parameter was assessed separately. According to these analyses, the structure optimization was performed to increase the SF values. The optimal and smart design showed that under different PGA conditions, the structure performance can be appropriately improved while utilization of the initial (or basic) parameters leads to the structure failure. Therefore, by increasing accuracy and speed, smart methods could improve the retaining structure performance in controlling the wall failure. The intelligent design process of this study can be applied to some other civil engineering applications such as slope stability.

Keywords: retaining wall structures; smart design; dynamic condition; optimization

1. Introduction

Since the original work of (Mononobe and Matsuo 1929) and analytical work of (Carl and Gauss 1833), there have been several experimental, analytical and numerical studies of the dynamic behavior of retaining walls in order to offer a method for rational design (Gandomi *et al*. 2017). Different methodologies have been used to study walls against seismic or lateral loadings (Sharbatdar *et al*. 2008, Arabnejad Khanouki *et al*. 2010, Nguyen-Xuan *et al*. 2012, Mohammadhassani *et al*. 2014b, Khorramian *et al*. 2015, Khanouki *et al*. 2016, Rezaei 2016, Shafaei *et al*. 2016, Shariati *et al*. 2010, 2011, 2012, 2015, 2017, Amiri *et al*. 2018, Chen *et al*. 2018, Darbhanzi *et al*. 2018, Heydari and Shariati 2018, Ghaleini *et al*. 2018, Hosseinpour *et al*. 2018, Nguyen-Minh *et al*. 2018, Wei *et al*. 2018, Zandi *et al*. 2018, Koopialipoor *et al*. 2019e). The different methodologies used to study active earth pressures can be alienated into analytical, numerical, and experimental methods. While a vast amount of literature exists on the topic of seismically induced lateral earth pressures. A recent alternative to the Mononobe-Okabe (M-O) method for plastic soils was developed by (Mylonakis 2006). They proposed a closed-form stress plasticity solution for gravitational and earthquake-induced earth pressures on retaining walls. Moreover, (Nakamura 2011) and (Atik and Sitar 2009) recently conducted separate shake table tests using centrifuge facilities, and both separately concluded that the measured earth pressure during shaking was lower than the M-O method predictions. A research by (Nakamura 2011) also found that the inertial force was not always transmitted to the wall and backfill simultaneously. A research by (Dewoolkar *et al*. 2002) carried out centrifuge dynamic excitation tests with fixed-base cantilever walls supporting saturated, liquefiable, cohesion less backfills. From those experiments, (Dewoolkar *et al*. 2002) concluded that excess pore pressure generation contributed significantly to seismic lateral earth pressure in the saturated backfill. They also concluded that the maximum dynamic thrust was proportional to the input base acceleration. A research by (Green 2002) modeled the

∗Corresponding author, Ph.D.,
E-mail: danialarmaghani@gmail.com

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dynamically induced lateral earth pressure on the stem portion of a concrete cantilever earth retaining wall with dry medium dense sand using finite difference code FLAC and determined that at very low levels of seismic activity, the seismic earth pressures were in agreement with M-O predictions; however, as accelerations increased, seismic earth pressures were larger than those predicted by the M-O method. A research by (Gazetas *et al*. 2004) completed models of L-shaped walls, pre-stressed anchored pile walls, and reinforced soil walls, employing both linear and non-linear soil models. Using those models, (Gazetas *et al*. 2004) presented that including realistic effects such as the wall flexibility, foundation soil deformability, material soil yielding and soil wall separation and sliding tends to reduce the effects of dynamic excitations on those walls. They also used an FE model to simulate a case history in which a retaining wall performed well during an actual earthquake. Numerous numerical calculation e.g., finite element analyses (Moghaddam *et al*. 2009, Bazzaz *et al*. 2012, Mohammadhassani *et al*. 2015, Khorramian *et al*. 2017, Mansouri *et al*. 2017, Toghroli *et al*. 2018) or non-local methods (Bobaru *et al*. 2018, Mehrmashhadi *et al*. 2019a, c) have been developed to study the structural behavior. A research by (Psarropoulos *et al*. 2005) performed a study to confirm the assumptions of Veletsos and Younan analytical solution and to define the range if its applicability. The numerical models were developed using the commercial finite-element package ABAQUS. The versatility of the numerical methods, finite-element and finite-difference, permitted the treatment of more realistic situations that are not amenable to analytical solution including the heterogeneity of the retained soil, and translational flexibility of the wall foundation. To investigate the characteristics of the lateral seismic soil pressure on building walls, Bahadori *et al*. (2014) and Ghassemieh *et al*. (2015) performed a series of soil-structure-interaction analyses using SASSI. Using the concept of a single degree-of-freedom, (Ostadan 2005) proposed a simplified method to predict maximum seismic soil pressures for building walls resting on firm foundation material. This proposed method resulted in dynamic earth pressure profiles comparable to or larger than the Wood (Wood 1973) solution, with the maximum earth pressure occurring at the top of the wall.

Application of soft computing methods in different field of civil engineering has been used in many researches recently (Fanaie *et al*. 2015, 2016, Hamidian *et al*. 2012, Toghroli 2015, Toghroli *et al*. 2014, 2016, 2018a, Aghakhani *et al*. 2015, Mohammadhassani *et al*. 2015, Mansouri *et al*. 2016, Safa *et al*. 2016, Zhou *et al*. 2016a, b, Khorami *et al*. 2017, Mansouri *et al*. 2017, Sadeghipour Chahnasir *et al*. 2018, Sedghi *et al*. 2018, Shariat *et al*. 2018, Wang *et al*. 2018a, b, 2019, Zandi *et al*. 2018). The new and artificial intelligence (AI)-based methods have a wide application in a variety of engineering works (Toghroli *et al*. 2014, Gordan *et al*. 2018, Hasanipanah *et al*. 2018, Koopialipoor *et al*. 2018b, 2019a Zandi *et al*. 2018). Artificial neural networks (ANNs) are one of the AI subsets, whose various states have been used in civil engineering. Considering that different problems have various parameters, there has been an influx of research interest in the area of engineering with regard to finding a solution that can well connect them and create significant relationships. By establishing a nonlinear relationship between different variables, ANN causes these relations to be created. Fewer studies have been done on the use of these methods to assess these structures in retaining walls. Using smart methods, (Koopialipoor *et al*. 2019d) predicted SFs under static conditions of retaining wall structures. After establishing proper relations, they proposed optimization patterns for engineering design. The use of optimization algorithms is among issues of interest to many researchers. Using these algorithms, various problems can be optimized under proper conditions (Ebrahimi *et al*. 2016, Koopialipoor *et al*. 2018a). Genetic algorithm (GA), particle swarm optimization (PSO) and imperialism competitive algorithm (ICA) and artificial bee colony (ABC) algorithms are the most commonly used methods in this sector (Saemi *et al*. 2007, Oliveira *et al*. 2009, Mohammadhassani *et al*. 2013, Armaghani *et al*. 2018, Hajihassani *et al*. 2018, Liao *et al*. 2019).

To the best knowledge of the authors on retaining wall structure, numerical and AI models have been rarely used to assess the SF of these structures under dynamic condition. Therefore, in the current research, different models of retaining wall structure were presented under various dynamic loads. Then, using AI, a proper relationship was established among variables. The effect of different dynamic was investigated, and then, the appropriate solutions were suggested based on ABC optimization technique. These solutions can create the appropriate models for engineering design of retaining walls structures under dynamic conditions.

2. Research methodology

Mononobe-Okabe (M-O) method is still employed as the first option to estimate lateral earth pressures during earthquakes by geotechnical engineers. Considering some simple assumptions and using a closed form method, M-O solves the equations of equilibrium and suggests seismic active and passive lateral earth pressures. M-O, a seismic version of coulomb theory, was proposed based on pseudo static earthquake loading for granular soils. This method applies earthquake force components using two coefficients called seismic horizontal and vertical. Beside other complex theoretical models and numerical methods, M-O theory is one of the best initial estimates. Researches by (Carl and Gauss 1833, Mononobe and Matsuo 1929) proposed a method to determine lateral earth pressure of granular cohesion less soils during earthquake as reported by (Kramer 1996). Fig. 1 shows the effect of seismic forces in both directs such as horizontal and vertical on the gravity retaining wall.

The results of these experiments and analytical work then led to the development of what is now often referred to M-O method. This methodology was originally developed for gravity walls retaining cohesion less backfill materials; however, since then it has been extended to a full range of

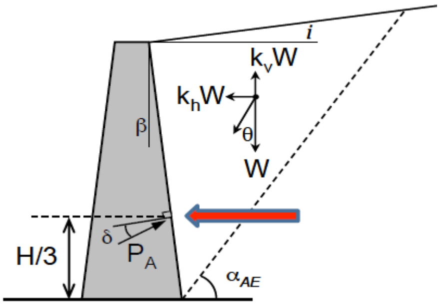

Fig. 1 Forces on retaining wall and seismic effects

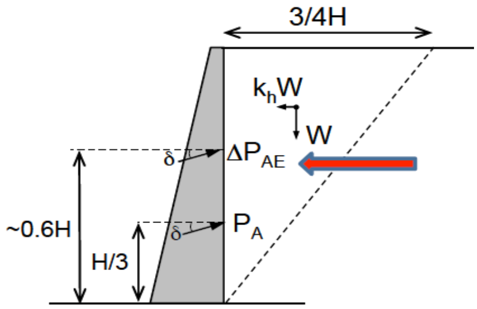

Fig. 2 Forces considered in Seed-Whitman analysis

different soil properties. The method is an extension of Coulomb's sliding wedge theory and for active conditions the M-O analysis incorporates the following assumptions:

(1) The backfill soil is dry, cohesion less, isotropic, homogenous and elastically non deformable material with a constant internal friction angle.
(2) The wall is long enough to make the end effect negligible.
(3) The wall yields sufficiently to mobilize the full shear strength of the backfill along potential sliding surface and produce minimum active pressures.
(4) The potential failure surface in the backfill is a plane that goes through the heel of the wall.

These assumptions make the problem facing with respect to force equilibrium and lead to the following expression for the resultant dynamic active thrustP_{ae}

$$P_{ae} = \frac{1}{2}\gamma\ k_{ae} H^2(1-k_v) \quad (1)$$

$$k_{ae} = \frac{Cos^2(\varphi-\psi-\beta)}{Cos\psi Cos^2\beta Cos(\delta+\beta+\psi)\left[1+\sqrt{\frac{Sin(\varphi+\delta)Sin(\varphi-\psi-i)}{Cos(\psi+\delta+\beta)Cos(i-\beta)}}\right]^2} \quad (2)$$

Where
H = height of wall
kv = coefficient of vertical acceleration of soil wedge
kh = coefficient of horizontal acceleration of soil wedge
$\psi = tan^{-1}(\frac{kh}{1-kv})$
γ = unit weight of backfill
φ = friction angle of backfill
δ = friction angle at wall-backfill interface
i = backfill slope with respect to horizontal
β = angle between inner face of wall and vertical

The M-O method gives the total active thrust acting on the wall and the point of application of the thrust is assumed to be at H/3 above the base of the wall.

A research by (Seed and Whitman 1970) performed a parametric study to evaluate the effects of changing the angle of wall friction, the friction angle of the soil, the backfill slope and the vertical acceleration on the magnitude of dynamic earth pressures. They observed that the maximum total earth pressure acting on a retaining wall can be divided into 2 components: the initial static pressure and the dynamic increment due to the base motion. They suggested that the static, dynamic increment and total lateral earth pressure can be related as (Seed and Whitman 1970)

$$Pae = Pa + \Delta Pae \quad (3)$$

$$Kae = Ka + \Delta Kae \quad (4)$$

Seed and Whitman (1970), based on a parametric sensitivity analysis, further proposed that for practical purposes

$$\Delta Kae \approx 3/4\ kh \quad (5)$$

$$\Delta Pae = 1/2\ \gamma H^2\ 3/4\ kh = 3/8\ kh\gamma H^2 \quad (6)$$

In addition, kh is horizontal ground acceleration as a fraction of gravitational acceleration. They observed that the peak ground acceleration occurs for only one instant of time and does not have sufficient duration to cause significant wall movements. Therefore, they recommended using a reduced ground acceleration of about 85% of the peak value in seismic design of retaining walls. After reviewing the results of experimental work on small 1g shaking table, Seed and Whitman (Seed and Whitman 1970) suggested the point of application of the active thrust should be at 0.6 H above the base of the wall as shown in Fig. 2. However, (Seed and Whitman 1970) concluded that "many walls adequately designed for static earth pressure will automatically have capacity to withstand earthquake ground motions of substantial magnitudes and in many cases, special seismic earth pressure provisions may be not needed", More recently, NEHRP (FEMA 750) (Building Seismic Safety Council 2010) recommended that "Unless permanent displacement of the wall acceptable kh should be taken equal to the site peak ground acceleration (PGA). The basis of this recommendation is not given and cannot be traced to any published information.

3. Data collection

To obtain the suitable datasets for SF analysis, modeling procedure was conducted in several steps. The process consisted of introducing boundary conditions, model dimensions, material properties and seismic motion.

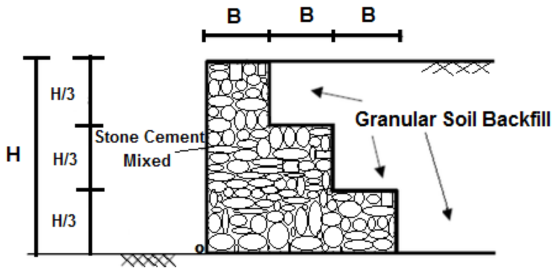

Fig. 3 Dimension model for gravity masonry retaining wall

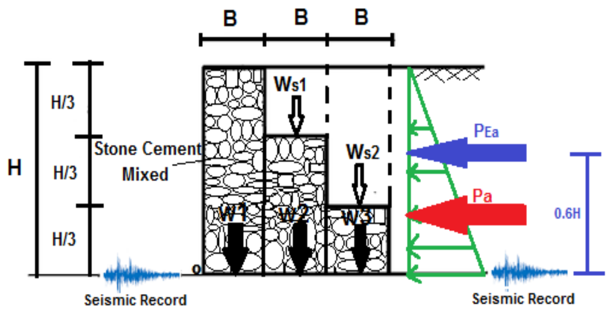

Fig. 4 Distribution of active force for static and dynamic conditions with body forces for soil and stone blocks

Mononobe's method utilizing visual basic language was applied to obtain SF values in this research. Many homogenous soils such as sand, gravel-sand and gravel behind the retaining masonry wall (in terms of material, γ = 17, 17.50, 18, 18.5 and 19 ton/m^3) with various conditions were modeled to obtain SF in the study. Retaining wall with heights of 3, 4, 5, 6, 7, 8, 9 and 10 m, were considered and designed. All the models were located on the bedrock with respect to the rigid behavior. In addition, the wall width of 0.5, 0.6, 0.7 and 0.8 m were assumed for all the models. Moreover, the range of gravity for stone mixed cement including 20 ton/m^3, 24 ton/m^3 and 28 ton/m^3. Fig. 3 shows a schematic view of retaining walls considered in modelling process of this study. It can be seen that, both angles β and i are zero. The Mohr–Coulomb (MC) failure criterion is considered for the analysis in this study. Cohesions of 0 kPa for granular soil and internal friction angles of 30°, 35°, 40°, and 45° were applied in the analyses process. Granular soil was used because of avoiding the pure water pressure behind the walls. It should be noted that, the earthquake motion effect plays an important role to control the retaining walls failure. Fig. 4 shows the distribution of active pressure for static and dynamic conditions and body forces for soil and stone blocks. As mentioned by Kramer (1996), PGA is a measure of earthquake acceleration on the ground. In this study, the amplitudes of PGA were considered to be 0.1 g, 0.2 g, 0.3 g, 0.4 g and 0.5 g for horizontal direction and it was set as zero for vertical direction. As mentioned earlier, SF values were computed under various conditions for a number of 9600 simulation models. The overall description of different designing parameters for retaining walls under various conditions is shown in Table 1.

Table 1 Overall description of the data used in this research

Parameter	Unit	Min	Ave	Max
Wall height (H)	m	3	6.5	10
Wall width (B)	m	0.5	0.65	0.8
Internal friction angles	Degree	30	37.5	45
Soil density	Kg/m^3	1700	1800	1900
Rock density	Kg/m^3	2000	2426.67	2800
Peak ground acceleration (PGA)	g	0.1	0.3	0.5
Safety factor	-	0.027	0.568	6.476

4. Result and discussion

4.1 ANN background and modeling

ANN is one of the simulation methods that deals with designing simple to complex problems based on various functions (Haykin and Network 1999, Koopialipoor *et al*. 2018d). This system contains deferent elements, each of which performs its tasks beside others to improve the model performance. The use of neural models to obtain the appropriate patterns among parameters has increased the application of these methods. These methods can be considered as suitable alternatives for statistical methods such as multivariate regression, linear correlations, etc.

Generally, neural networks require methods that can train them well. These methods which can be obtained by different algorithms are able to control/adjust the performance of the system. Back-propagation (BP) algorithm is one of these algorithms, which has been used by various researchers (Safa *et al*. 2016, Koopialipoor *et al*. 2019c). This training algorithm includes different layers, which is recommended to be used with three layers. Each layer contains nodes, which are divided in a certain way given their location. Nodes which are located in the first layer are introduced as input data/parameter. Second layer (or hidden layer) contains, in fact, including neurons, which play an important role in establishing a significant relationship. Finally, the output is located in the last part and it is the goal of simulation systems such as ANN.

One of the important parts of the neural network is how to assign dataset to a system (Toghroli *et al*. 2014, Koopialipoor *et al*. 2019b). In order to design models, a neural network requires data which are created by that model. Then, given the new data, its performance is assessed. Data assigning in neural networks is done as follows: data are divided into two parts of training and testing. Based on the previous research, a high percentage of data (80% of the total data) is assigned to the training part and the rest to the test (Mohammadhassani *et al*. 2014a, Hasanipanah *et al*. 2017, Sadeghipour Chahnasir *et al*. 2018).

In this research, wall height, wall thickness, internal friction angle of the soil, soil density, rock density and PGA are used for smart design of retaining wall which introduced in Table 1. They were used as independent variables or model inputs. Then, SF values of retaining wall were

Table 2 Results of safety factor designed models under dynamic conditions for retaining wall structure

Model No.	No. of hidden neuron	Training performance		Testing performance		Training score		Testing score		Total score
		R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	
1	2	0.9617	0.0253	0.9572	0.0272	1	1	1	1	4
2	4	0.9709	0.0175	0.9758	0.0159	2	2	4	4	12
3	6	0.9728	0.0171	0.9689	0.0182	3	3	2	2	10
4	8	0.9753	0.0162	0.9736	0.0165	4	4	3	3	14
5	10	0.9908	0.0085	0.9915	0.0086	5	5	5	5	20

obtained under dynamic conditions. Various conditions and models were used in order to design the smart main model. The number of neurons is one of the important parameters that affect performance of the created ANN models. Therefore, an appropriate number of neurons should be considered to obtain the structural SF of retaining wall under dynamic condition. In this research, number of hidden neurons of 2, 4, 6, 8 and 10 were considered and through a trial-and-error process, the best one among them was selected as the optimum number of hidden neuron. In Table 2, the results of constructed ANN models using various numbers of hidden neurons are presented. Considering the close results, the best performance should be generally obtained for data using a criterion. Therefore, based on recommendation by (Zorlu *et al*. 2008), a simple ranking method can be used to score different parts of smart systems. Scores are assigned as follows: the lowest system error of a model (such as root mean square error, RMSE) will receive the greatest score/rank value while the highest coefficient of determination (R^2) value will get the greatest score/rank. This method of scoring is implemented for testing and training parts of models. Finally, the score of all parts of a model are summed up and the model with the highest score is determined as the superior model. In Table 2, it is observed that the model No. 5 has assigned the greatest score to itself. The accuracy values obtained for training and testing sets are R^2 = 0.9908 and 0.9915 and RMSE = 0.0085 and 0.0086, respectively. These values showed that the designed smart model can well establish a relationship between dependent and independent variables to assess the SF under dynamic conditions for retaining wall structure.

Finally, the results of training and testing sets of model No. 5 (the selected model among all developed models) are displayed in Figs. 5 and 6, respectively. As shown in the figures, the new designed smart model shows an appropriate performance to assess the SFs of retaining walls, which can be considered in design stage in the following section. The predicted and the measured values are depicted in Fig. 7 for 100 data which have been selected randomly. As it can be seen from this figure, the predicted and measured values of SF are very close to each other. As a result, the selected ANN model presents appropriate accuracies for different values and it can be used as a new

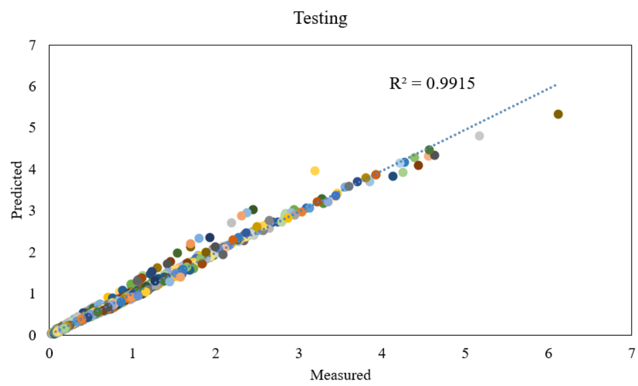

Fig. 6 Results of testing part of ANN for retaining wall structure

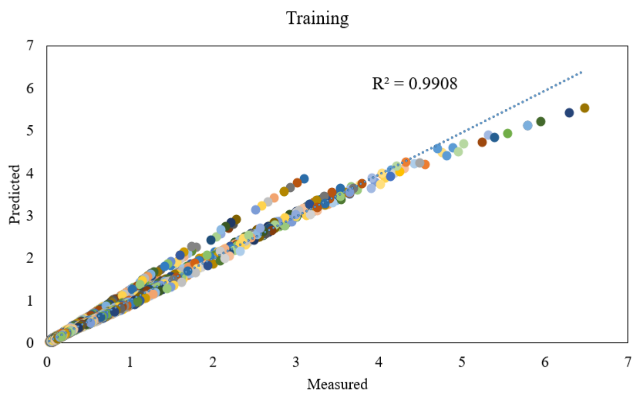

Fig. 5 Results of training part of ANN for retaining wall structure

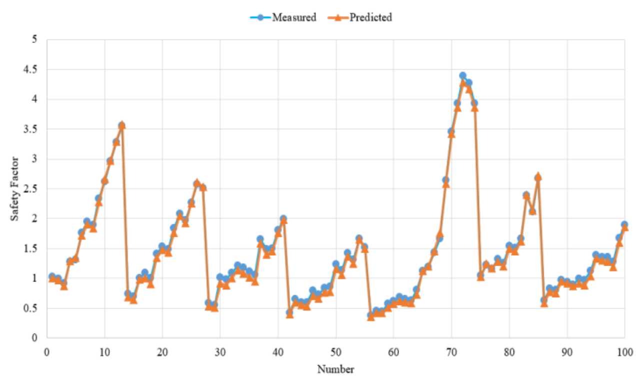

Fig. 7 Capability of the developed ANN models in predicting SF values for randomly selected 100 datasets

model for conditions in which different variables exist in the problem.

4.2 Dynamic analysis of retaining wall structure

Dynamic behavior of structures (in general) originates from a variety of parameters. They can be affected by geometry, soil conditions, and design of structural materials, and acceleration values (that is applied to the structure due to seismic load). As an important structure, the retaining wall structures which are widely-used in different applications of structural and geotechnical fields can show various performances under the influence of different parameters. In the current research, the intended structure performance was assessed under different conditions. Each parameter has its own effect under different PGA conditions. Figs. 8-12 show the effects of different parameters on retaining wall SF values. Fig. 8 shows the effect of height factor on retaining wall structure. As shown, the slope of the variation in different values of acceleration is very high. These values range from the highest value (i.e., 6) to the values less than 1. Generally, this shows the greater force is applied to the walls with higher values of height in dynamic state. The structure thickness parameter, which is in fact the resistant factor against static and dynamic forces, shows less changes compared to the height state (see Fig. 9). However, it should be mentioned that different thicknesses cannot be used in reality, and thickness is a parameter in which the engineering limitation is governed. Angle of internal friction of the soil influences the structure during earthquake using the determined grading. Basically, when grading value is greater, less pressure is applied during earthquake and its performance at higher intensities is accompanied with a smaller loss in the SF (see Fig. 10). The soil density relatively shows appropriate performance under different seismic conditions. It means that by increasing earthquake acceleration, the value of the wall SF decreases and the effect of density variations reduces. The reason is because of the fact that soil part acts as resistant force (see Fig. 11). Finally, density of the rocks used in wall structures indicates that this resistant factor shows more sensitive performances related to soil density. When there are many values for PGA, the walls with material of rocks with higher densities

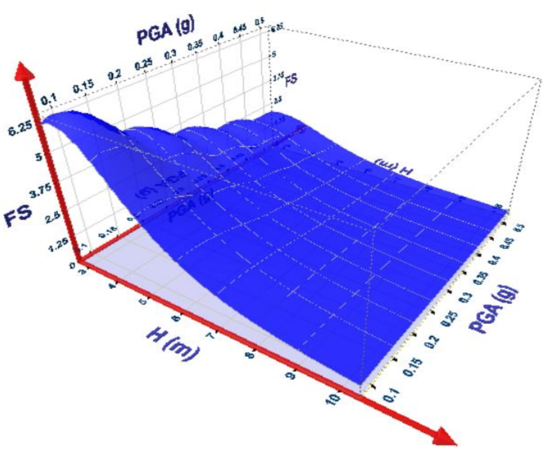

Fig. 8 The effect of height parameter on SF of retaining walls under dynamic conditions

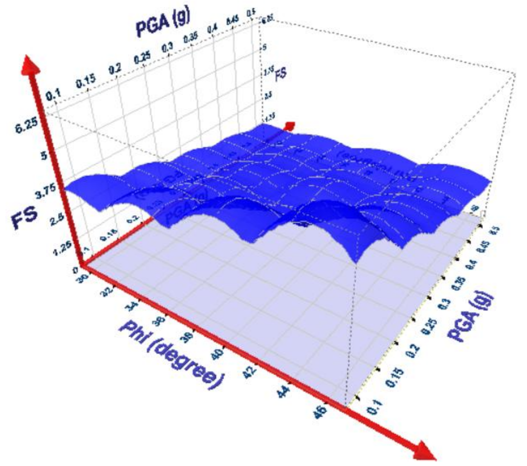

Fig. 10 The effect of soil friction angle on SF of retaining walls under dynamic conditions

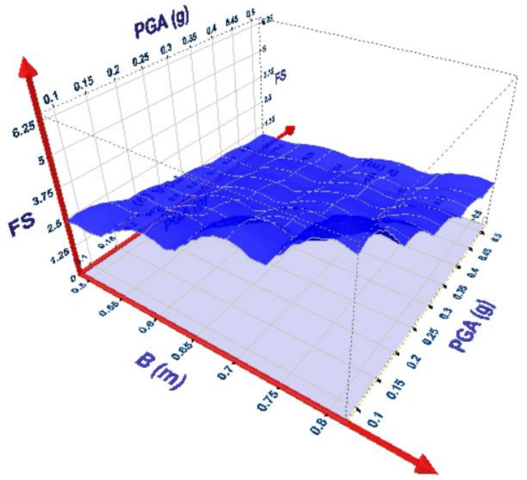

Fig. 9 The effect of wall thickness on SF values of retaining walls under dynamic conditions

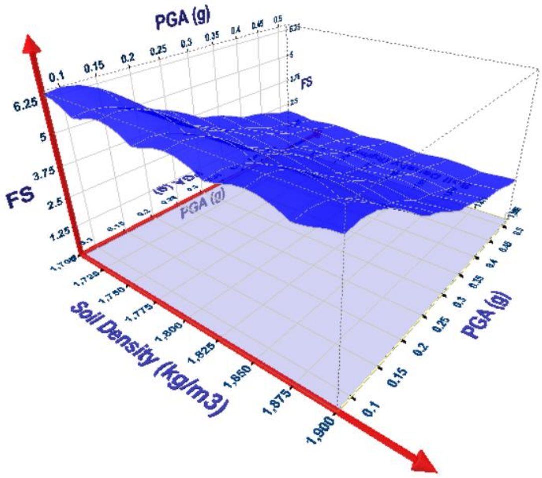

Fig. 11 The effect of soil density on SF of retaining walls under dynamic conditions

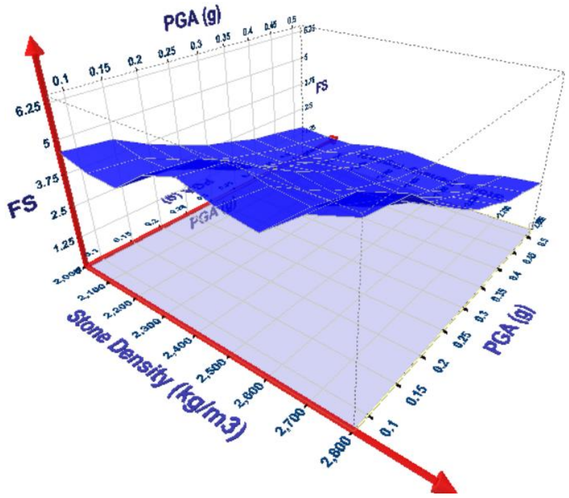

Fig. 12 The effect of rock density on SF of retaining walls under dynamic conditions

outperform those walls with material of rocks with lower densities (see Fig. 12).

Given the above-mentioned discussion, determining appropriate parameters under dynamic conditions may improve the performance of retaining wall structures. In this part, using optimization algorithms such as artificial bee colony, designing parameters of retraining walls can be optimized in order to obtain the optimum values for input parameters under dynamic conditions.

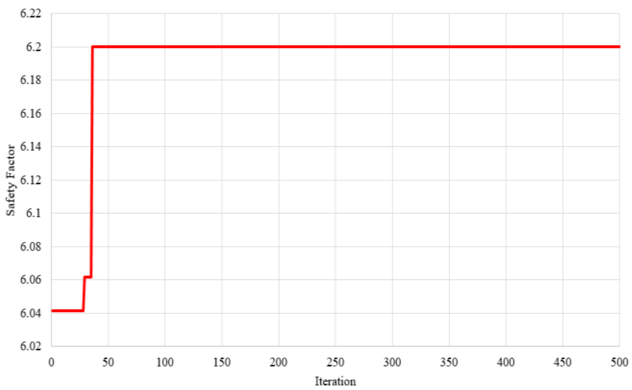

Fig. 13 Optimization results of retaining wall structure under dynamic conditions

4.3 Optimized structure design using ABC

In this part, the optimum and smart design is performed for retaining wall structures. One of the algorithms which have been recently used in the engineering fields is artificial bee colony (ABC) algorithm (Brajevic and Tuba 2013, Ghaleini *et al*. 2019). It was introduced and developed by (Karaboga 2005) for the first time. This algorithm is widely-used in different problems of civil engineering and geotechnical engineering. In short, this algorithm includes three types of bees: employed bees, onlooker bees and scout bees, each of these bees have different tasks to do, and in general, they seek to find the best results in coordination with each other. More information about this algorithm can be found in recent research (Irani and Nasimi 2011, Singh and Sundar 2011, Koopialipoor *et al*. 2018b).

The best solution is obtained when the best performance (lowest error) is achieved using trial and error procedure. Thus, a variety of models were designed and created in order to obtain the appropriate values for the optimization algorithm that governs these conditions. Finally, a number of 500 iterations and 300 bees were used in the best model which can optimize this problem. In Fig. 13, an example of optimization results obtained by ABC algorithm for SF design of retaining wall structure is shown.

As various designing and engineering limitations should be considered to optimize the wall parameters, the range of values is introduced to the optimization system based on Table 1. In the first stage, it is supposed that all variables can change within their range. Therefore, the SF was obtained in constant PGAs. In Table 3, the results of this optimization algorithm are shown. As a result, the optimized values of SF are greater than the designed ones. In addition, the optimum value of each input parameter was obtained. In Table 3, 5 samples were selected randomly in order to compare results of optimization design with the measured data. For all cases, SF values have been significantly increased i.e., (from 1.77 to 2.9), (from 0.34 to 2.68), (from 0.61 to 1.72), (from 2.71 to 2.86) and (from 1.18 to 1.95) for case number 1 to 5, respectively. Therefore, by developing ABC technique, optimum values of the model inputs together with SF can be obtained to have better design parameters.

In the second stage, a limitation was applied to the height of the structure ranging from 4 m to 6 m. Different values of input parameters were considered while wall

Table 3 Results of the first stage of optimization design

Sample	Wall height (m)		Wall width (m)		Internal friction angles (degree)		Soil density (Kg/m^3)		Stone density (Kg/m^3)		PGA (g)	SF	
	I	O	I	O	I	O	I	O	I	O		I	O
1	3	3.2	0.7	0.8	45	43.3	1850	1889	2000	2535	0.3	1.77	2.9
2	4	3.2	0.5	0.8	30	42.8	1700	1769	2000	2753	0.3	0.34	2.68
3	4	3	0.6	0.8	30	35.6	1900	1700	2800	2137	0.3	0.61	1.72
4	3	3.1	0.7	0.8	45	42.9	1700	1799	2800	2699	0.3	2.71	2.86
5	4	3.1	0.8	0.7	30	44.5	1750	1843	2800	2097	0.3	1.18	1.95

*O = optimum; I = initial value

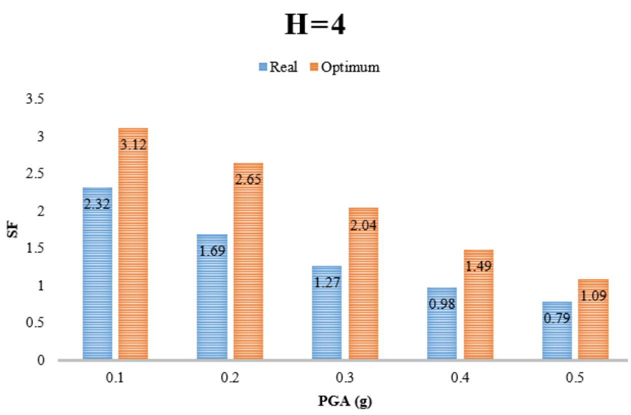

Fig. 14 A comparison of actual and optimized results of SF (wall height of 4 m)

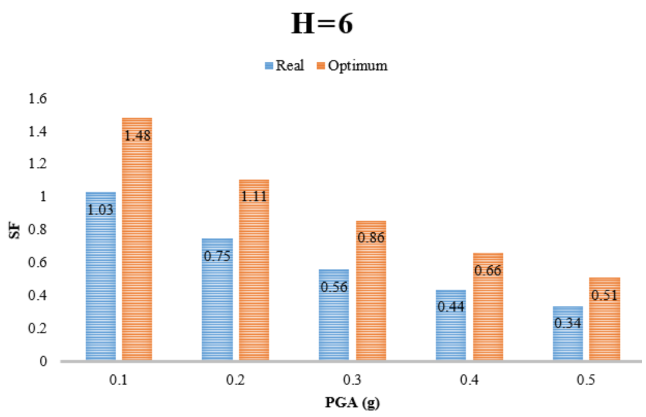

Fig. 16 A comparison of actual and optimized results of SF (wall height of 6 m)

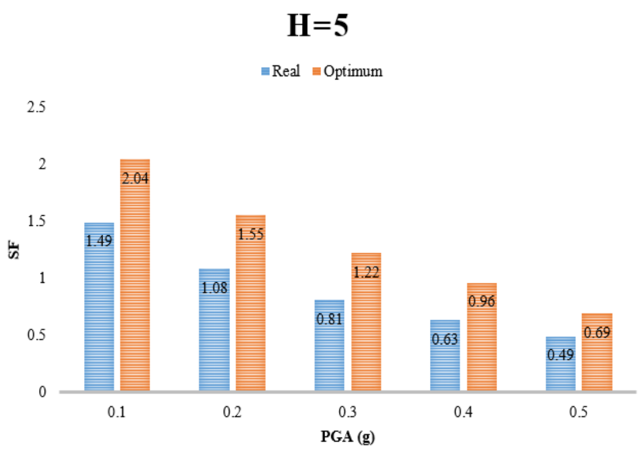

Fig. 15 A comparison of actual and optimized results of SF (wall height of 5 m)

width was fixed as 0.8 m. In addition, PGAs of 0.1 g, 0.2 g, 0.3 g, 0.4 g and 0.5 g were considered for each wall height and then, results of real SF and optimum SF are presented in last 2 columns. This table shows that, within this range, the values of the structure SF under dynamic conditions are obtained as maximum values. As shown, if designed values were put against these dynamic conditions, they could lead to the retaining wall structure failure. Therefore, using smart and optimum design, SF values of retaining walls can be significantly increased. Moreover, considering higher values of PGA, the difference between real and optimum SF will be increased.

Figs. 14-16 display a comparison between actual/real SF values and optimized values for height wall of 4 m, 5 m and6 m, respectively. As it can be seen, at wall height of 4 m, all SFs in all PGA are above 1 and provide a completely stable condition. However, actual values designed in PGA

Table 4 Results of the second stage of optimization

Model	Wall height (m)	Wall width (m)	Internal friction angles (degree)	Soil density (Kg/m^3)	Stone density (Kg/m^3)	PGA (g)	Real SF	Optimum SF
		0.8	43.9	1703	2568	0.1	2.32	3.12
		0.8	44.9	1732	2764	0.2	1.69	2.65
1	4	0.8	44.7	1717	2787	0.3	1.27	2.04
		0.8	44.0	1722	2766	0.4	0.98	1.49
		0.8	43	1726	2777	0.5	0.79	1.09
		0.8	44.7	1762	2709	0.1	1.49	2.04
		0.8	44.6	1751	2684	0.2	1.08	1.55
2	5	0.8	43.4	1721	2798	0.3	0..81	1.22
		0.8	44.9	1739	2776	0.4	0.63	0.96
		0.8	44.8	1709	2600	0.5	0.49	0.69
		0.8	44.6	1708	2768	0.1	1.03	1.48
		0.8	44.0	1735	2799	0.2	0.75	1.11
3	6	0.8	44.5	1739	2761	0.3	0.56	0.86
		0.8	44.5	1746	2769	0.4	0.44	0.66
		0.8	44.4	1724	2794	0.5	0.34	0.51

values of 0.4 and 0.5 are unstable. At wall height of 5 m, the walls in real mode are stable to PGA values of 0.2 g, while for optimum mode, it maintains the stability of the structure up to 0.3 g. Stability of different structures against dynamic loading has been comprehensively investigated (Firouzianhaji *et al*. 2014, Wang *et al*. 2014, Behera *et al*. 2017, Gudehus and Touplikiotis 2018, Koopialipoor *et al*. 2018c, Abedini *et al*. 2019, Mehrmashhadi *et al*. 2019b). However, under the conditions below 1, optimal values have better performance under dynamic conditions. The same trend can be seen for wall height of 6 m. As a result, in all cases with different parameters, optimal design of the retaining wall structure can help in sustainability.

5. Conclusions

Retaining wall structures are one of the most important structures for support of excavation and slope stability applications. In this research, various designs were created to be placed under different acceleration conditions. These parameters include the wall height and thickness, soil density, rock density, and internal friction angle of the soil. In these conditions, the SF of retaining wall was assessed/calculated under different PGAs. The total number of designed models was more than 9500 different cases. The use of different models causes the modeling accuracy to increase. However, the analysis of these designs is less common in simple methods. Therefore, smart models were utilized in order to establish appropriate relations among different variables. In the current research, by its appropriate performance, the neural network could obtain a relationship to assess the SF during the dynamic loads for the retaining wall structure. Performance of ANN model was obtained for training and testing sets as R^2 = 0.9908 and 0.9915 and RMSE = 0.0085 and 0.0086, respectively.

In optimization stage, the effect of different parameters was assessed based on design and engineering limitations. Then, the retaining structure was optimized against dynamic loads in accordance with these limitations. Given the optimum designs under first stage conditions, the maximum values of 2.9, 2.68, 1.72, 2.86, and 1.95 were obtained versus PGA = 0.3, respectively. This is while, if designs were not optimized, the failure risk in the structure for these dynamic conditions would reduce to 1.77, 0.34, 0.61, 2.71, and 1.18. Therefore, using smart system-based models, the obtained SF values can be increased and subsequently, it will reduce the earthquake dangers. In the second stage, using smart design, a good improvement was achieved considering different values of wall height (i.e., 4 m, 5 m, 6 m) under dynamic conditions. It was found that considering higher values of PGA, the difference between real and optimum SF will be increased. Generally, this study introduced an intelligent design process for retaining wall structures in order to increase their SF values. The same process can be applied for some other civil engineering applications such as slope stability.

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