Constitutive Behavior of Fine-Grained Soil: A Review

Priyanka P Manjanath[1], Mary Dhanya[2]

[1]PG student, Civil Department, Toc H Institute of Science and Technology, Kerala, India
[2]Asst.Professor, Civil Department, Toc H Institute of Science and Technology, Kerala, India

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Abstract - *Soil is a complex material consisting of solid grains in contact with each other and voids containing water or air. Soils show anisotropic, non-linear and time-dependent responses in different cases of loading conditions. The presence of fine-grained soil influences the geotechnical design considerations significantly. It is necessary for geotechnical engineers to better understand the stress-strain behavior of these soils. A better understanding of the constitutive behavior of fine-grained soils helps in safer and effective design and analysis of geo-structures constructed with or on such fine-grained soil deposits. In numerical modeling methods, the relation of stress and strain of soils is represented by the constitutive model. It models the behavior of soil in a single element. Constitutive models can provide a brief idea about how soil will behave under different loading conditions. For modeling the stress-strain behavior of soils, several constitutive models have been established over time. These models can be applied in finite element modeling for application in geotechnical engineering and also for the soil-structure problems analysis under different loading conditions. One such model Duncan-Chang Model is based on the stress-strain curve in drained triaxial compression tests of clays and sands and can be approximated by a hyperbolic function. It is an incremental, non-linear, stress-dependent model. The most commonly used model is the Duncan-Chang model, since its soil parameters can be easily obtained directly from standard triaxial studies. This seminar is an overview of the suitability of the constitutive model proposed by in different studies for determining the stress-strain behavior of cohesive soils.*

Key Words: **Constitutive model, Hyperbolic, Stress-strain, Duncan-Chang, Fine-grained**

1. INTRODUCTION

The relevance of determining soil properties by a predictive method is of high importance to get faster results. It is a very suitable method to know the soil behavior in case of the unavailability of laboratory requirements and adequate time. Constitutive models can be used to describe the different aspects of soil behavior in detail. It can also be used to apply in finite element modeling for geotechnical engineering applications. It is very important to predict the stress-strain behavior of soil for estimating settlement, conducting stability analysis, and to determine the stress conditions on earth retaining and underground structures. There exist many varieties of models to represent the stress-strain and failure behavior of soils. All these models inhibit certain advantages and limitations which largely depend upon their application.

2. CONSTITUTIVE MODELS

Constitutive models describe the responses of material to different mechanical and/or thermal loading conditions. It gives the stress-strain relations to formulate the governing equations, with the help of conservation laws and kinematic relations. Various constitutive models have been proposed by several researchers to explain various aspects of soil behavior in detail and also to use such models in finite element modeling for geotechnical engineering applications. There exist many varieties of models to represent the stress-strain and failure behavior 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 modeling 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.

2.1 Importance of Constitutive models in Geotechnical engineering

The constitutive models can be used to analyze various types of geotechnical. Constitutive modeling finds application in geotechnical engineering mostly in the cases of tunnels, dams, embankments, soil structure interaction, soil reinforcement and anchorage, settlements due to fluid extraction, natural and unbraced cut slopes, etc. It is possible to analyze and predict the behavior of any type of complex soil structure and soil-structure interaction problems.

2.2 Different types of Constitutive models

Over a period of time, constitutive models have progressed from being easy to more complex to capture soil behavior under complex loading conditions. For soil behavior 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 behavior 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 (Green Elastic Model) 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 behavior 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.

2.3 Requirements of Constitutive models

Constitutive models which can be used to replicate the important aspects of the soil stress-strain behavior under different loading conditions are very important. To develop such a model, advanced studies need to be conducted to study the behavior 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.

3. DEVELOPED MODELS TO PREDICT THE SOIL BEHAVIOR IN DIFFERENT CONDITIONS

A moisture-content based constitutive model based on the hyperbolic model was proposed by Guo-xiong MEI, Qi-ming CHEN and Peng-ming JIANG (2010) [5]. 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 used to determine the properties of unsaturated soil and conventional saturated soil mechanics are used to analyze 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. A comparison between measured and predicted stress-strain curve for soil sample with 25.42% moisture content was used to verify that the proposed model gives a good prediction of the stress-strain behavior of unsaturated cohesive soil. The linear model provides excellent fits to the experimental data to confirm that the relationship between stress and strain of unsaturated cohesive soil is hyperbolic.

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 and Chang Chin-Yung (1970) [4]. 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 that is stress-dependent and formulated using power-law functions. Its criterion of failure is based on the Mohr-Coulomb model. As its soil parameters can be easily obtained directly from standard triaxial measurements, the Duncan-Chang model is commonly used.

Abdul Kareem H Ahmed and Helal Ahmed (2007) [1] aimed at researching the hyperbolic parameter values required for nonlinear finite element analysis with the help of information used from the triaxial compression tests for the soils subjected to the effect of wetting and drying cycles. The model can be applied for the calculation of movements in stable earth masses and is not suitable for predicting instability or collapse loads.

The variables of stress state and constitutive equations are based on the principles unsaturated soil mechanics, the basic concepts for characterization of unsaturated soils and measurement of matric suction. The study conducted by Rahardjo Harianto, Kim Yongmin and Satyanaga Alfrendo (2019) [9] suggested that it is possible to estimate the permeability function of unsaturated soils available from the Soil Water Characteristic Curve (SWCC) and the coefficient of permeability. They also found that the statistical model is rigorous and can yield the most precise permeability function.

The suitability of the hyperbolic model for widely varying plasticity characteristics, initial moisture content, and initial density has to be validated. In the study conducted by Murugan Arun R B and Stalin V K (2009) [7], a few equations to predict the stress-strain behavior, time-shrinkage behavior, and suction-water content of soil for any liquid limit, initial moisture content, and density are suggested using the hyperbolic model.

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 and Venkata Rama Subba Rao Godavarthi (2019) [8] 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. 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. Empirical correlations can be very helpful for the engineers to rapidly estimate E and C_u using N value.

The applicability of standard penetration tests to estimate undrained shear strength of soils of Imphal was also studied by Ngangbam Bulbul Singh, Ningthoujam Jibanchand and K Rambha Devi (2019) [10]. By comparing the laboratory and the predicted shear strength values of fine-grained soils in Imphal, the analysis focuses primarily on the applicability of the existing correlations between the Standard Penetration Test number and undrained shear strength of fine-grained soils in Imphal. It was observed that existing correlations that take the effect of plasticity into account correlate better than those which do not take effect of plasticity into account.

Soil modulus is a foundation settlement input parameter used for the purpose of preliminary analysis and design of shallow foundations placed on cohesive soils. Akpila S B and Omunguye I W (2014) [2] conducted a study based on the stress-strain behavior of soils in four areas. The study consisted of 81 unconsolidated undrained triaxial test results and the deviator stresses, cross-sectional area, induced strains, major and minor principal stresses were evaluated. Shallow foundation settlement input parameter of soil modulus is then obtained from the predictive models, for preliminary analysis and design. Soil modulus can easily be obtained from predictive models and can be used for preliminary analysis and design of shallow foundations in cohesive soils.

To understand the stress-train-time behavior of wet clays that are subjected to three-dimensional stress and strain states, constitutive models can be developed and used. Borja R I and E Kavazanjian (1985) [3] proposed a constitutive model for predicting the stress-strain-time behavior of wet clays. The constitutive equation is shown to predict accurately the stress-train-time behavior of undisturbed wet clay in triaxial and plane strain stress conditions.

Wang Yuanlong, Zhu Jungao and Zhou Jianfang (2012) [11] incorporated the investigation of mechanical behavior of cohesive soil by mixing gravel by conducting consolidated drained triaxial tests. Several triaxial tests for three soils were performed, and their stress-strain and strength behavior were investigated. A multi-function triaxial apparatus is employed to perform the test. Duncan-Chang nonlinear elastic model was used for numerical analysis to find out soil parameters. It was found that the Duncan's model was not useful for the tested soil.

The use of the predictive method of determination of stress-strain behavior 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.

4. CONCLUSION

Assessment of geotechnical structures can be done using the equations based on constitutive models. Results from various types of tests can be used to develop the constitutive models depending upon the needs, type of soil, and various other factors. Fine-grained soils are the most complicated engineering material. In many instances, different types of relationships may be utilized to determine the geotechnical parameters from the values extracted from the in-situ tests, according to the inaccessibility of equipment and also financial and time constraints in a project. Based on many factors like available data and degree of accuracy required, various types of models can be generated using manual as well as advanced computing techniques. Accuracy of the model can be improved by incorporating more number of input variables and an increasing number of data sets. It is of great importance in civil engineering to make realistic predictions of the behavior of soil under various conditions for estimating settlement, conducting stability analysis, and to determine the stress conditions on earth retaining and underground structures.

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