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MODELING THE UNDRAINED RESPONSE OF A SAND WITH ADDITION OF MICA PARTICLES USING STEPWISE REGRESSION

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Abstract

This study presents an experimental work on coarse rotund sand - mica mixture and availability of a stepwise regression (SR) method for the results formulation. The experimental database used for SR modelling is based on a laboratory study of saturated coarse rotund sand and mica mixtures with various mix ratios under a 100 kPa effective stresses. In the tests, deviatoric stress (q), pore water pressure generation (u), and strain levels (ε) have been measured in a 100 mm diameter conventional triaxial testing apparatus. The input variables in the developed SR models are the mica content, and strain, and the outputs are deviatoric stress, pore water pressure generation, and undrained Young's modulus. The performance of accuracies of proposed SR models are quite satisfactory. The proposed SR models are presented as simple explicit mathematical functions for further use by researchers.

Streszczenie

Artykuł przedstawia badania doświadczalne prowadzone dla mieszaniny gruboziarnistego okrągłego piasku i miki oraz możliwości metody regresji krokowej (SR) dla wyrażenia za pomocą wzoru wyników badań. Dane doświadczalne zastosowane w modelowaniu regresji krokowej SR są oparte na studium laboratoryjnym nasyconych mieszanin gruboziarnistego okrągłego piasku i miki dla zmiennych proporcji mieszanin poddanych efektywnym naprężeniom równym 100 kPa. Podczas badań w konwencjonalnym aparacie trójosiowego ściskania dla próbek o średnicy 100 mm, dokonuje się pomiarów dewiatora naprężenia (q), wytworzonego ciśnienia wody w porach (u) oraz poziomu odkształcenia (ε). Danymi wejściowymi w rozwijanych modelach regresji krokowej SR są: zawartość miki, odkształcenie; natomiast danymi wynikowymi są: dewiator naprężenia, wytworzone ciśnienie wody w porach oraz niedrenowany moduł Younga. Osiągniętą dokładność proponowanych modeli regresji krokowych uważa się za dość satysfakcjonującą. Proponowane modele regresji krokowej są przedstawione w prostych ustalonych funkcjach matematycznych w celu zastosowania ich w przyszłości przez naukowców.

Keywords: **Leighton Buzzard Sand; Mica, Triaxial testing; stepwise regression.**

1. INTRODUCTION

The presence of platy mica particles in coarse rotund sands alters the mechanical behavior of sandy soils. The mechanical response of micaceous sands has been subject to intensive research in soil mechanics [1-6]. As early as 1925, Terzaghi stated that much more experimental works were required for the foundation settlements prediction, as particle size alone was not enough to estimate a reasonable indication for the foundation settlements prediction. Gilboy (1928) [2] studied the influence of mica content on the compressibility of sand, and concluded that an increase in mica content resulted in an increase in the void ratio of the uncompressed material as well as an increase in compressibility. The observations, first made by Gilboy (1928), that any system of analysis or classification of soil which neglects the presence and effect of the flat-grained constituents will be incomplete and erroneous. Olson and Mesri (1970) [4] concluded that for all apart from the most active of reconstituted clays, mechanical properties were the governing factors in determining compressibility. A recent experimental study by Theron (2004) [7] was conducted on mixtures of mica and sand, and demonstrated the enormous impact of particle shape on the mechanical properties.

Most current basic soil mechanics text show that mica particles; (i) cause undrained strength anisotropy from a brittle response in triaxial extension tests to a ductile behaviour in triaxial compression tests [6], (ii) decrease strength [8], (iii) alter internal shear mechanism [9], and (iv) increase compressibility [10]. Micaceous sands are deemed unacceptable for earthworks because of the reasons raised above. Actually, a number of slope failures have been attributed to the presence of mica [6]. The behaviour of micaceous sands was studied in connection with flow slides that occurred during construction of river training for the Jamura Bridge in Bangladesh [6], and Merriespruit gold tailings dam in South Africa which failed in such a catastrophic fashion in 1994 [11-12]. Interestingly the behaviour of mica is clay-like, but particle size analyses and the origins of the geomaterial prove that they contain little clay-sized material, and do not have colloidally-active minerals. This study presents an alternative approach for modeling of coarse rotund sand-mica mixtures based on experimental results using Stepwise Regression (SR). 3 different SR models are proposed for deviatoric stress (q), pore water pressure (u), and undrained Young's Modulus (Eu). The assumptions of SR models developed to predict behaviour of the mixtures are found to be quite accurate.

2. EXPERIMENTAL STUDY

2.1. Materials

Two different geomaterials were used in the experimental work; these were Leighton Buzzard Sand and mica. The Leighton Buzzard Sand used in the experiments was a fraction B supplied by the David Ball Group, Cambridge, U.K., confirming to BS 1881-131:1998. Its specific gravity, minimum and maximum dry densities were found to be 2.65, 1.48 g/cm^3 and 1.74 g/cm^3 respectively. As can be seen from the Figure 1a and 2, more than 90% of the coarse sand particles, which are rounded and mainly quartz, are between (around) 0.6 mm and 1.1 mm.

Mica used in the experiments 52-105 micron muscovite mica was supplied by Dean and Tranter Ltd. It's specific gravity, minimum and maximum dry densities were found to be 2.9, 0.725 g/cm^3 and 0.916 g/cm^3 respectively [7]. Figures 1b and 2 show the SEM picture, and size gradation for the mica particles respectively.

Leighton Buzzard Sand and mica were mixed at various percentage of mica. The percentage of mica meant in this study refers to the dry weight of mica relative to the total dry weight of the mixture. Two mica percentages were considered, namely; 5%, 15% and then all results were compared with the clean Leighton Buzzard Sand.

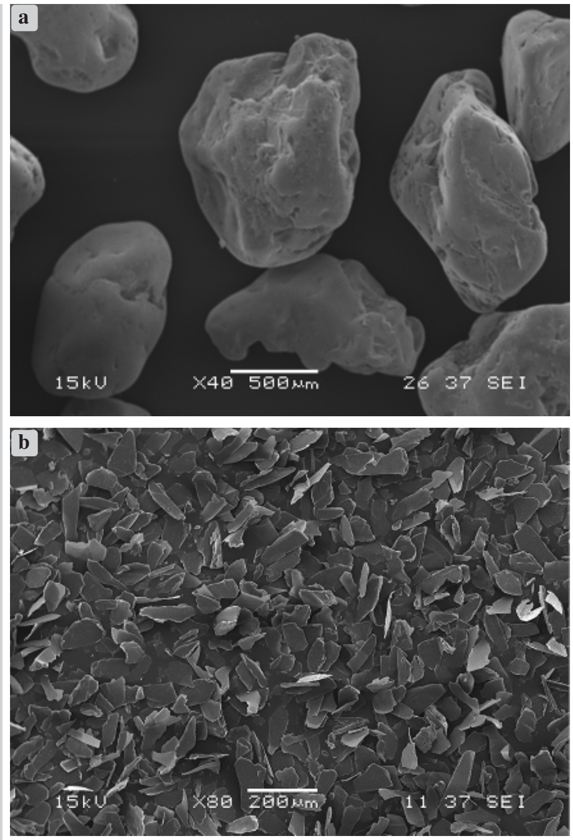

Figure 1.
a) SEM Picture of the Leighton Buzzard Sand used in the experimental study
b) SEM Picture of mica used in the experimental study

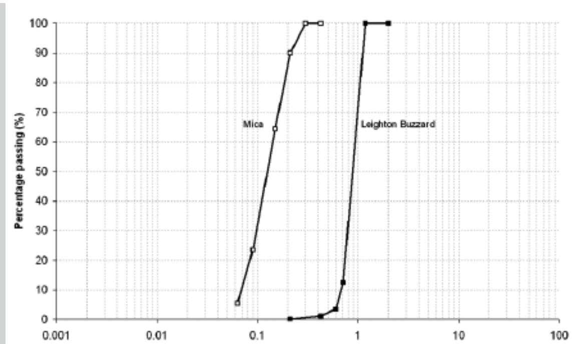

Figure 2.
Grain size distributions of Leighton Buzzard Sand and mica

2.2. Testing Apparatus and Procedures

The tests were performed in a conventional 100-mm-diameter Wykeham Farrance compression triaxial machine. Strain controlled loading was applied using a digitally controlled STALC 4958 type internal load cell at a constant rate of displacement. In order for the cell and the back pressures to be measured, two pressure transducers, PDCR 810 produced by Druck Limited, were used. Pairs of strain gauges were submersible LVDTs produced by R.D.P. Electronics Ltd., which were employed to measure the axial displacement in the middle third of the specimen in diametrically opposite positions.

Leighton Buzzard Sand, water and mica were mixed in the desired proportions to produce a uniform paste. A cylindrical membrane was attached to the bottom endplate using two o-rings and the split mould was placed around the endplate. Prepared uniform paste was then gently spooned into the split mould on the pedestal. Great care was taken to ensure that no vibration was employed. When the mould was completely filled, the excess sand particles were removed and the weight of the specimen was recorded. The top end plate was attached with two o-rings and 20 kPa suction was applied to the inside of the specimen. The split mould was carefully split to prevent any disturbance to the specimen. The test cell was then assembled and filled with water to apply cell pressure. After the test cell was completely assembled, the loading frame was placed. The suction inside the specimen was decreased while gradual increasing of the cell pressure up to the desired value was achieved.

A series of isotropically consolidated undrained triaxial compression tests were carried out on the specimens at 100 kPa effective consolidation stress. During the consolidation process, the pore-pressure, cell pressure, volume, strain measurements were closely examined and recorded. Following the consolidation, the drainage valve to the specimen was closed, and then compressive load was commenced at a constant displacement rate of 0.015 mm/min.

3. EXPERIMENTAL RESULTS

The study provides an additional data set to compare the Leighton Buzzard Sand-mica mixtures in a triaxial apparatus. The test results show that the characteristics of the Leighton Buzzard Sand tested may be principally ascribable to the presence of the flat grains. The writer postulates that platy particles occupy the voids between Leighton Buzzard Sand particles. Depending on the amount of platy particles present (i.e., mica), the Leighton Buzzard Sand particles are either in contact with each other and the behaviour of the samples tested are controlled by Leighton Buzzard Sand particles, or they are separated by platy particles.

In the light of Clayton et al. (2004) [10], the shape of particles controlling the mechanical behaviour of the Leighton Buzzard Sand-mica mixtures seems to be dependent on the contact mechanism between the Leighton Buzzard Sand particles. When the Leighton Buzzard Sand particles are in clear contact to each other, and the mica particles only partially fill the pores, the mechanical behaviour of the mixes under these situations is governed by the Leighton Buzzard Sand. As the mica particles fill the pore spaces, the Leighton Buzzard Sand particles are held apart, and the platy mica fines start to control the behaviour of the mixes. The contacts between the Leighton Buzzard Sand particles reduce; the behaviour of the samples becomes clay like. With large volume of platy particles, the Leighton Buzzard Sand particles are suspended in a mica matrix which dominates the mechanical behaviour of the mixes. In brief, this shows the significance of the amount and position of the mica particles among the mixes, and also shows that the compressibility of Leighton Buzzard Sand increases with platy particles content.

Figure 3 and 4 show the effects of increasing mica content on the stress-strain, and pore water pressure -strain behaviour of the material. The clean loose sand specimen behaves as might be expected, but the dilation of 5% and more by weight of mica causes the suppression of any dilation, low undrained shear strengths, and high level of pore pressure generation during shear.

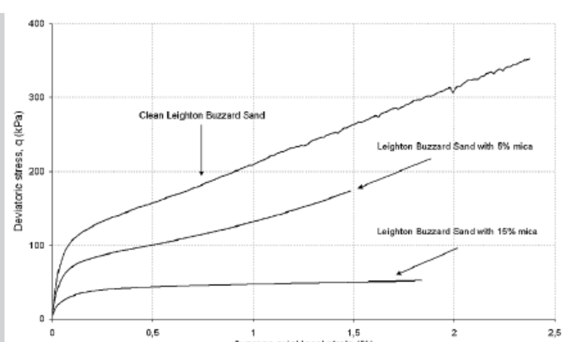

Figure 3.
Stress-strain curve for the loose sand, and sand with different proportions of mica (percentages by dry weight)

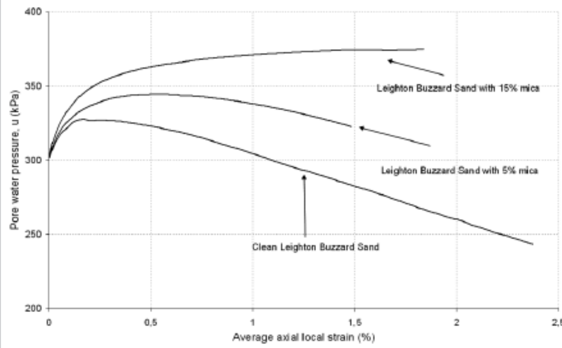

Figure 4.
Stress-strain curve for the loose sand, and sand with different proportions of mica (percentages by dry weight)

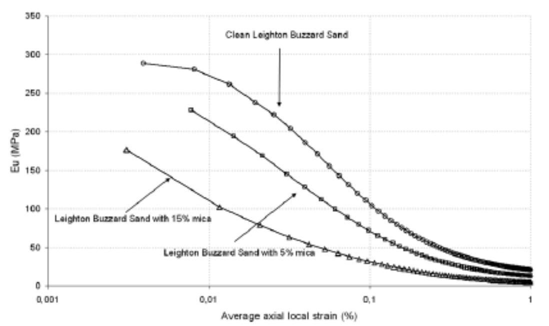

Figure 5.
Undrained Young's modulus as a function of axial local strain

The influence of mica on the small strain stiffness was also investigated by considering undrained secant Young's modulus (Figure 5). Comparing the small strain stiffness behaviour of the mica-Leighton Buzzard Sand mixtures at 100 kPa effective consolidation pressure, it is noted that the addition of mica to the Leighton Buzzard Sand particles resulted in reduced specimen stiffness. Following the above, it can be concluded that the Young's modulus of the mixtures tested decreases with increasing platy particle content. Accordingly, it may give insight that any system of analysis which neglects the presence and the effect of the pore fluid characteristics as well as that of the flat-grained constituents will be incomplete.

4. STEPWISE REGRESSION MODEL

As dealing with large number of independent variables, it is necessary to determine the best combination of these variables to estimate the dependent variable. Modeling by Stepwise Regression (SR) is a robust tool for selection of the best subset models [13]. Subset models' determination is based on deleting or adding the variable(s) with the greatest impact on the residual sum of squares. The selection of variables may be done in three ways; forward, backward or a combination of them. In the first one, the subset models are selected by adding one variable at a time to the previously selected subset. In each successive step, the variable in the subset of variables is added to the subset. Without an ending rule, forward selection lasts until all variables are included to the model. However, backward stepwise method chooses the subset models by commencing with the full model and then eliminating at each step the one variable whose deletion will cause the residual sum of squares to increase the least and continues until the subset model contains only one variable [14].

In both forward and backward methods, it should be noted that the influence of deleting or adding a variable on the contributions of other variables into the model is not being taken in to account. Hence stepwise regression is a forward selection process that re-evaluates in each step the significance of all previously included variables. If the partial sums of squares for a previously considered variables do not meet a minimum requirement to stay in the model, the selection way changes to backward one and variables are dropped one at a time as all remaining variables meet the minimum requirement. Stepwise selection of variables needs more computing than forward or backward way but, it has an advantage in potential subset models evaluated before the model for each subset size is fixed. It seems to be reasonable that the stepwise selection have a significant chance of choosing the best subsets in the sample data, however selection of the best subset for each subset size is not under guarantee. Stepwise selection of variables uses both the forward and backward elimination criteria to stop the rule. The variable selection process ends when all variables in the model meet the requirements to stay and no variables outside the model meet the requirement to enter [14].

This paper aims at single empirical formulation of deviatoric stress (q), pore water pressure (u), and undrained Young's modulus (Eu) of coarse rotund sand-mica mixtures stepwise regression based on experimental results. Therefore an extensive experimental program has been performed on various coarse rotund sand-mica mixtures. The details of the experimental study including the ranges of parameters have already been given in previous sections. Deviatoric stress, pore water pressure, and Young's modulus values have been modeled as a function of mica content in percentage, and strain, and the following equations have been obtained:

$q = 50- 7.9*C_m^{1/2}+ 22.3*\varepsilon^{3/2}- C_m*\varepsilon^2+ 142.4*\varepsilon^{1/2}- 31.4*C_m^{1/2}*\varepsilon^{1/2}$

$u = 324.8- 5.4*C_m^{1/2}+ 22.5*\varepsilon^3+ 24*C_m^{1/2}*\varepsilon^{1/2}- 46.7* \varepsilon^{3/2}$

$Eu = -14.2+ 41.2* \varepsilon^{-(1/2)}-0.002* C_m^2* (1/\varepsilon)- 6.81* C_m^{1/2}*\varepsilon^{-(1/2)}- 1.3*(1/\varepsilon)+0.4* C_m^{1/2}*(1/\varepsilon)$

Where;

q = deviatoric stress (kPa)

u = pore water pressure (kPa)

Eu = undrained Young's modulus (MPa)

ε = shear strain (%)

C_M = mica content (%)

Figure 6 presents the E values obtained from the tests and SR models for the Leighton Buzzard Sand with mica fines. Comparison between SW and test results is observed very closely as presented in Figures 7, 8 and 9 for deviatoric stress, pore water pressure, undrained Young's modulus respectively.

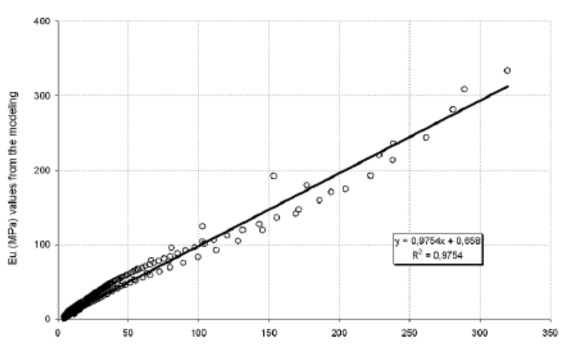

Figure 6.
Comparison between the undrained Young's modulus (Eu) values from test results and those from modeling

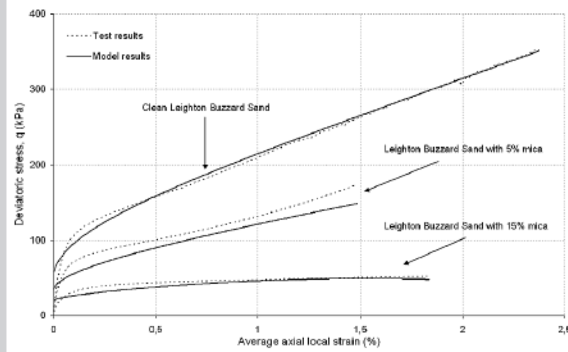

Figure 7.
Comparison of the test and modeling results for deviatoric stress (q)

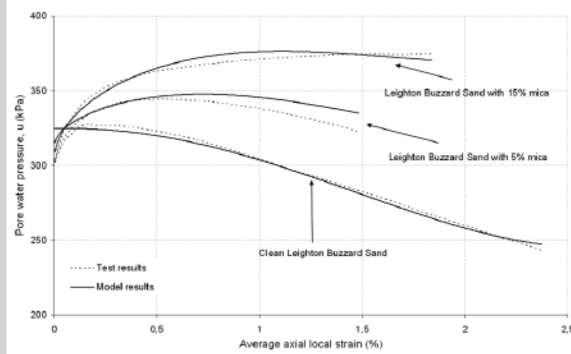

Figure 8.
Comparison of the test and modeling results for pore water pressure (u)

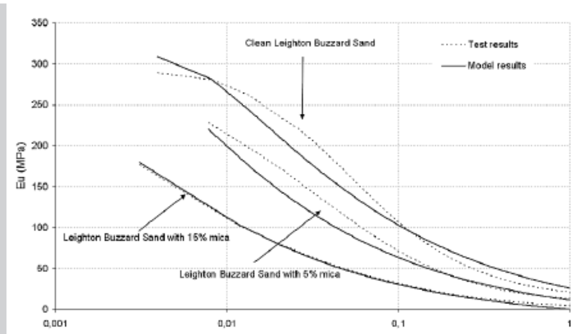

Figure 9.
Comparison of the test and modeling results for Young's modulus (Eu)

5. CONCLUSIONS

The objective of the study was to determine experimentally the variation of the deviatoric stress, pore water pressure, and Young's modulus. It was then aimed to develop empirical stepwise regression (SR) based models for the prediction of deviatoric stress, pore water pressure, and Young's modulus of rotund sand-mica mixtures as a function of mica content and strain level. The experimental data presented here in the paper reveals that the high compressibility of the mixes is likely to be a result of particle shape.

Modeling of granular materials is often a complex phenomenon particularly where a mixture of two or more materials exist. In this context, it is showed that alternative methods such as soft computing techniques can be used to overcome this difficulty. This study is a pioneer work that inquires into the capability of SR approach for the empirical modeling of coarse rotund sand - mica mixtures regarding deviatoric stress, pore water pressure, and Young's modulus. The predictions of developed SR equations for deviatoric stress ($R^2 = 0.98$), pore water pressure ($R^2 = 0.97$), and undrained Young's modulus ($R^2 = 0.97$) are observed to be quite accurate compared to test results. Researchers can use these three models safely for the prediction of damping ratio and shear modulus of Leighton Buzzard Sand fraction B -mica mixtures. The outcomes of this study are quite satisfactory which may serve SR approach to be widely used in geotechnical engineering applications.

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