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Numerical modelling of the stress strain behaviour of Kuttanad clay.
Modelado numérico del comportamiento tensión deformación de arcilla Kuttanad.

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ABSTRACT

Soil has been used as a construction material since antiquity with both success and failure. As the earth material is widely available and relatively economical, it has been found very useful in the construction of foundations, subgrades, embankments and as backfill. The collapsibility of soil is mainly due to the decrease of shear strength and macro-deformation with the increase of moisture content. This can result in some serious problems, such as the differential settlement of the foundation, landslides, and slope instability, resulting in a series of damages of infrastructures and loss of human lives to some degree. Fine-grained soils are the most complicated engineering material. These clays are characterized by high compressibility, low shear strength and high percentage of organic matter, which are unfavourable from the geotechnical point of view. It is of great importance in civil engineering to make realistic predictions of the behaviour of soil under various conditions. Studying the effect of moisture content on the shear strength of cohesive soil during different confining pressure helps to find a relationship between them. Triaxial tests under unconsolidated undrained conditions are carried out at different moisture contents, each at four different confining pressures (50, 100, 150, and 200 kPa). The relation of stress and strain of soils is analysed using the hyperbolic mathematical model which can provide a brief idea about how soil will behave under different conditions. Mathematical equations were determined based on the hyperbolic mathematical model to predict the stress-strain behaviour of Kuttanad soil. Comparison of measured and predicted stress – strain curves for an additional group of soil sample with 37.22 % moisture content shows that the proposed moisture content-dependent hyperbolic model provides good prediction of stress-strain behaviour of cohesive Kuttanad soil. The accuracy of the developed model is tested by employing Coefficient of determination (R^2).

Keywords— Shear strength, Triaxial test, Clay, Hyperbolic, Moisture content

RESUMEN

El suelo se ha utilizado como material de construcción desde la antigüedad con éxito y fracaso. Como el material de la tierra está ampliamente disponible y es relativamente económico, se ha encontrado muy útil en la construcción de cimientos, subrasante, terraplenes y como relleno. La colapsabilidad del suelo se debe principalmente a la disminución de la resistencia al cizallamiento y la macrodeformación con el aumento del contenido de humedad. Esto puede resultar en algunos problemas serios, como el asentamiento diferencial de la cimentación, deslizamientos de tierra e inestabilidad de taludes, resultando en una serie de daños a las infraestructuras y pérdida de vidas humanas en algún grado. Los suelos de grano fino son el material de ingeniería más complicado. Estas arcillas se caracterizan por una alta compresibilidad, baja resistencia al cizallamiento y alto porcentaje de materia orgánica, que son desfavorables desde el punto de vista geotécnico. Es de gran importancia en la ingeniería civil hacer predicciones realistas del comportamiento del suelo en diversas condiciones. Estudiar el efecto del contenido de humedad sobre la resistencia al corte del suelo cohesivo durante diferentes presiones de confinamiento ayuda a encontrar una relación entre ellos. Las pruebas triaxiales en condiciones no consolidadas sin drenaje se llevan a cabo a diferentes contenidos de humedad, cada uno a cuatro presiones de confinamiento diferentes (50, 100, 150 y 200 kPa). La relación de tensión y deformación del suelo se analiza utilizando el modelo matemático hiperbólico que puede proporcionar una breve idea sobre cómo se comportará el suelo en diferentes condiciones. Las ecuaciones matemáticas se determinaron con base en el modelo matemático hiperbólico para predecir el comportamiento tensión-deformación del suelo de Kuttanad. La comparación de las curvas de tensión-deformación medidas y predichas para un grupo adicional de muestra de suelo con un contenido de humedad del 37,22% muestra que el modelo hiperbólico dependiente del contenido de humedad propuesto proporciona una buena predicción del comportamiento de tensión-deformación del suelo cohesivo de Kuttanad. La precisión del modelo desarrollado se prueba empleando el coeficiente de determinación (R2).

Palabras clave: resistencia al corte, prueba triaxial, arcilla, hiperbólico, contenido de humedad

INTRODUCTION

Soil is a construction material in various engineering projects, and it supports structural foundations. It is a complicated material that behaves non-linearly and often shows anisotropic and time-dependent behaviour when subjected to stresses. It is very important to predict the stress and strain imposed on a given point in a soil mass due to certain loading conditions. The collapsibility of soil is mainly due to the decrease of shear strength and macro deformation with the increase of moisture content. It can cause differential settlement of foundation, slope instability and, landslides which will result in the damages of infrastructures and loss of human lives to some degree. It is very important to predict the stress-strain behaviour of soil for estimating settlement, conducting stability analysis, and to determine the stress conditions on earth retaining and underground structures. An unsaturated soil has four phases, i.e. soil, air, water, and air−water interface or contractile skin phases. Matric suction is considered as an important stress state variable in an unsaturated soil. Significant research has been carried out to understand and measure the matric suction, in terms of the Soil Water Characteristic Curve. But the process to achieve the Soil Water Characteristic Curve is time-consuming and difficult. A constitutive equation helps to relate stress with strain, the two physical quantities mostly used when describing solid behaviour. Constitutive equations are usually governed by the properties of a material and can be as simple as a linear relationship or more complex. In Geotechnical Engineering the solid is a geo-material and constitutive equations predict the behaviour of it. Constitutive models are mathematical models with parameters estimated from laboratory or field data. Thus, they cannot capture with full accuracy the complexity of soil behaviour. Constitutive models are complicated and require a number of parameters with little physical correlation.

It is crucial to determine constitutive models to analyse the mechanical behaviour of geomaterials and geotechnical engineering stability. Thus, identification of a geomaterials constitutive model is a very important aspect of back analysis. Some mathematical and computational intelligence methods have been used to solve this problem, and many related studies have been performed in the past. In this study, previous researches on constitutive model approach using conventional approach have been reviewed. The advantages of numerical analyses for solving practical problems have been recognised, and developments in software and hardware allow their application in practice with reasonable effort.

A moisture-content based constitutive model based on the hyperbolic model was proposed by Guoxiong MEI et.al, (2010).This was developed based on Kondner's hyperbolic model. The method for obtaining the Soil Water Characteristic Curve is tedious and time consuming. Conventional triaxial test apparatus is usually used to determine the properties of unsaturated soil and conventional saturated soil mechanics are used to analyse them Regression models were proposed for parameters a and b in the hyperbolic mathematical model. In order to verify that the proposed model offers a reasonable estimate of the stress-strain behaviour of unsaturated cohesive soil, a comparison between the measured and projected stress-strain curve for soil samples with 25.42 % moisture content had been used. [7]

A model which is based on a stress-strain curve in drained triaxial compression test of both clay and sand was contributed by Duncan M James et.al, (1970). It can be approximated with a high degree of precision by a hyperbola. This model is a nonlinear elastic model with loading and unloading/reloading elastic modulus which depends on the stress and it is formulated using power-law functions. Its criterion of failure is based on the Mohr Coulomb model. [5]

Laboratory and field tests are essential to estimate the geotechnical parameters. But in some situations this might be difficult. It may be due to the unavailability of laboratory equipment, economic and time constraints, etc. Sateesh Narepalem et.al, (2019) conducted a comprehensive study to look at the suitability of the hyperbolic model to determine undrained stress strain (σ-ε) response of cohesive soils of the Vijayawada region, India. In this study, σ-ε curves are plotted obtained from Unconfined Compression tests conducted on fine grained soil samples having different Standard Penetration Test values. A simplified hyperbolic model was proposed to gauge the σ-ε curve in terms of Standard Penetration Test value (N value). The study aims at predicting undrained shear strength/undrained cohesive strength (C_u) and the coefficient of elasticity (E) from N value. Linear model was found to have good accuracy and simple in predicting undrained cohesion. Empirical correlations can be very helpful for the engineers to rapidly estimate E and C_u using N value. [11]

MATERIAL AND METHODS

The methodology adopted for this study is as follows. The area of interest and the research problem was identified. The information required for the progress of work was collected through the literature survey. The soil samples from the Kuttanad region of Kerala were collected. The soil is tested to determine its basic properties such as Average Moisture Content, Particle size distribution, Specific gravity, Atterberg limits, Optimum Moisture Contents and Maximum Dry Density. The Unconfined Compressive Strength of the soil was also determined. Triaxial tests are conducted in Unconsolidated Undrained conditions at different confining pressures and moisture contents (with moisture content ranging from dry to wet side of Optimum value). The test results are then plotted as a curve of deviator stress, $\sigma_1-\sigma_3$, against axial strain, ε_1 (σ_1 and σ_3 are major and minor principal stresses, respectively for different moisture contents). A mathematical model is proposed using OriginPro software. The regression models are verified by comparing the results of regression models with the results obtained from triaxial compression tests for an additional group of soil samples. The analysis of results is then discussed and concluded.

The disturbed soil samples were collected from this region at a depth of 1m beneath the ground level and then transported to the laboratory in polythene gunny bags. It is air-dried before starting the experiment and then oven dried and broken into small pieces. It was then sieved through a 1 mm sieve and the fine soil was then stored in an air-tight container until test preparation commenced. Table 1 shows the basic properties of Kuttanad clay used in the study. Triaxial tests were conducted on soil with different moisture content from dry and wet side of optimum value (32.86%, 33.33%, 34.58%, 34.89%, 35.65%, 36.21%, 38.46% and 39.13%) which was measured after each test. At each moisture content, four undrained triaxial compression tests were performed at confining pressures of – 50 kPa, 100 kPa, 150 kPa, and 200 kPa.

Table 1 Properties of Kuttanad Clay

Sl No	Properties of Kuttanad clay		Values
1	Colour		Dark Grey
2	Natural moisture content (%)		25.50
3	Specific gravity		2.69
4	Liquid limit (%)		74
5	Plastic limit (%)		52.10
6	Plasticity Index (%)		21.90
7	Particle size distribution (%)	Clay	38.00
		Silt	53.00
		Sand	9.00
8	Optimum moisture content (%)		30.00
9	Maximum dry density (g/cm^3)		1.339
10	Unconfined compressive strength (kN/m^2)		41.68
11	Cohesion, c (kN/m^2)		20.84

RESULTS AND DISCUSSIONS

Hyperbolic stress-strain model: Stress - Strain curves are drawn with Deviator stress (σ_1 - σ_3) against Axial strain (ε) calculated using the experimental observations and calculations. The test results were plotted as a curve of deviatoric stress, $\sigma_1 - \sigma_3$, against axial strain, ε_1. σ_1 and σ_3 are major and minor principal stresses, respectively. Typical stress−strain curves are presented in Figures 1 and 2 for moisture contents of 33.33% and 38.46%. As can be seen from these figures, the stress−strain curves could be approximated by hyperbolas.

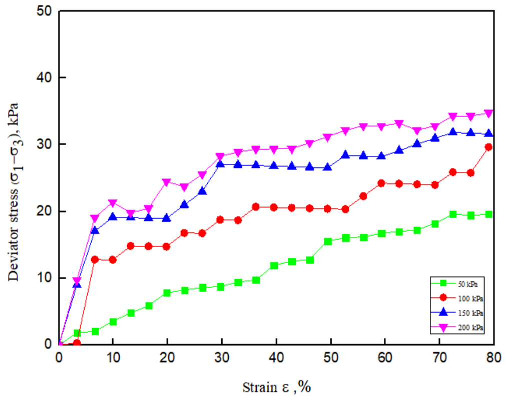


Fig.1 Stress-Strain curve for 33.33 % moisture content

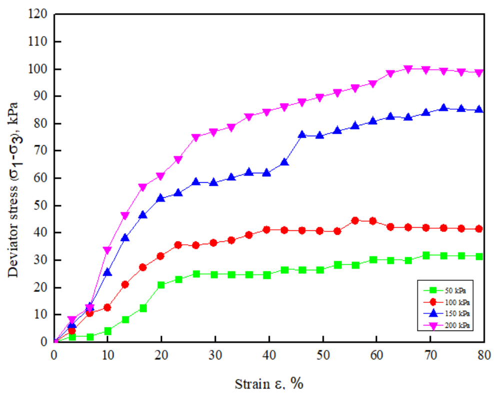


Fig. 2 Stress-Strain curve for 38.46 % moisture content

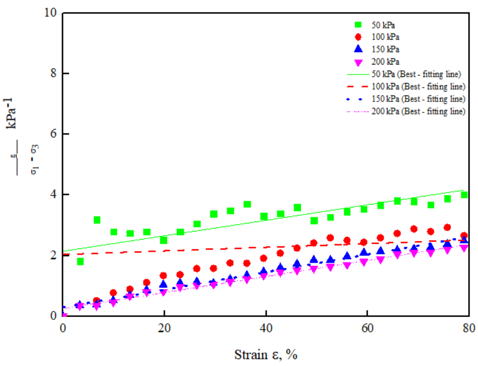
To study the stress – strain relationship of unsaturated cohesive soil, the data were analysed using the hyperbolic mathematical model, expressed as

$$\sigma_1 - \sigma_3 = \frac{\varepsilon_1}{a+b\,\varepsilon_1}$$

Where a and b are constants, whose value may be determined from conventional triaxial compression tests; 1/a is the initial tangent modulus, E_i; and 1/b is the ultimate principal stress difference. Rearranging the terms in previous equation, we get

$$\frac{\varepsilon_1}{\sigma_1 - \sigma_3} = a + b\,\varepsilon_1.$$

Where $\varepsilon_1/(\sigma_1-\sigma_3)$ is a linear function of the axial strain, ε. The best-fit straight line on this transformed plot corresponds to the best-fit hyperbola on the stress strain plot. For each stress-strain curve, the values of $[\varepsilon/(\sigma_1- \sigma_3)]$ are calculated for each single curve, and then, $[\varepsilon/(\sigma_1- \sigma_3)]$ are plotted against ε. Typical lines are presented in Figures 3 and 4. For each of these plotted curves the values of the hyperbolic constants namely a and b are obtained, where a is the value of the y-axis intercept and b is the slope of the curve. The intercept a of this straight line on the $\varepsilon/(\sigma_1-\sigma_3)$ axis is the reciprocal of the initial Young's modulus E_i of the soil specimen. The slope b of the line is the reciprocal of the asymptotic deviator stress $(\sigma_1 - \sigma_3)_{ult}$.



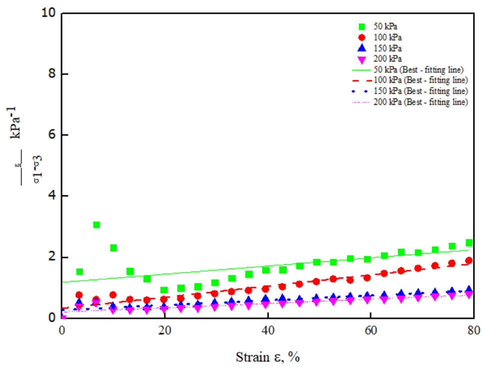
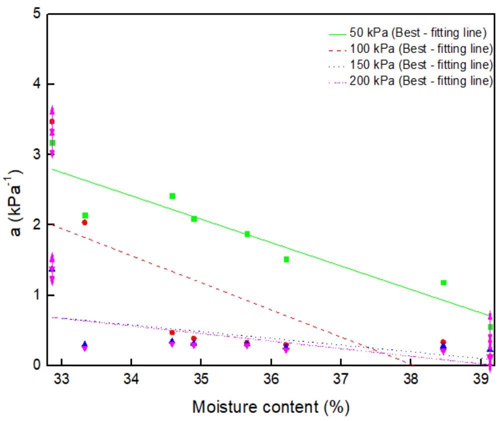


Fig. 3 Typical Stress-Strain response in $\varepsilon/(\sigma_1 - \sigma_3)$ - ε space for 38.46 % moisture content

Fig. 4 Typical Stress-Strain response in $\varepsilon/(\sigma_1 - \sigma_3)$ - ε space for 33.33 % moisture content

Parameters a and b: Parameters a and b can be obtained through the linear regression analysis of experimental data using the software OriginPro 9.0. It is a Statistical analysis software program designed to perform complex statistical analysis. Regression analysis is done and then the best fit parameters are estimated using the least-square method. The variation of parameters a and b with the moisture content at different confining pressures are shown in Figures 5 and 6.



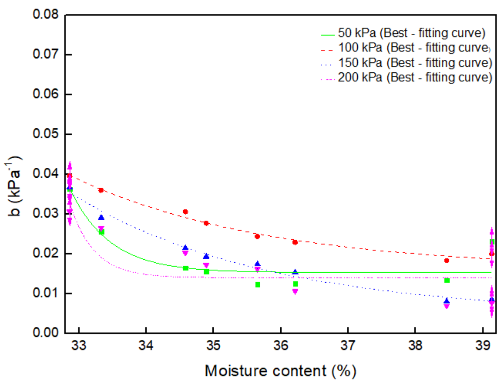


Fig. 5 Variation of parameter a with moisture content at different confining pressure

Fig. 6 Variation of parameter b with moisture content at different confining pressure

A linear model is proposed for parameter a, and a non - linear model is proposed for parameter b.

$$a = A_1 + B_1 w$$

$$b = A_2 + B_2 \exp(-w/t_2)$$

Where w is the moisture content; A_1, B_1, A_2, B_2, and t_2 are regression parameters. The regression parameters and the corresponding coefficients of correlation for parameters a and b are summarized in Tables 2 and 3.

Table 2 Model regression parameters and corresponding coefficients of correlation for a

Confining pressure, kPa	A_1, kPa^{-1}	B_1, kPa^{-1}	R^2
50	13.7518	-0.33341	0.85784
100	14.69885	-0.38635	0.77139
150	3.82441	-0.0955	0.86862
200	4.22362	-0.10768	0.85959

Table 3 Model regression parameters and corresponding coefficients of correlation for b

Confining pressure, kPa	A_2, kPa^{-1}	B_2, kPa^{-1}	t_2, kPa^{-1}	R^2
50	0.01528	1.74898E22	0.5967	0.76307
100	0.01601	2110.58947	2.88401	0.97886
150	0.00462	2665.38874	2.89054	0.98304
200	0.01399	5.31873E37	0.36172	0.42668

VERIFICATION MODEL: The regression models in proposed for parameters a and b were verified by comparing the results of regression models with the results obtained from UU triaxial tests conducted in the laboratory for an additional group of soil samples, which have a measured moisture content of 37.22%. The values of regression parameters obtained using proposed model can be applied to the individual equations proposed for a and b, which can in turn be used in the Hyperbolic model. Figure 7 shows the detailed comparison of the measured and predicted stress−strain curves. The comparison indicates that the agreement between the measured and predicted stress−strain behaviour of cohesive soil is good with coefficients of correlation equal to 0.94744, 0.98701, 0.98388 and 0.96186 for confining pressures of 50 kPa, 100 kPa, 150 kPa, and 200 kPa, respectively.

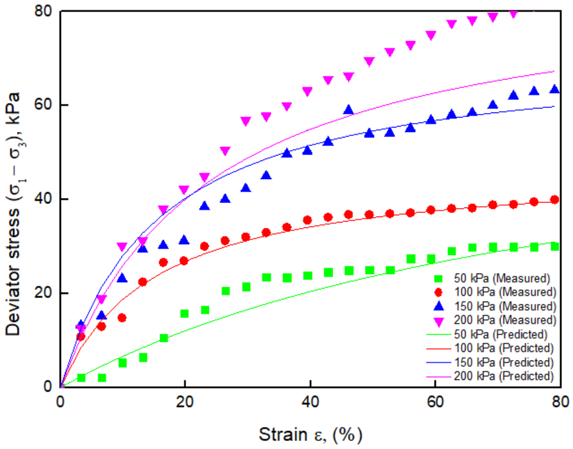


Fig. 7 Comparison of measured and predicted stress – strain curves for soil sample with 37.22 % moisture content

As conclusion, this work intends to propose a mathematical model to determine the stress – strain relationship of the Kuttanad Clay, based on the moisture content based hyperbolic mathematical model. The comparison of the measured and predicted stress−strain curves for an additional group of soil samples, which have a measured moisture content of 37.22%, showed a good prediction of the stress−strain behaviour of unsaturated cohesive soil. More number of triaxial tests needs to be conducted in soil samples with different moisture contents at confining pressures – 50 kPa, 100 kPa, 150 kPa, and 200 kPa. Future research is recommended to evaluate the difference between the remoulded and undisturbed soil samples. An increase in the data can help in achieving a more appropriate model. More number of parameters, like soil index properties can be used as independent variable while creating the regression model.

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