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Multiple regression, ANN (RBF, MLP) and ANFIS models for prediction of swell potential of clayey soils

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ABSTRACT

In the recent years, new techniques such as; artificial neural networks and fuzzy inference systems were employed for developing of the predictive models to estimate the needed parameters. Soft computing techniques are now being used as alternate statistical tool. Determination of swell potential of soil is difficult, expensive, time consuming and involves destructive tests. In this paper, use of MLP and RBF functions of *ANN* (artificial neural networks), *ANFIS* (adaptive neuro-fuzzy inference system) for prediction of *S%* (swell percent) of soil was described, and compared with the traditional statistical model of *MR* (multiple regression). However the accuracies of *ANN* and *ANFIS* models may be evaluated relatively similar. It was found that the constructed RBF exhibited a high performance than MLP, *ANFIS* and *MR* for predicting *S%*. The performance comparison showed that the soft computing system is a good tool for minimizing the uncertainties in the soil engineering projects. The use of soft computing will also may provide new approaches and methodologies, and minimize the potential inconsistency of correlations.

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1. Introduction

Many buildings are constructed with foundations that are inadequate for existing soil conditions. Because of the lack of suitable land, homes are often built on the marginal land that has insufficient bearing capacity to support the substantial weight of a structure. Land becomes scarce with city growth and it often becomes necessary to construct buildings and other structures on the sites in unfavorable conditions. The most important characteristic of clayey soils is their susceptibility to the volume change from swelling and shrinkage. Such volume changes can give rise to ground movements which may result in damage to buildings (Bell & Jermy, 1994; Bell & Maud, 1995). The clays most prone to swelling and shrinkage are over-consolidated clays (Dhowian, Ruwiah, & Erol, 1985) and Tertiary and Quaternary alluvial/colluvial soils (Donaldson, 1969). Swelling potential of expansive clayey soils is due to reductions of overburden stress, unloading conditions, or exposure to water and increase in moisture content. Bell and Maud (1995) suggest that low rise buildings are particularly vulnerable to ground movements as they generally do not have sufficient weight or strength to resist such movement. Geotechnical engineers have long recognized that swelling of expansive soils caused by moisture variation may result in considerable distress and consequently in severe damage to the overlying structures (Basma, 1991). If the substrata are not heavily loaded, structures on the surface will be affected by heave. As reported by Bell, Cripps, Culshaw, and Entwisle (1993) depending on the catalogue of Burland (1984), the annual cost of the problem in the USA and Sudan in the mid 1980's was \$6–\$8 billions and \$6 millions, respectively (Yilmaz, 2008).

A great deal of structural movement has been unduly blamed on expansive soils. Many floor slabs, constructed in an expansive soil area, crack and sometimes heave due to improperly designed concrete. It is a well known fact that the improper curing of concrete, in addition to the lack of expansion joints, will cause cracking (Chen, 1975).

In order to classify swelling soils and design structures either upon or inside a clayey soil, swell potential of the soil have a vital importance. Swell potential of the soil is mainly used in numerical and analytical methods in design approaches for estimation of surface heave and swelling pressure acting on a building.

Correlations have been a significant part of soil mechanics from the earliest days. In some cases it is essential as it is difficult to measure the amount directly and in other cases it is desirable, to ascertain the results with other tests through correlations. The correlations are generally semi-empirical based on mechanics or purely empirical based on statistical analysis. However, determination of swell potential of a soil material is time consuming, expensive and involves destructive tests. If reliable predictive models could be obtained to correlate swell percent (*S%*) to quick, cheap and nondestructive test results, they will be very valuable for at least the preliminary stage of designing a structure. The use of

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empirically obtained parameters from the index test results may not be reliable for engineering projects. However, these data would be very valuable for at least the preliminary stage of designing a structure, when the data joined with interpretation is based on engineering experiences.

However, the literature contains a considerable number of empirical equations obtained from the conventional statistical techniques for assessing the swell potential of soils. In recent years, some new soft computing techniques such as artificial neural networks, fuzzy inference systems, evolutionary computation, etc. and their hybrids have been successfully employed for developing predictive models to estimate the needed parameters. These techniques have more attraction in many research fields because a wide range of uncertainty can be tolerated by them, and soft computing techniques are now being used as alternate statistical tool.

This study aims to determine the empirical relationships for estimation of swell percent of soils by using multiple regression (MR), MLP and RBF functions of ANN (artificial neural network) and ANFIS (adaptive neuro-fuzzy inference system) models, and compare the prediction capabilities of the models. Soil samples (215) were tested for determination of swell percent (*S*%), liquid limit (LL), activity (A) and cation exchange capacity (CEC), and in order to establish predictive models, statistical and soft computing techniques such as multiple regression, artificial neural networks by means of MLP and RBF and adaptive neuro-fuzzy inference system models were used, and prediction performances were then analyzed.

It was found that the relationships developed in this study will allow LL, A and CEC to be used a rapid, easy to determine, low cost means to estimate the swelling potential with sufficient accuracy to allow for adequate foundation design in situations where urgency and/or lack of money prevents a thorough geotechnical investigation from being conducted. Moreover, the comparison of performance indices and coefficient of correlations for predicting swell percent revealed that prediction performances of the RBF function of artificial neural network model is higher than those of multiple regression equations, MLP function of artificial neural networks and artificial neuro-fuzzy inference system.

2. Experimental framework

In this study, the data were provided from extensive field studies and our database was constructed over 15 years. As is well known sufficient number of data having high quality is required in order to construct reliable predictive model, that's why 215 samples were used in the analyses; however we have the data of 350 or more soil samples. Soils were tested for determination of swell percent, Atterberg limits, cation exchange capacity and grain size distribution according to the procedure suggested by international standards.

In order to determine the swelling percent of the soils samples, swelling tests were carried out thereon in accordance with ASTM D-4546 (1994). A 0.07 kgf/cm^2 pre-loading pressure and samples with a radius of 5.0 cm were used in our tests.

When clay minerals are present in fine-grained soil it can be remoulded in the presence of some moisture without crumbling. This cohesive nature is caused by the adsorbed water surrounding the clay particles. LL increases with the increasing of the quantity of expansive clay minerals such as montmorillonite, etc. The liquid limit and plastic limit values of the samples were determined according to the procedure outlined in British Standard (BS) 1377 (BS, 1975).

Swelling properties of the soils are affected by CEC, in other words the swelling capacity is closely related to the CEC. The amount of swelling increases with increasing of CEC (Christidis, 1998). Al-Rawas (1998) has also reported that the cations are the factors controlling the expansive nature of soils. One of the fundamental differences between clay minerals lies in the amount and kind of exchangeable cations present on their surfaces and the excess negative charge of the crystal lattice which these cations neutralize. The property of ion exchange is of great fundamental and practical importance in the investigation of the clay minerals. The CEC of a soil is the number of moles of adsorbed cation charge that can be desorbed from unit mass of soil, under given conditions of temperature, pressure, soil solution composition and soil-solution mass ratio (Sposito, 1989). For soils in which the readily exchangeable cations are solely monovalent or bivalent, the "index" cation can be Na^+, whereas for soils also bearing trivalent readily exchangeable cations, Ba^{2+} is the "index" cation of choice. Often NH_4^+ has been used as an "index" cation. In this study NH_4^+ was used as an index cation (Yilmaz, 2006).

In the last stage of the laboratory experiments, CEC of the soils was measured by using the ammonium acetate (NH_4OAc) method. The basis of this method is the replacement of sodium (Na^+) ions with ammonium (NH_4^+) ions. In the tests, the soils were first saturated with the sodium ions and then replacing of sodium ions with ammonium ions were provided by adding a solution containing ammonium at a pH of 7 (Bache, 1976). At the end of the CEC tests, the amount of sodium in the solution was determined by the atomic adsorption method.

The results obtained and their basic test statistics are tabulated in Table 1. The swell percent of the soils ranged between 1.1 and 15.2 with an average value of 6.75. While the average value of liquid limit was 56.5%, values varied from 4% to 112%. The respective average values of activity and cation exchange capacity were determined as 0.85% (0.11–1.84%) and 47.1 meq/100 g (5.1–94.9 meq/100 g).

It was particularly paid to attention to select the data set having a normal distribution. In order to characterize the variation of *S*% used as an independent value, descriptive statistics such as; minimum, maximum, mean, mode, median, variance, standard deviation, skewness and kurtosis etc. were calculated using the SPSS Version 10.0.1 (1999) package. Table 2 shows that the independent value shows almost normal distribution. However it is close to the normal distribution, data are skewed left and showed a kurtosis (Fig. 1). It can be seen that the respective skewness and kurtosis values of 0.207 and −0.471 were very low. In conclusion, it was evident that the analyses will work well in case.

3. Data processing and analyses

In order to establish the predictive models among the parameters obtained in this study, simple regression analysis was performed in the first stage of the analysis. The relations between *S* with other parameters were analyzed employing linear, power, logarithmic and exponential functions. Statistically significant and strong correlations were found to be linear, and regression equations were established among index parameters with *S* (Table 3). All obtained relationships were found to be statistically significant according to the Student's *t*-test at 95% level of confidence.

Table 1
Basic statistics of the results obtained from tests.

	S (%)	LL (%)	A (%)	CEC (meq/100 g)
Minimum	1.1	4	0.11	5.1
Maximum	15.2	112	1.84	94.9
Average	6.75	56.5	0.85	47.1
Std. Dev.	3.435	26.576	0.356	24.312

S, swell percent; LL, liquid limit; A, activity; CEC, cation exchange capacity.

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