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A review on modelling of the stress-strain behaviour of soil.
Una revisión sobre el modelado del comportamiento tensión-deformación del suelo.

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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. In civil engineering, it is very important to make realistic predictions of the behaviour of soil under various conditions. Triaxial tests are to be carried out to study soil behaviour. The results will indicate the shear damage characteristics during the test. The relation of stress and strain of soils can be expressed using constitutive models. It can provide a brief idea about how soil will behave under different conditions. Application of Neural Network can be used to develop a data-driven constitutive modelling of the soil.
Keywords- Shear strength, Triaxial test, moisture content, constitutive model

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, subrasantes, 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. En ingeniería civil, es muy importante hacer predicciones realistas del comportamiento del suelo en diversas condiciones. Se realizarán ensayos triaxiales para estudiar el comportamiento del suelo. Los resultados indicarán las características del daño por cizallamiento durante la prueba. La relación de tensión y deformación de los suelos se puede expresar utilizando modelos constitutivos. Puede proporcionar una breve idea sobre cómo se comportará el suelo en diferentes condiciones. La aplicación de la red neuronal se puede utilizar para desarrollar un modelo constitutivo del suelo basado en datos.

Palabras clave: resistencia al corte, ensayo triaxial, contenido de humedad, modelo constitutivo

INTRODUCTION

In different construction projects, soil is the main building material and it supports structural foundations. It is a complex material that when subjected to stresses, behaves non-linearly and often exhibits anisotropic and time-dependent behaviour. Due to certain loading conditions, predicting the stress and strain exerted on a given point in a soil mass is very critical. Soil collapsibility can cause differential foundation settlement, slope instability, and landslides that will result to some degree in damage to infrastructure and loss of human life. For estimating settlement, carrying out stability analysis, and determining the stress conditions on earth retention and underground structures, it is very important to predict the stress-strain behaviour of soil.

A constitutive equation helps to link stress with strain, the two physical quantities mostly used when describing solid behaviour. Usually, constitutive equations are governed by a material's properties and may be as simple or more complex as a linear relationship. The solid is a geo-material in Geotechnical Engineering and the behaviour of it is predicted by constitutive equations. Mathematical models with parameters that are estimated from laboratory or field data are constitutive models. They can therefore not capture the complexity of soil behaviour with full accuracy. Constitutive models are complex and require, with little physical correlation, a number of parameters. To enhance the accuracy of prediction, data-driven constitutive models can be built using artificial intelligence.

CONSTITUTIVE MODELS

Constitutive models are used to describe the responses of a particular material to different loading conditions. It gives the stress-strain relations which can be used to formulate the governing equations, with the help of conservation laws and kinematic relations. Several researchers have proposed various constitutive models in the past so as to explain various aspects of soil behaviour in detail and also to use such models in finite element modelling for geotechnical engineering applications. There exist many varieties of models to represent the stress-strain and failure behaviour of soils. All these models inhibit certain advantages and limitations which largely depend upon their application. With advanced computing technology, the incorporation of these numerical models in finite element modelling can be easily done. These constitutive models are often made use of because it provides a reasonable fit to data obtained from a range of laboratory test. It is important to conduct various computation measurement comparisons along with additional full-scale experiments to determine the degree of accuracy in the models to adjust and use them accordingly.

Over a period of time, constitutive models have progressed from being easy to more complex to capture soil behaviour under complex loading conditions. For soil behaviour simulation, Mohr-Coulomb model, Modified cam clay model, Hooke's model, Plaxis hardening soil model, Hyperelastic model, Hypoelastic model, etc., are different types of models widely used. Hooke's model is a linear elastic model which is based on the linear elasticity theorem of Hooke. The Mohr-Coulomb model is a perfectly plastic linear elastic model and represents the first-order soil behaviour approximation. Hyperbolic /Duncan-Chang Model also known as hyperbolic Model is based on stress-strain curve of drained triaxial compression tests of clays and sands and can be approximated by a hyperbolic function. Hyperelastic is a kind of constitutive model for ideally elastic materials, in which the stress is a function of current strain rather than a function of history of strain. In those materials that exhibit nonlinear, but reversible stress-strain behaviour even at small strain, Hypo elastic models are used. The strain hardening theory was used to develop the stress-strain model for normally consolidated or overconsolidated soils in the triaxial test known as Cam Clay Model. Constitutive models which can be used to replicate the important aspects of the soil stress-strain behaviour under different loading conditions are very important. To develop such a model, advanced studies need to be conducted to study the behaviour of the soil under various loading conditions. It also requires the employment of mathematical tools based on sound theoretical frameworks such as elasticity and plasticity theories. The constitutive models should be such that, from relatively simple tests, the necessary soil parameters can be obtained.

ANALYSIS OF SOIL USING NUMERICAL METHODS

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. Since the actual mechanical activity of the geomaterials is very complex, it is difficult to define an effective geomaterials constitutive model based on conventional methods. 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 research on constitutive model approach using conventional approach and by using Artificial Intelligence methods like Artificial neural network, evolutionary computation, etc. have been reviewed. Over the last decades, numerical methods have gained increasing importance in practical geotechnical engineering and numerical methods have become a standard tool in geotechnical design, widely accepted by the geotechnical profession. 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. 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. Based on these reasons, modified conventional triaxial compression tests were performed in this study to find a stress-moisture content-strain relationship for unsaturated cohesive soil and bypass the suction concept. The stress-strain behaviour of in-situ soil at a depth of 5 m was investigated by conducting undrained triaxial compression tests using remoulded soil samples and analysed using the hyperbolic mathematical model at different confining pressures (100, 150, 200 and 250 kPa) and moisture contents (10.32%, 11.84%, 12.53%, 14.84%, 15.58%, 16.59%, 17.09%, 17.65%, 19.65%, 19.82%, 20.21%, 23.05%, 23.82%, 24.94%, 27.13% and 28.18%). 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. To confirm that the relationship between stress and strain of unsaturated cohesive soil is hyperbolic, the linear model makes excellent fits to the experimental results (Guo-xiong et al. 2010).

A model which is based on a stress-strain curve in drained triaxial compression test of both clay and sand was contributed. 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. As its soil parameters (Modulus number, Unloading modulus, Modulus exponent, Failure ratio, Cohesion, Friction angle and Poisson's ratio) can be easily obtained directly from standard triaxial measurements, the Duncan Chang model is commonly used. There are more advanced models that are based on the theory of elasto-plasticity that can capture these features in ways that are more mathematically elegant, but this model has been included in RS^2 and RS^3 since it is well-known and has a history in soils mechanics (Duncan and Chang, 1970).

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. A comprehensive study was conducted 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 (N) 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 (Sateesh and Godavarthi, 2019).

ANALYSIS OF SOIL USING COMPUTATIONAL METHODS

Due to recent advances in computational technology, numerical analysis has become a standard tool to investigate the geotechnical problems. However, numerical simulations and their contributing physical-mechanical parameters are becoming increasingly difficult to obtain. On one hand the adequate results for numerical analysis of the complicated geotechnical problems (especially those involving multi-phase calculations) can be acquired only by generating an effective three-dimensional numerical model; on the other hand the behaviour of soils subjected to complicated stress paths can only be predicted by employing appropriate advanced constitutive models. For the two aspects to be adequately addressed analyses require enormous computational time. The physical-mechanical parameters required for numerical modelling might be measured from complex tests or from curve-fitting of results from one-element numerical simulations. For the sake of simplicity in such cases, an innovative idea of adaptive constitutive soil modelling is developed.

A study was conducted using the auto progressive training of the Neural Network. The Neural Network is quite successful at modelling the constitutive behaviour. The network is attached to an iterative non-linear finite element analysis so that the stress - strain relationship can be gradually extracted to train the Neural Network. This idea is later expanded with the addition of history points to the inputs and outputs of the Neural Network which increases the accuracy of the prediction (Ghaboussi, 1991).

The nested adaptive neural networks in an auto progressive training with data from a wide variety of non-linear stress paths can be used. In this study, a method had been developed to extract the material constitutive behaviour from a non-uniform material test. This method has been applied to a series of triaxial compression tests with end friction on sand. This method employs the use of a neural network material model in a finite element analysis. This study reveals the effect on predictions when testing data what were not included in the training (Ghaboussi and Sidarta, 1998)

In a study, one new method to establish the visco-elastic constitutive model for rock was proposed according to the results of laboratory tests. In this research, the model structure was constructed by Genetic Programming using a combination of elastic units and viscous units; the elastic and viscous coefficients for the model were determined via a modified particle swarm optimization. The new method was verified by conducting creep tests on two soft rocks Genetic Programming was first used for constitutive modelling in this study (Feng et al. 2006).

For the inverse extraction of non-linear material behaviour, another technique developed called the SelfSim method, is used. An improved SelfSim is combined with a recent genetic programming technique called linear Genetic Programming (LGP) for the development of this technique. A comprehensive database is prepared using the SelfSim, including stresses and strains of the structural elements. Then the strain-stress relationship is developed using a steady-state LGP. The derived formula based on LGP is very simple, straightforward and can be even used for design and pre-design purposes. So as to check the reliability and capability of the model, the implementation of LGP-based model is also tested in a general purpose finite element programme. Since the proposed model is an explicit formula, it is standard and practically useful for its implementation. The results show that the procedure is reliable and can be used with a high degree of accuracy to derive and formulate non-linear constitutive material models (Gandomi, 2014).

A study focused on the training of a simple Neural Network with a 2D Cartesian strain vector as an input and the Cartesian stress vector as an output was conducted. The test data in this case are created in Plaxis using the Hardening Soil model. This paper presents a methodology for converting or recasting complex constitutive models for geomaterials developed based on any constitutive theory into a fully trained Artificial Neural Network (ANN), which is then embedded in an appropriate finite element solution code (Stefanos, and Gyan, 2015).

The use of the predictive method of determination of stress-strain behaviour of soil by using constitutive models is of great use especially in cases of unavailability of laboratory equipment and also economic and time constraints in a project.

CONCLUSION

The literature survey indicates that several factors may affect the stress-strain characteristics of soil. Artificial neural networks have been widely used in various engineering disciplines including geotechnical engineering for estimation and other different applications. For the successful prediction of the observed behaviour of geotechnical structures, appropriate constitutive models can be embedded in a finite element engine. To estimate the response of geomaterials to different loading conditions in the most accurate way, the constitutive models have to be made complex by including a large number of material parameters and constants in it. By manipulation of appropriate data, artificial neural networks can be used to simulate the stress-strain response of any material. Artificial neural networks can be used to simulate stress-strain response of any material by using appropriate data. The neural network-based constitutive models can capture nonlinear material behaviour with high accuracy. For this purpose, synthetic data from any constitutive model can be successfully used to train a Neural Network based Constitutive Model. These will certainly leads to computational efficiency since the computation of stress increment for a strain increment from a trained Neural network based constitutive models is almost instantaneous. An intelligent finite element method developed based on the integration of an Artificial Intelligent based Constitutive Model in a finite element framework can be used as a substitute for the conventional constitutive models for the material. Assessment of environmental changes on geotechnical structures can be done using the equations based on hyperbolic models.

From the journals, it can be concluded that the use of the predictive method of determination of stress-strain behaviour of soil by using constitutive models for geotechnical engineering projects is of great use especially in cases of unavailability of laboratory equipment and also economic and time constraints in a project.

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