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Theoretical study on constitutive modelling of frozen soils

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Abstract
Artificial Ground Freezing techniques eliminate the need for structural supports during the course of an excavation, as frozen ground is solid and waterproof. At present, it is adopted as an effective way to deal with various construction ground control challenges such as the mitigation of seepage infiltration into tunnels and shaft excavations; or ground strengthening for excavation. In-depth knowledge of the frozen soil characteristics through experiments and the development of suitable constitutive models that suit the geological conditions of our country are necessary to predict the strength and behaviour of the frozen soils. This paper presents a review on the various constitutive models used in soil analysis. Authors hope that this article will help to develop better understanding of frozen soil properties and emphasize the need for accurate constitutive models incorporating the characteristics of soils in our country.

Keywords: Artificial Ground Freezing, Constitutive Modelling, Mohr Coulomb criteria, Drucker Prager Model

Introduction
The technique of Artificial Ground Freezing (AGF) is now commonly used in the cold regions of the world. Extension and improvement of transportation networks in densely populated areas with thickly packed infrastructure is becoming unavoidable now-a-days, especially in urban areas. An alarming increase in the population of vehicles is creating severe traffic congestion. Hence this will surely be a promising ground improvement technique in the coming years all around the World as infrastructural expansion is possible only through underground space exploration.

Artificial Ground Freezing is gaining importance because of its advantage in eliminating the need for structural supports during the course of excavation. In this method, the strong solid frozen barrier created around the zone of excavation prevents the intrusion of water into the area of excavation thereby creating a safe working environment for labourers. In all other existing excavation methods, there are possibilities of dangers creeping in due to various reasons during the progress of the work.

AGF involves circulating refrigerated liquid through a series of subsurface pipes to freeze the ground temporarily around the zone of excavation until the work is completed as shown in fig 1. Most of the theoretical and experimental studies in the cold regions are conducted on soils which are in the naturally frozen state. All the available literature and existing models are based on these results. For introducing the AGF technique for any underground construction in our country, a thorough knowledge of the geotechnical characteristics of soils, especially in the frozen state, is necessary.

The intrinsic material properties such as moisture content, organic matter, air bubbles, grain size, salts and externally imposed testing conditions such as strain-rate, stress and strain history, temperature and confining pressure governs the mechanical behaviour of frozen soil.

Constitutive Models in Soil Analysis
When frozen soil is subjected to loading, the uniaxial stress strain curve exhibits an elasto-plastic behaviour. So constitutive models are required for studying the behaviour of soil subjected to loading. Soil is a complicated material that behaves non-linearly and often shows anisotropic and time dependent behaviour when subjected to stresses. Generally, soil behaves differently in primary loading, unloading and reloading.

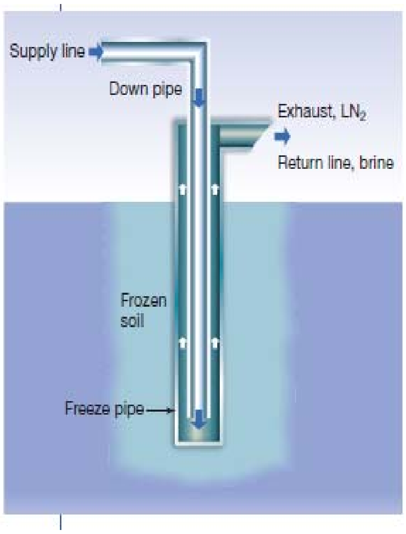

Fig 1: Artificial ground freezing principle

It exhibits non-linear behavior well below failure condition with stress dependent stiffness. Soil undergoes plastic deformation and is inconsistent dilatancy. Soil also experiences small strain stiffness at very low strains and upon stress reversal. Thesis general behaviour was not possibly being accounted for in simple elastic-perfectly plastic Mohr-Coulomb model. Although the model does offer advantages which makes it a favourable option as soil model.

Soil behaviour that should be considered also includes factors such as compaction, dilatancy and memory of pre-consolidation stress.

In addition to soil behaviour, its failure in three-dimensional state of stress is extremely complicated. Numerous criteria have been devised to explain the condition for failure of a material under such a loading state. The various models available are:

1. Tresca's model
2. Von Mises model
3. Mohr's Coulomb model
4. Drucker Prager model

Tresca's Model

The Tresca failure criterion is used regularly in geotechnical engineering to compute the failure loads of clay soils deforming under undrained conditions.

When this criterion is used together with the finite element method a plastic flow rule must also be incorporated in the elasto-plastic soil model. Tresca's yield surface is given

$$F=\sqrt{J_2}\,\text{Cos}\theta - S_U = 0$$

J_2 is the second stress invariant, which is a measure of the distance between the current stress state and the hydrostatic axis in the deviatoric plane. θ is the Lode angle, which defines the orientation of the stress state with respect to the principal stresses in this plane. S_u is the undrained shear strength of the soil. K is a vector of state parameters whose values are not important in the present context

Von Mises Yield Criterion

Yield will occur at a particle when some combination of the stress components reaches some critical value

Yield criterion can also be expressed as

$$F((\sigma),(K)) = J-\propto$$

σ is the material parameter representing shear strength of soil specimen. The elastic behavior is controlled by assuming Young's modulus and Poisson's ratio.

Mohr-Coulomb Criteria

Mohr-Coulomb model is a two-parameter model with criterion of shear failure

According to Mohr Coulomb method failure in a soil sample will occur when the shear stresses in any plane are such that

$$\tau = C + \sigma \tan \phi$$

where

C is the cohesion intercept

ϕ is the angle of internal friction

σ is the normal stress

The model's stress-strain behaves linearly in the elastic range, with two defining parameters from Hooke's law (Young's modulus, E and Poisson's ratio, ν). There are two parameters which defines the failure criteria (the friction angle, ϕ and cohesion, c)

Mohr-Coulomb model is a simple and applicable to three-dimensional stress space model. Only two strength parameters to describe the plastic behavior.

By means of true Triaxial tests that stress combinations causing failure in real soil samples agree quite well with the hexagonal shape of the failure contour. This model is applicable to analyse the stability of dams, slopes, embankments and shallow foundations. The simplification of Mohr-Coulomb model where the hexagonal shape of the failure cone was replaced by a simple cone was known as the Drucker-Prager model (Drucker & Prager, 1952).Generally, it shares the same advantages and limitations with the Mohr-Coulomb model. But the latter model was preferred over this model

Drucker Prager Model

The Drucker–Prager failure criterion was established as generalization of the Mohr–Coulomb criterion for soils by (Drucker and Prager 1952). It can be expressed as

$$\sqrt{J_2}=\lambda I_1 + k$$

where k and λ and are material constants, J_2 is the second invariant of the stress deviator tensor and I_1 is the first invariant of the stress tensor. The original criterion describes a right-circular cone in the stress space when $\lambda > 0$ and a right circular cylinder when $\lambda = 0$ which is Von Mises criterion

Parameters used in Drucker Prager model

- Structural material properties must be input as isotropic elastic linear.
- Young's modulus (EX)
- Poisson's ratio (PRXY or NUXY)
- Poisson's ratio defaults to 0.3 and should not be equal to or greater than 0.5.
- Choose Drucker-Prager (DP) in non-linear, inelastic, non-metal plasticity models.
- The input data consist of 3 constants.
  - ➢ Cohesion value (must be > 0)
  - ➢ Angle of internal friction
  - ➢ Dilatancy angle

Advantages of Drucker Prager model
- Simple to use.
- Can be matched with Mohr- Coulomb by a proper selection of constants.
- Computer codes available
- The effect of volume change is considered in the analysis by means of Dilatancy angle where all other model fails to do so.
- Satisfies uniqueness requirements.
- More parameters are considered in analysis.
- Constitutive relations can be obtained easily.

Experimental Setup

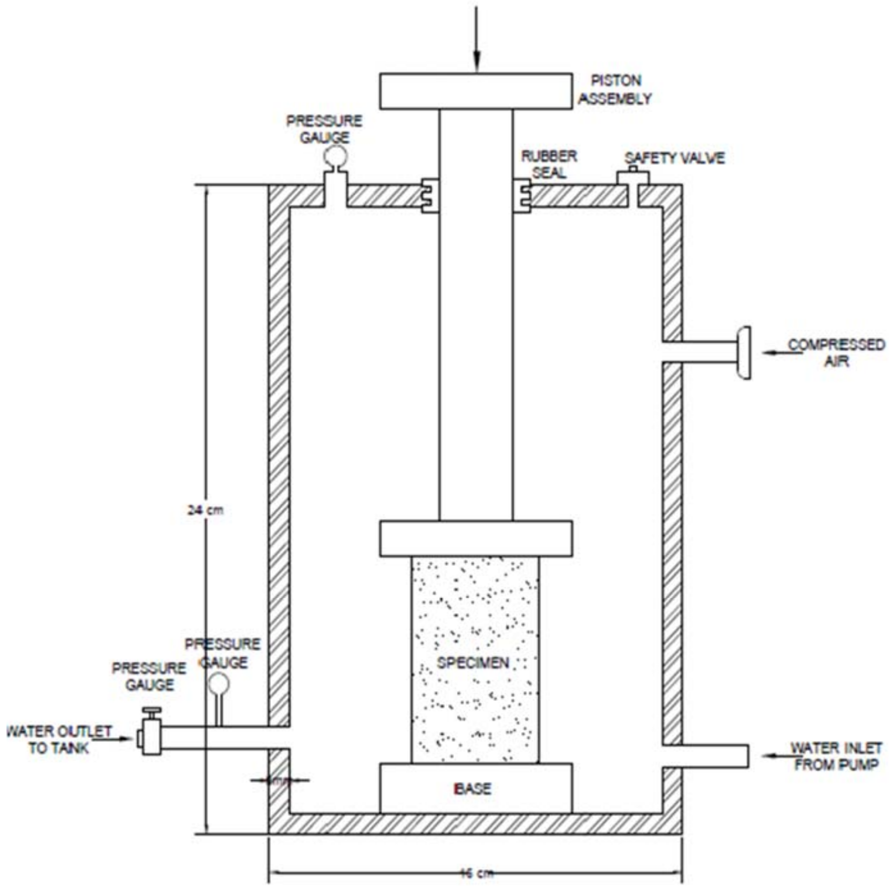

Fig 2: Experimental setup in the work

The proposed experimental setup as shown in fig 2 is designed to measure the parameters of Drucker Prager model which includes the cohesion, dilatancy angle and angle of internal friction.

A Gist of the Experimental Work
- Development of High Pressure Low Temperature (HPLT) Triaxial Test Cell. It allows the stress conditions found at greater depths to be modelled.
- Proper instrumentation of the Triaxial cell and the use of data acquisition system for accuracy and reliability of results obtained.
- Samples selected for study (Sand, Silt and Clay)

Apply confining pressure as in hydrostatic compression tests and once it is stabilized apply deviatoric stress $\sigma_1 > \sigma_2 = \sigma_3$.. Triaxial tests are to be conducted under different temperatures and confining pressure conditions. Then plot the stress strain curve.
For the current analysis the most favourable and suitable model is Drucker Prager model due to its wide application and advantages.

Conclusions
This paper puts emphasis on the need to adopt this technology in our country, especially in the area of tunneling as it is a very easy and environmental friendly technique. Determining the strength of frozen soil calls for more research for expanding its applications in underground construction. Currently, this technique is being used in the cold regions of the world. Studies on the mechanical behaviour of frozen soil and the development of a new constitutive model integrating the intrinsic soil properties of our country will help to predict the characteristics of the frozen soil which is reliable. Moreover, it will contribute to the research and development in the area of frozen soil mechanics.
There are numerous elastoplastic models available for modelling and analysing soil specimen. In the present study the modelling is planned to be done using ANSYS 15 FEA Code. All the elastoplastic models mentioned above are not available in ANSYS. Only Mohr Coulomb model and Drucker Prager model is available. So the next objective was to select the best model among them to perform the analysis. Mohr coulomb model was limited to linear analysis. Since

frozen soil behaves in a non linear manner the above model will not meet the requirement. Thus Mohr coulomb model was rejected for the analysis and then the Drucker Prager model of non linear analysis was selected for the current problem since it provides more accurate results than the other one.

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