Visual Abstract

Forecasting the bearing capacity of the mixed soil using artificial neural network

Abdoullah Namdar
Faculty of Architecture and Civil Engineering, Huaiyin Institute of Technology, Huai'an, China
Department for Management of Science and Technology Development, Ton Duc Thang University, Ho Chi Minh City, Vietnam
Faculty of Environment and Labour Safety, Ton Duc Thang University, Ho Chi Minh City, Vietnam
abdoullah.namdar@tdtu.edu.vn

ABSTRACT. The bearing capacity of soil changes owing to the mechanical properties of the soil and it influences the structural stability. In most of the geotechnical engineering projects, there are several soil mechanic experiments, that need interpretation before application. The mechanical properties of soil interaction make the prediction of soil bearing capacity complex. However, the enhancement of construction project safety needs the interpretation of soil experiments and design results for proper application in a geotechnical engineering project. In this study, artificial neural network is proposed for the evaluation of the mixed soil characteristics to forecast the safe bearing capacity of soil due to the mechanical properties of the soil interaction phenomenon. The results for prediction of the safe bearing capacity reveal that the R^2 and RMSE for all mechanical properties effects on safe bearing capacity are 0.98 and 0.02, these values can provide a suitable accuracy for the prediction of the safe bearing capacity of the mixed soil. The higher inaccuracy is obtained when only the influence of single mechanical property on the mixed soil is considered in the prediction of the safe bearing capacity. This study supports the enhancement of geotechnical engineering design quality through the prediction of safe bearing capacity from characterized mechanical properties of the soil.

KEYWORDS. Bearing Capacity; Mechanical Properties; Artificial Neural Network; Mixed Soil.

OPEN ACCESS

Citation: Namdar, A., Forecasting the bearing capacity of the mixed soil using artificial neural network, Frattura ed Integrità Strutturale, xx (2020) 285-294.

Received: 26.04.2020
Accepted: 09.05.2020
Published: 01.07.2020

INTRODUCTION

Laboratory experimental activity was performed for the characterization of red soil in soil mixture process and the assessment of soil mixture mechanical properties was performed for developing acceptable safe bearing capacity [1]. The bearing capacity of mixed soil foundation was investigated by changing the concrete footing dimensions and the soil mechanical properties systematically [2-3]. To study the bearing capacity of subsoil in the coastal region, the tsunami behavior was numerically simulated and mangrove for enhancement of subsoil was proposed [4]. The bearing capacity of soil foundation also was related to the seismic displacement of the soil foundation [5]. The bearing capacity of the embankment soil foundation was enhanced by developing dense zones in the subsoil [6]. The bearing capacity of the clay and composite ground were investigated [7-8], and soil mixture such as silty clay, soft Bangkok clay, fly and bottom ash mixtures, sand-clay mixtures using kenaf fiber reinforcement, chemical etc, were used to improve soil strength and stiffness [9-13]. With attention to the influence of the mineralogy on the soil and other construction materials [14-16], the bearing capacity of the soil is significantly controlled by the soil mineral.

There are several types of research on the analytical, experimental and numerical analysis of the soil foundation, and the soil dynamic and static response evaluated with experimental, analytical and numerical results are reported in the literature [1-6, 14-15]. On the other hand, different prediction techniques were applied on mild steel pressure vessel, crack propagation, compressive failure surface of cement concrete, natural stone and concrete footing design [17-22]. To identify and apply the best results in the geotechnical engineering design the advanced technique for decision making is needed. However, the mechanical properties of soil interaction make the prediction of soil bearing capacity difficult. The goal of this study is to forecast the influence of mechanical properties of soil on bearing capacity of the mixed soil, and to predict each element of soil mechanical properties separately. To combine all the mechanical properties on the safe bearing capacity of the soil foundation, the artificial neural network (ANN) is applied.

METHODOLOGY

The maximum dynamic load and the statics load individually or combined that can be applied on the soil foundation without the unallowable settlement, deformation and shear failure are called the safe bearing capacity of the soil foundation. The safe bearing capacity of the soil foundation is a margin safety in geotechnical engineering design.

The mechanical properties of the soil play an important role in the soil foundation and they support structural stability in transferring load from the structure to the subsoil. The appropriate interpretation of soil experiments results significantly enhance quality of geotechnical engineering design. On the other hand, the mechanical properties of soil interaction make complex the prediction of the foundation soil bearing capacity. The mechanical properties of the mixed soil and the calculated safe bearing capacity are shown in Tab. 1. Fig. 1 shows a flowchart to explain the steps in this investigation. The entire study contains five steps which are review analysis, problem identification, data selection, statistical analysis and interpretation of results for drawing conclusions. The procedure of the present work includes the behavior assessment of optimum moisture content, density, angle of friction and cohesive of the mixed soil, and the evaluation of the safe bearing capacity through the artificial neural network. In this study, for the interpretation of soil experimental results, each mechanical property of soil versus safe bearing capacity is graphically proposed and compared. It is aimed at analyzing the effect of the optimum moisture content (OMC) (%), the density (kN/m^3), the angle of friction (deg) and the cohesive of soil (kN/m^2) on the safe bearing capacity of the soil separately. Fig. 2 shows the distribution of the optimum moisture content, the density, the angle of friction and the cohesive of the mixed soil. The following are the steps of the research methodology.

Step 1, review analysis: The safe construction of a structure depends on the safe bearing capacity of soil foundation. The geotechnical engineering design of a soil foundation needs to decide if the soil behaves differently from place to place owing to the variation of the mineralogy and morphology of the natural soil. These combination parameters create a difficult situation to choose a safe bearing capacity in civil engineering project by the geotechnical designer.

Step 2, problem identification: The mechanical properties of soil interaction make the prediction of soil bearing capacity complex. It is needed to find an effect of each mechanical properties on mixed soil safe bearing capacity and to present guidelines to find the best decision. The soil mixture is a technique based on the soil mineralogy and morphology to control soil strength and stiffness, but because of probability function in soil mixture design and development of unexpected results during soil mixture process, feasible techniques are to be applied on soil mixture in geotechnical engineering design and soil foundation strengthening. However improper soil mixture design or use of unsuitable mixed soil hurt the strength of the soil foundation and they lead to a collapse of the structural elements and the whole structure, consequently.

Step 3, data selection: The several soil mechanic experiments need interpretation before application. The mechanical properties of the mixed soil and the calculated safe bearing capacity are shown in Tab. 1, that is reported in the literature. The distribution of the optimum moisture content, density, angle of friction and cohesive of the mixed soil analyzed and their influence on the safe bearing capacity at each mixture design are studied. This process is repeated for 31 soil mixture models and significant factors impacting on the safe bearing capacity are identified and explained. It is well known that with the increasing number of collected data from the geotechnical site investigation or the laboratory experimental soil simulation the accuracy of the statistical analysis is more accurate in prediction and assessment.

Step 4, statistical analysis: Each element of soil mechanical properties behaves differently in a group of selected data from those reported in the literature [1], and the interaction between these elements requires a suitable technique for selecting the range of safe bearing capacity in the soil mixture design.

To establish a histogram for safe bearing capacity of soil, the class interval of 500 was selected and the frequency of safe bearing capacity computed. To find intensity of repeating safe bearing at each 500 interval, relative frequency is divided into classes. After drawing rectangle for each class in construct histogram, the probability of safe bearing capacity was draw for the prediction. The Central Limit Theorem was used for probability analysis. In application of the Central Limit Theorem, a large enough sample is needed. It was suggested sample size of 30 or more is sufficient for application of Central Limit Theorem [23]. In this study, 31 sample were selected from an experimental investigation, so the Central Limit Theorem is applicable for probability analysis and prediction of safe bearing capacity.

For this work, the following equations are used:

$$\bar{X} = \frac{X_1 + \ldots + X_n}{n} = \text{Sample mean} \tag{1}$$

$$S_n = X_1 + \ldots + X_n = \text{Sample observation} \tag{2}$$

$$\bar{X} \sim N\left[\mu, \frac{\sigma^2}{n}\right] \text{ approximately} \tag{3}$$

$$S_n \sim N\left(n\mu, n\sigma^2\right) \text{ approximately} \tag{4}$$

where X_1, X_2, ………, X_n constitute the random sample from population, μ is the Mean and σ^2 is the Variance [23].

ANN is applied to predict soil foundation behavior considering the mechanical properties of the mixed soil. ANN contents three layers, which are the input, the hidden and the output layers. These three layers integrate assessment and prediction of safe bearing capacity mechanism of the soil foundation. In this study, one hidden layer has been used in the ANN analysis. The minimum hidden layer in the ANN is one and maximum hidden layers depend on the problem complexity. The safe bearing capacity prediction by the effect of optimum moisture content (%), density (kN/m^3), angle of friction (deg) and cohesive of soil (kN/m^2) was performed using ANN. For the cover effect of each element of the mechanical properties in the prediction of the safe bearing capacity, R^2 and RMSE of optimum moisture content (%), density (kN/m^3), angle of friction (deg) and cohesive of soil (kN/m^2) on the safe bearing capacity of the soil are separately analyzed in the first stage. In the second stage, R^2 and RMSE of the safe bearing capacity are analyzed considering all mechanical properties together.

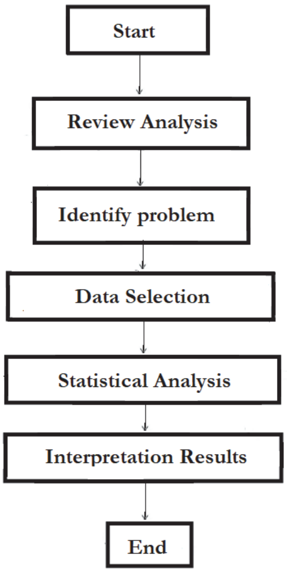

Figure 1: Flowchart for explaining stepwise in this investigation.

Step 5, interpretation results for drawing conclusion: The morphology of mixed soil from the internal angle of friction, the mineralogy of mixed soil from soil cohesive, the moisture content and the density of the mixed soil have been interpreted to identify the best occurrence of safe bearing capacity. The method performed in the present work can be a guideline to be applied to soil mixed design in geotechnical engineering to improve subsoil strength and stiffness at acceptable quality.

Mixture Number	Optimum Moisture Content (%)	Density (kN/m^3)	Angle of Friction (deg)	Cohesive (kN/m^2)	Safe Bearing Capacity (kN/m^2)
1	11.2	21.94	38	21	2036.22
2	10.61	21.83	39	12	1926.51
3	10.72	23.46	39	46	3334.44
4	12.15	23.82	36	28	1833.97
5	9.58	23.02	40	8	2060.95
6	22.39	20.09	32	20	888.70
7	18.86	20.95	32	26	1026.83
8	14.56	23.35	18	44	427.74
9	14.23	20.96	30	28	718.00
10	16.83	21.61	36	22	1567.43
11	18.27	21.56	15	47	349.69
12	16.76	21.07	22	49	608.36
13	20.21	21.83	21	33	431.67
14	18.68	21.179	27	38	786.91
15	19.34	20.96	29	8.5	487.99
16	16.55	20.31	31	22	834.95
17	21.14	21.18	20	27	341.94
18	20.79	21.18	20	23	311.26
19	16.31	20.96	33.5	12	879.86
20	20.88	20.96	24	23	439.56
21	23.00	21.5	23	10	287.22
22	20.06	22.05	23	32	503.18
23	20.11	21.07	23	22	398.52
24	20.75	20.41	19	22	280.01
25	22.69	20.748	22	16	310.33
26	18.87	21.72	21	28	389.32
27	20.31	21.94	24	26	479.81
28	19.51	21.72	17.5	28	298.58
29	20.52	22.59	17	9	170.00
30	18.99	22.47	18	24	286.20
31	14.56	21.61	28	26	700.05

Table 1: Soils mechanical properties and safe bearing capacity [1].

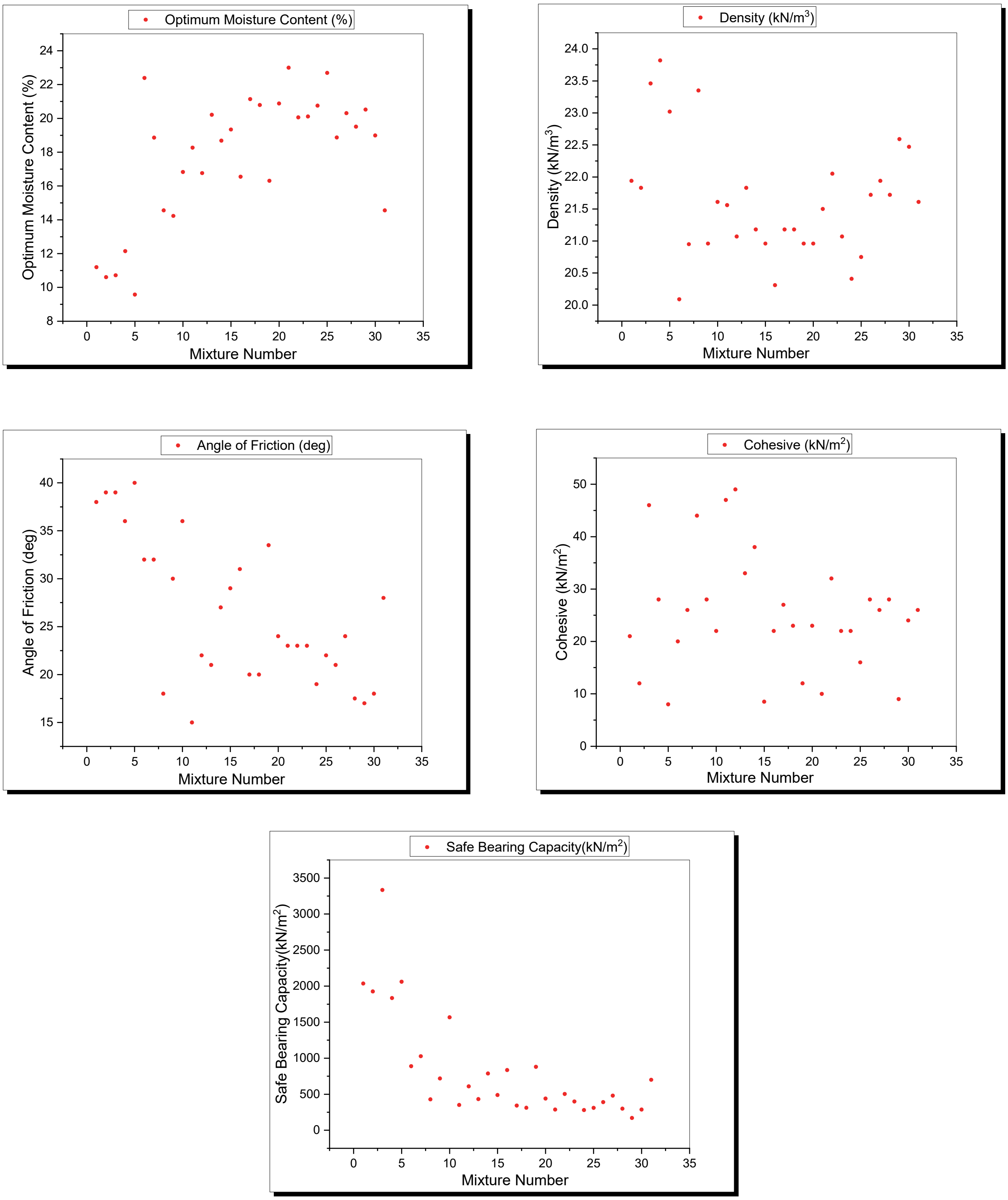

Figure 2: The distribution of the mechanical properties of the mixed soil.

RESULTS AND DISCUSSION

The safe bearing capacity of the soil is a critical factor in the geotechnical engineering design and plays the main role in structural stability. The enhancement of the safe bearing capacity of the soil foundation is considered important in geotechnical design basis. The soil mixture significantly changes the safe bearing capacity of the soil foundation. The soil mixture process develops safe bearing capacity in the high tolerance, it occurs because of the soil mechanical properties interaction. After the performance of the soil mixture, there is a complex result that requires to be investigated for enhancing structural stability. Fig. 2 shows the distribution of the optimum moisture content, density, angle of friction, cohesive and safe bearing capacity of the mixed soil are following different mechanisms. Fig. 3 shows the distribution of the safe bearing capacity associated to characterized optimum moisture content, density, angle of friction and cohesive of the mixed soil. Safe bearing capacity exhibits different mechanisms because of the mechanical properties of the soil interaction, and the safe bearing capacity develops differently at each soil mixture model. Fig. 3 is based on calculation done to show the direct relationship between different soil mechanical properties and the direct relationship between the safe bearing capacity and each individual soil mechanical property, in order to analyze the influence of each single mechanical property of the mixed soil on safe bearing capacity. However, to find influence all mechanical properties on safe bearing capacity, ANN, that is a soft computing technique, is necessary. Artificial neural network. The ANN gathering all mechanical properties affects the safe bearing capacity.

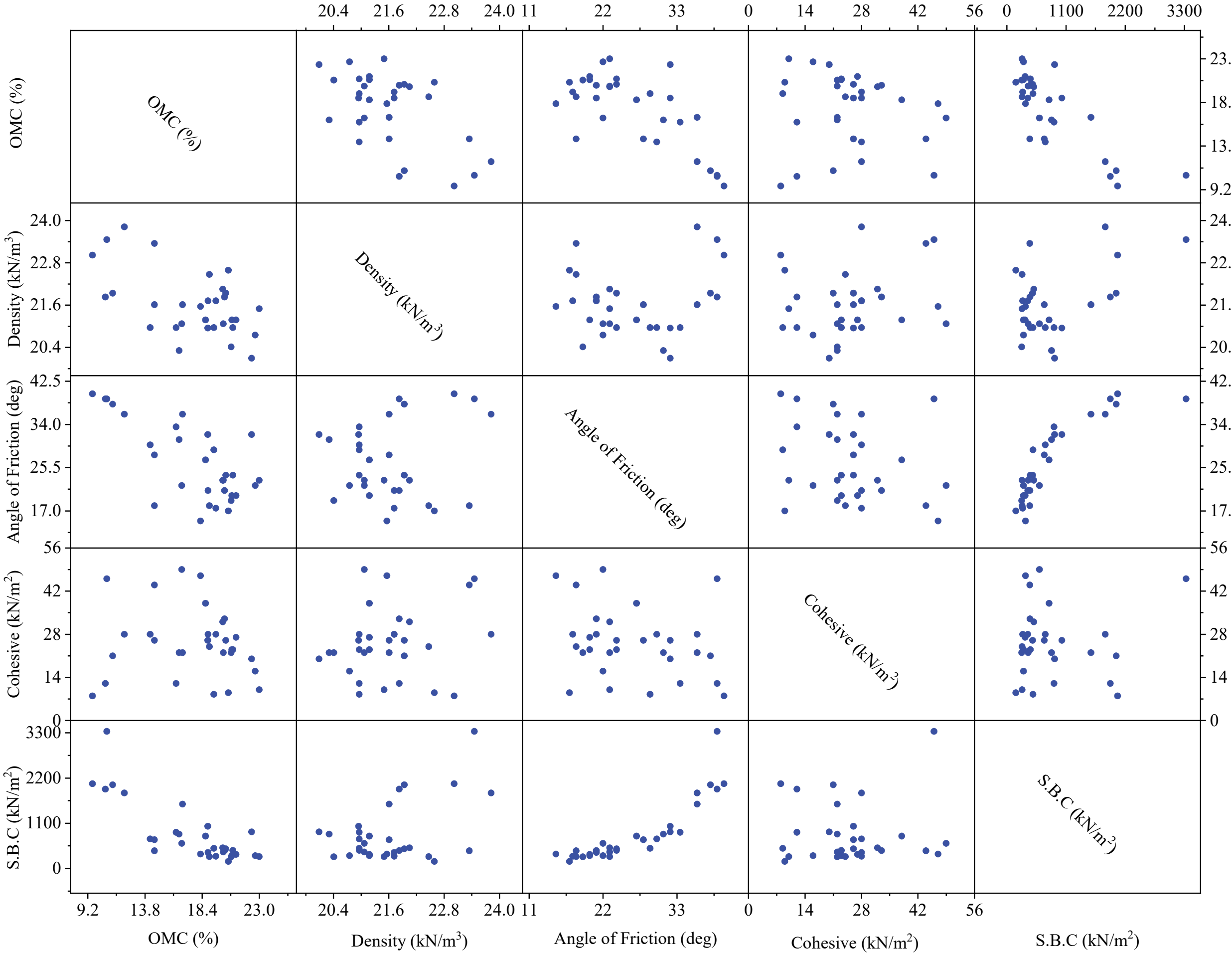

Figure 3: The prediction of safe bearing capacity (S.B.C) according to the mechanical properties.

Fig. 4 shows the safe bearing capacity frequency. The histogram presented in Fig. 4 is based on a soft computing technique (SCT) for the evaluation of the frequency of repeated safe bearing capacity, and it supports soil mixture design. The histogram is depicted for safe bearing capacity prediction analysis and it shows the distribution of values for the probability of safe bearing capacity in soil mixture design. The shape of the histogram is skewed right. There is a large number of cases with low value of safe bearing capacity and few for high value.

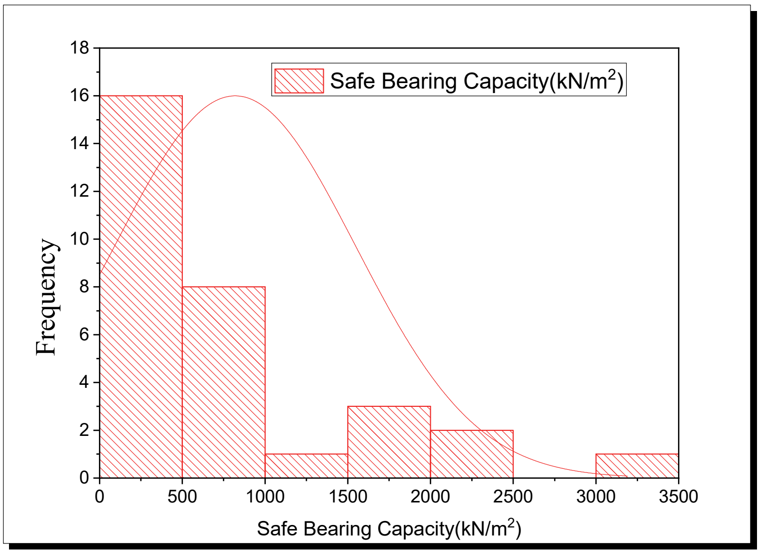

Figure 4: The safe bearing capacity according to the number of occurrences.

The internal angle of friction of soil has more influence on safe bearing capacity prediction. The increasing density, cohesive and internal angle of friction of mixed soil results in increasing the safe bearing capacity of the soil foundation, while the soil with higher moisture hurts the safe bearing capacity. The increase of optimum moisture content of the soil causes the reduction of density, cohesive and internal angle of friction of mixed soil and it results in the reduction of soil safe bearing capacity. The input, hidden and output layers of the ANN are constructed for assessing the effect of modification of soil mechanical properties in the prediction of the safe bearing capacity mechanism of the soil foundation.

Tab. 2 shows the statistical analysis for examining the influence of each mechanical properties on safe bearing capacity. For the cover effect of each element of the mechanical properties in the prediction of the safe bearing capacity, R^2 and RMSE showed that the combination of all mechanical properties together enhances the accuracy of the safe bearing capacity prediction results. The mechanical properties interaction increases the safe bearing capacity of the mixed soil. According to Tab. 2, the value of the R^2 and RMSE for all mechanical properties effects on safe bearing capacity are 0.98 and 0.02, these values can provide a suitable accuracy for the prediction of safe bearing capacity of the mixed soil. The higher inaccuracy obtained when only the influence of the cohesive of the mixed soil is considered in the prediction of the safe bearing capacity.

Mechanical properties	R^2	RMSE
Optimum Moisture Content	0.731	0.683
Density	0.597	0.293
Angle of friction	0.861	0.230
Cohesive of Soil	6.04E-4	10.97
All mechanical properties	0.98	0.02

Table 2: Statistical analysis for realizing the influence of each mechanical properties on safe bearing capacity.

DISCUSSION

The mineralogy and the morphology of the soil interaction in the soil mixture process cause the distribution of the mechanical properties of the mixed soil and they lead to the development of the different levels of safe bearing capacity for each mixed soil. The moisture content of a mixed soil significantly affects the mineralogy and the morphology of the soil interaction. The optimum moisture content (%), density (kN/m³), angle of friction (deg) and cohesive of soil (kN/m²) never behave linearly in a group of mixed soils because of mechanical properties interaction. The mineralogy, the morphology and the moisture content are changed with soil mixture and result in developing a new safe bearing capacity. For the design of the mixed soil, the attention to the soil mineralogy supports the geotechnical engineering design. Analyzing the soil mechanical properties influence on the safe bearing capacity of the soil guides the geotechnical engineer to use proper soil which impacts on mineralogy and morphology of the mixed soil for achieving the best safe bearing capacity. For example, selecting the suitable percentage of a soil may increase soil strength because of the soil mineralogy or morphology. On the other hand, a combination of soil mineralogy and morphology controls moisture content of the soil. However, adjusting the moisture content of the mixed soil governs the strength of the soil. The results of this study reveal the importance of mineralogy science for civil engineering. It is an indirect relationship between mechanical properties of the mixed soil and the load transfer from the structure to the subsoil. Considering the effect of optimum moisture content (%), density (kN/m^3), angle of friction (deg) and cohesive of soil (kN/m^2) on the safe bearing capacity of the soil separately could not provide a suitable prediction, while combining the effect of all mechanical properties on predicting safe bearing capacity provides suitable results in safe bearing capacity prediction. It has been reported in [24] that the mechanical properties of the soil foundation significantly control the lateral and vertical displacements of the subsoil and the failure pattern of the subsoil.

In this study, an experimental report was used for the prediction and the probability analysis of the soil safe bearing capacity using advance SC techniques. There are several excellent research works available in the literature which apply different methods of statistical analysis, for example many research works can be referred to investigation on materials damage assessment [25-28], fatigue strength [29-31], crack analysis [32-33], strain analysis [34-35], and nonlinear displacement mechanism [24]. The application of statistical analysis on these researches enrich literature for industrial and educational sections.

CONCLUSION

In most of the mixed soil used in a construction site, the safe bearing capacity behaves differently and results in various structures stability. The mineralogy and the morphology of mixed soil are considered in the safe bearing capacity of soil through the application of the artificial neural network (ANN) for the prediction of soil foundation behavior considering mechanical properties of the mixed soil. This feasible technique supports the application of soil mixture in geotechnical engineering design. The following goal has been reached in the present study.

- The internal angle of friction of soil has more influence on the safe bearing capacity prediction.
- Increasing density, cohesive and internal angle of friction of mixed soil results in increasing safe bearing capacity of the soil foundation, while increasing moisture has a negative influence on the safe bearing capacity of the soil. However, the combination of soil mineralogy and morphology controls moisture content of the soil and adjusting the moisture content of the mixed soil governs the strength of the soil mixture. Increasing optimum moisture content of the soil causes the reduction of density, cohesive and internal angle of friction of mixed soil, resulting in a reduction of soil safe bearing capacity.
- Most of the safe bearing capacity occurs below 1000 (kN/m^2). It is important for achieving high bearing capacity with proper interaction of mechanical properties of the mixed soil.
- For prediction of the safe bearing capacity, the R^2 and RMSE for all mechanical properties effects on safe bearing capacity are 0.98 and 0.02, these values can provide a suitable accuracy for prediction safe bearing capacity of the mixed soil. The higher inaccuracy is obtained when only the influence of the cohesive of the mixed soil is considered in prediction of the safe bearing capacity. It can be concluded that the mechanical properties interaction increases the safe bearing capacity. The method presented in the present work can be a guideline to apply soil mixed design in geotechnical engineering to improve the subsoil quality.
- Plasticity is the main factor involved in the soil safe bearing capacity [1], it has not been evaluated in the present work and it could be a future research work. In the study of the plasticity, the level of moisture content and the mineralogy are two variables that could be analyzed using a suitable statistical technique to find their relationship with soil foundation safe bearing capacity.

REFERENCES

[1] Namdar, A. and Pelko, M. K. (2009). Bearing capacity of mixed soil model, Fract. Struct. Int., 3 (7), pp. 73-79. DOI: 10.3221/IGF-ESIS.07.06.

[2] Namdar, A. and Feng, X. (2014). Evaluation of safe bearing capacity of soil foundation by using numerical analysis method, Fract. Struct. Int., 8 (30), pp. 138-144. DOI: 10.3221/IGF-ESIS.30.18.

[3] Namdar, A. and Pelko, M. K. (2009). Numerical analysis of soil bearing capacity by changing soil characteristics, Fract. Struct. Int., 3 (10), pp. 38-42. DOI: 10.3221/IGF-ESIS.10.05.

[4] Namdar, A. and Nusrath, A. (2010). Tsunami numerical modeling and mitigation, Fract. Struct. Int., 4 (12), pp. 57-62. DOI: 10.3221/IGF-ESIS.12.06.

[5] Namdar, A. (2016). A numerical investigation on soil-concrete foundation interaction, Proc. Struct. Integ., 2, pp. 2803-2809. DOI: 10.1016/j.prostr.2016.06.351.

[6] Namdar, A. and Gopalakrishna, G. S. (2008). Seismic mitigation of embankment by using dense zone in subsoil, Emir. J. Eng. Res., 3(13), pp. 55–61.

[7] Skempton, A.W. (1951). The bearing capacity of clays, Build. Res. Congr. 1, pp. 180–189.

[8] Pengpeng, N., Yaolin, Y. and Songyu, L. (2019). Bearing capacity of composite ground with soil-cement columns under earth fills: Physical and numerical modelling, Soils Found., 59, pp. 2206–2219. DOI: 10.1016/j.sandf.2019.12.004.

[9] Horpibulsuk, S., Phetchuay, C., Chinkulkijniwat, A. and Cholaphatsorn, A. (2013). Strength development in silty clay stabilized with calcium carbide residue and fly ash, Soils Found., 53(4), pp. 477–486. DOI: 10.1016/j.sandf.2013.06.001.

[10] Vichan, S. and Rachan, R. (2013). Chemical stabilization of soft Bangkok clay using the blend of calcium carbide residue and biomass ash, Soils Found., 53 (2), pp. 272–281. DOI: 10.1016/j.sandf.2013.02.007.

[11] Kim, B., Prezzi, M. and Salgado, R. (2005). Geotechnical properties of fly and bottom ash mixtures for use in highway embankments, J. Geotech. Geoenviron. Eng., 131(7), pp. 914–924.

[12] Esmaeilpour Shirvani, N., Taghavi Ghalesari, N., Khaleghnejad Tabari, M. and Janalizadeh Choobbasti, A. (2019). Improvement of the engineering behavior of sandclay mixtures using kenaf fiber reinforcement, Transp. Geotech., 19, pp. 1–8. DOI: 10.1016/j.trgeo.2019.01.004.

[13] Estabragh, A.R., Rafatjo, H. and Javadi, A.A. (2014). Treatment of an expansive soil by mechanical and chemical techniques, Geosynth. Int., 21, pp. 233–243. DOI: 10.1680/gein.14.00011.

[14] Namdar, A. (2010). Mineralogy in geotechnical engineering, J. Eng. Sci. Tech. Rev., 3 (1), pp. 108-110.

[15] Namdar, A. (2012). Natural minerals mixture for enhancing concrete compressive strength, Fract. Struct. Int., 6 (22), pp. 26-30. DOI: 10.3221/IGF-ESIS.22.04.

[16] Muhammad, N., Zakaria, I. and Namdar, A. (2013). Modification of kaolin mineralogy and morphology by heat treatment and possibility of use in geotechnical engineering, Int. J. Geomater., 5(2), pp. 685-689. DOI:10.21660/2013.10.3217.

[17] Huffman, P. J., Ferreira, J., Correia, J., De Jesus, A., Lesiuk, G., Berto, F., Fernandez-Canteli, A. and Glinka, G. (2017). Fatigue crack propagation prediction of a pressure vessel mild steel based on a strain energy density model, Fract. Struct. Int., 11(42), pp. 74-84. DOI: 10.3221/IGF-ESIS.42.09 .

[18] Funari, M. F., Greco, F., Lonetti, P. and Spadea, S. (2018). A numerical model based on ALE formulation to predict crack propagation in sandwich structures, Fract. Struct. Int., 13(47), pp. 277-293. DOI: 10.3221/IGF-ESIS.47.21.

[19] Tzamtzis, A. and Kermanidis, A. T. (2015). Fatigue crack growth prediction in 2xxx AA with friction stir weld HAZ properties, Fract. Struct. Int., 10(35), pp. 396-404. DOI: 10.3221/IGF-ESIS.35.45

[20] Caporale, A. and Luciano, R. (2014). A micromechanical four-phase model to predict the compressive failure surface of cement concrete, Fract. Struct. Int., 8(29), pp. 19-27. DOI: 10.3221/IGF-ESIS.29.03.

[21] Contrafatto, L. and Cosenza, R. (2014). Prediction of the pull-out strength of chemical anchors in natural stone, Fract. Struct. Int., 8(29), pp. 196-208. DOI: 10.3221/IGF-ESIS.29.17.

[22] Namdar, A. (2020). The application of soil mixture in concrete footing design using the linear regression model, Mat Design Process Comm., e179. DOI: 10.1002/mdp2.179

[23] Navidi, W., Statistics for Engineers and Scientists, 3rd ed, (2011). Published by McGraw-Hill.

[24] Namdar, A. and Dong, Y. (2020). The embankment-subsoil displacement mechanism, Mat. Des. Process Comm., e155. DOI: 10.1002/mdp2.155.

[25] Fernandino, DO., Tenaglia, N., Di Cocco, V., Boeri, RE. and Iacoviello, F. (2020). Relation between microstructural heterogeneities and damage mechanisms of a ferritic spheroidal graphite cast iron during tensile loading, Fat. Fract. Eng. Mater. Struct., 6(43), pp. 1262-1273. DOI: 10.1111/ffe.13221.

[26] D'Angela, D., Ercolino, M., Bellini, C., Di Cocco, V. and Iacoviello, F. (2020). Characterisation of the damaging micromechanisms in a pearlitic ductile cast iron and damage assessment by acoustic emission testing, Fat. Fract. Eng. Mater. Struct., 5(43), pp. 1038-1050. DOI: 10.1111/ffe.13214.

[27] D'Angela, D., Ercolino, M., Bellini, C., Di Cocco, V. and Iacoviello, F. (2020). Analysis of acoustic emission entropy for damage assessment of pearlitic ductile cast irons, Mat. Des. Process Comm., pp. 1-5. DOI: 10.1002/mdp2.158.

[28] Fernandino, D. O., Di Cocco, V., Tenaglia, N., Bellini, C., Iacoviello, F. and Boeri, R. E. (2019). Microstructural damage evaluation of ferritic-ausferritic spheroidal graphite cast iron, Fract. Struct. Int., 14(51), pp. 477-485. DOI: 10.3221/IGF-ESIS.51.36.

[29] Berto, F., Campagnolo, A., Welo, T., Vantadori, S. and Carpinteri, A. (2017). Multiaxial fatigue strength of titanium alloys, Fract. Struct. Int., 11(41), pp. 79-89. DOI: 10.3221/IGF-ESIS.41.12.
[30] Marsavina, L., Iacoviello, F., Pirvulescu, LD., Di Cocco, V. and Rusu, L. (2019). Engineering prediction of fatigue strength for AM50 magnesium alloys, Int. J. Fat., 127, pp. 10-15. DOI: 10.1016/j.ijfatigue.2019.05.028.
[31] Bellini, C., Di Cocco, V., Favaro, G., Iacoviello, F. and Sorrentino, L. (2019). Ductile cast irons: Microstructure influence on the fatigue initiation mechanisms, Fat. Fract. Eng. Mater. Struct., 9(42), pp. 2172-2182. DOI: 10.1111/ffe.13100.
[32] Iacoviello, F., Di Cocco, V. and Bellini, C. (2019). Fatigue crack propagation and damaging micromechanisms in Ductile Cast Irons, Int. J. Fat., 124, pp. 48-54. DOI:10.1016/j.ijfatigue.2019.02.030.
[33] Iacoviello, F., Di Cocco, V. and Bellini, C. (2019). Overload effects on fatigue cracks in a ferritized ductile cast iron, Int. J. Fat., 127, pp. 376-381. DOI: 10.1016/j.ijfatigue.2019.06.028.
[34] Berto, F., Campagnolo, A., Meneghetti, G. and Tanaka, K. (2016). Averaged strain energy density-based synthesis of crack initiation life in notched steel bars under torsional fatigue, Fract. Struct. Int., 10(38), pp. 215-223. DOI: 10.3221/IGF-ESIS.38.29.
[35] Susmel, L., Berto, F. and Hu, Z. (2018). The Strain energy density to estimate lifetime of notched components subjected to variable amplitude fatigue loading, Fract. Struct. Int., 13(47), pp. 383-393. DOI: 10.3221/IGF-ESIS.47.28.