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Finite Element Analysis of Artificially Frozen C-Phi soil

Gouri Mohan L, K. K. Abdul Rasheed, Reebu Zachariah Koshy

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 behavior of the frozen soils. Numerical analysis of frozen soil can be used for mass works like tunneling which cannot be experimentally verified. This paper presents a validation of experimental results obtained from laboratory setup and soil freezing system for C-Phi soil. The main aim is to compare numerical and experimental results and hence obtaining the shear strength parameter of the soil, similar to the conventional triaxial test setup. To perform numerical analysis Finite element tool ANSYS 19 is used. Soil model is made in ANSYS 19 and required loads are inputted to performed the analysis similar to the experimental method. The result obtained from experimental test setup and numerical analysis was verified and compared and it was found that values of numerical results lies closer to experimental results.

Keywords: Artificial Ground Freezing, C-phi soil, Finite element analysis, Frozen soil, Triaxial test setup

I. INTRODUCTION

Artificial Ground Freezing (AGF) is a construction technique which has been in practice for over a century, mainly in the cold regions of the world. AGF is the process of converting soil moisture into ice by continuously refrigerating the soil [3]. This method is adopted to increase the compressive and shear strength of the soil and thereby making the water bearing strata temporarily impermeable. 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 labor [4].

The stability of the frozen soil wall is prone to dangers induced by the deformation behavior of the frozen wall before and after construction. 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 behavior of frozen soil [5]. To study the mechanical behavior of the soil, an experimental investigation is done on newly developed triaxial test setup. In this paper, a finite element analysis is done in order to validate the experimental results obtained [2]. When frozen soil is subjected to loading, the uniaxial stress strain curve exhibits an elastoplastic behavior. So constitutive models are required for studying the behavior of soil subjected to loading. Soil is a complicated material that behaves non-linearly and often shows anisotropic and time dependent behavior when subjected to stresses. Generally, soil behaves differently in primary loading, unloading and reloading [6]. It exhibits non-linear behavior well below failure condition with stress dependent stiffness.

Soil undergoes plastic deformation and experiences small strain stiffness at very low strains and upon stress reversal [7]. This general behavior was not possibly being accounted for in a simple elastic-perfectly plastic Mohr-Coulomb model, although the model does offer advantages which makes it a favorable option as soil model. Soil behavior that should be considered also includes factors such as compaction, dilatancy and memory of preconsolidation stress. In addition to soil behavior, its failure in three-dimensional state of stress is extremely complicated. Based on these factors a suitable soil model for ANSYS is adopted and tested to arrive at appropriate results.

Finite element analysis of frozen soil can be effectively adopted for large scale works like tunneling where ground is frozen to act as solid and thereby eliminating supporting structures. For such massive work collecting individual soil sample and testing for frozen condition may not give the actual site results. Here the finite element analysis tool can be effectively used to determine the actual stress developed in frozen soil.

II. EXPERIMENTAL INVESTIGATION

The mechanical properties of raw soil samples tested in the laboratory are dependent upon the quality of the specimens. Soil sample was collected from the pit at a particular depth was used for this work [2]. Soil sample collected was modified into three representative sample.

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For studying the variation in frozen soil with properties of the soil, the following three set of soil sample are adopted (i) C-φ Soil (ii) C-φ Soil replaced with 50% coarse grained soil and (iii) C-φ Soil replaced with 50% fine grained soil. The shear parameters of soil in the normal condition can be determined using conventional triaxial apparatus. The strength and mechanical behavior of this material can be determined experimentally and can be even predicted numerically.

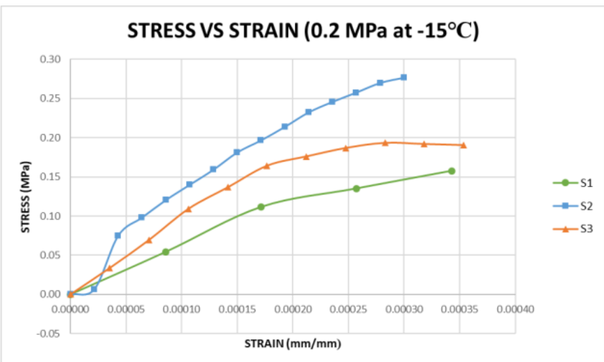
As this technology is not yet explored in our country, there is no available test set up for testing frozen soil. As part of this study a triaxial compression apparatus is designed and fabricated to test frozen soil samples incorporating the features of the existing triaxial apparatus. Test setup is shown in fig 1.

Fig. 1.Full Experimental setup

Properties of soil specimen used for the experiment is given in Table I. Experiment is done by freezing the soil specimen to required temperature in a freezer and triaxial test is done on the specimen in specially designed apparatus without losing the frozen conditions. Thereby obtaining the required stress strain curves from readings obtained. Stress strain curves obtained for 3 soil samples at -15℃ and -30℃ testing conditions are given in fig 2.

Table- I: Properties of soil specimen

Properties	Sample 1	Sample 2	Sample 3
Length (mm)	75	75	75
Diameter (mm)	62.5	62.5	62.5
Loading rate (KN/min) Vertically applied	42.95	42.95	42.95
confining pressures (Kpa) Laterally appiled	200	200	200
Unit weight (KN/m3)	13.33	12.36	11.87



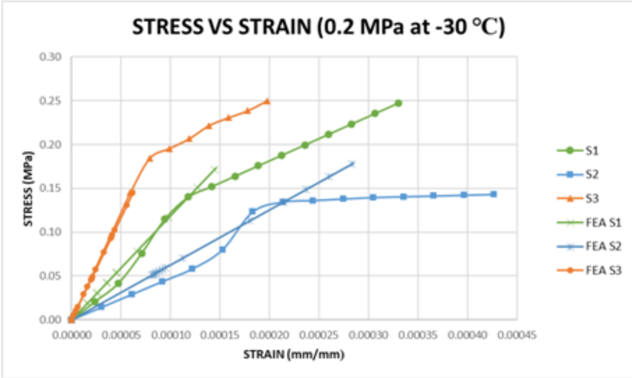


Fig. 2.Experimental results obtained for -15℃ and -30℃

III. FINTIE ELEMENT ANALYSIS

ANSYS mechanical is a finite element tool for structural analysis including linear and nonlinear and dynamic problems. Software provides equations solvers for wide range of the design problems. Using ANSYS, simulated computer models of structures, electronic or machine components to simulate strength, toughness, elasticity, temperature distribution, electromagnetism, fluid flow etc. can be created.

The complete Finite Element Analysis for the verification and validation of the frozen soil at various temperature tested was conducted in ANSYS Mechanical Workbench R19.0. Before starting the analysis, a thorough study has been conducted on the type on Geomechanics material model that need to be considered in numerical analysis of frozen as well as unfrozen soil. The comparison of the Geomechanics materials models available in ANSYS Workbench such as Drucker-Prager, Extended Druger-Prager and Mohr-Coulomb were compared for both frozen as well as unfrozen. A flow chart for the procedure of finite element analysis used is shown in fig 3.

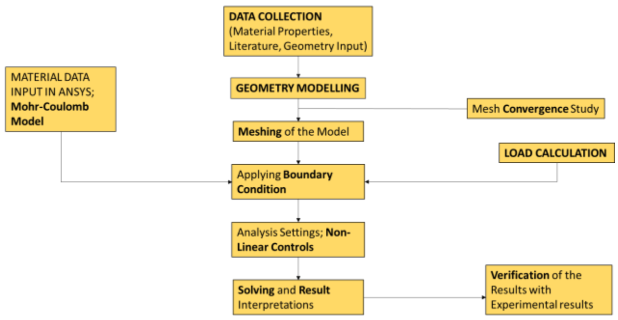


Fig. 3. Methodology

A. Initial Modelling

The samples were modelled in ANSYS Design Modeller according to the specimen dimension used in the experimental testing [2] as shown in Fig. 2. During the modelling separate face imprints were provided were strain gauges were attached for probing the required output according to the scope of the analysis. Here at those locations the Max Von-misses stress and Max Von-misses strains were measured and compared against the experimental values.

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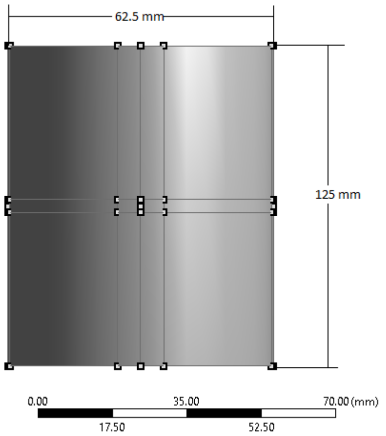

Fig. 4.Dimensions of the specimen modelled

Properties required for inputting into ANSYS is computed from stress stain curves and is shown in tables below.

Table- II: Properties of unfrozen soil specimen

Unfrozen Soil			
Properties	**Sample 1**	**Sample 2**	**Sample 3**
Young's modulus (MPa)	2.21	2.15	2.03
Poisson's ratio	0.25	0.25	0.25
Initial cohesion (Kpa)	36.07	23.4	31.85
Initial inner friction angle (Degrees)	4.896	10.11	2.24
Dilatancy angle (Degrees)	0	0	0
Residual inner friction angle (Degrees)	3.917	8.088	1.792
Residual cohesion (Kpa)	28.83	18.65	25.48

Table- III: Properties of frozen soil specimen at -15°C

Frozen soil at -15°C			
Properties	**Sample 1**	**Sample 2**	**Sample 3**
Initial cohesion (Kpa)	25.130	2.760	20.390
Initial inner friction angle (Degrees)	10.680	23.529	13.907
Dilatancy angle (Degrees)	0.000	0.000	0.000
Residual inner friction angle (Degrees)	8.544	18.823	11.125
Residual cohesion (Kpa)	20.104	2.208	16.312

Table- IV: Properties of frozen soil specimen -30°C

Frozen soil at -30°C			
Initial cohesion (Kpa)	30.670	26.861	42.760
Initial inner friction angle (Degrees)	16.180	9.622	19.946
Dilatancy angle (Degrees)	0.000	0.000	0.000
Residual inner friction angle (Degrees)	12.944	7.698	15.957
Residual cohesion (Kpa)	24.536	21.489	34.208

B. Meshing

The meshing of the models was done in ANSYS Mechanical with the SOLID65 element type. The SOLID65 element type was called into the mechanical interface using APDL command macros. A separate mesh convergence study was conducted to choose the appropriate element size and shape. From the mesh convergence study, it was found that the better results were obtained at 2.5 mm as shown in Table V. A linear hexa shape element was chosen for the analysis. Total number of element and nodes in the specimen is 30750, 32860 respectively.

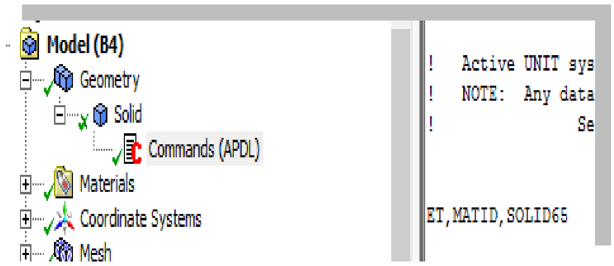

Fig. 5. APDL Macros inserted for element

Table- V: Mesh Convergence Study

Stress (MPa)	**Element Size (mm)**
0.0164	10.0
0.0340	8.0
0.0814	7.0
0.1042	6.0
0.1082	4.5
0.1247	4.0
0.1666	3.25
0.2076	3.0
0.2125	2.5
0.2185	2.0
0.2191	1.5

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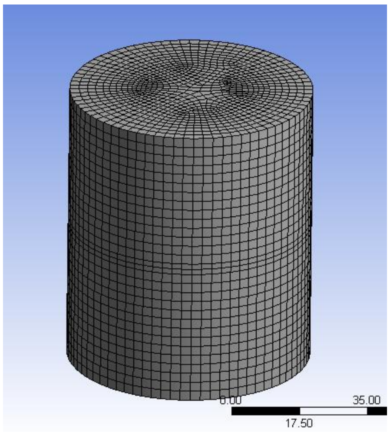


Fig. 6. Meshed model of the specimen.

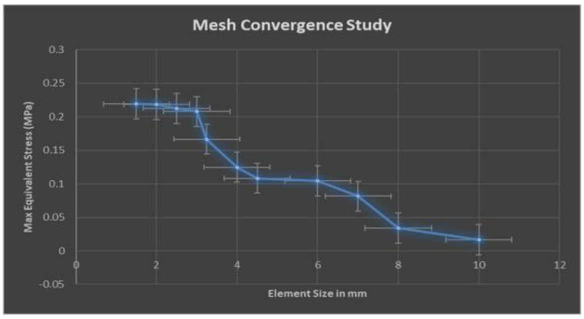


Fig. 7. Mesh Convergence graph of the specimen FEA.

C. Application of Load and Boundary conditions

In this finite element analysis two types of loading were applied; one is the vertically downward loading and a confining pressure applied over the cylindrical surface area of the specimen. The confining pressure considered was 0.2 MPa. The vertical loading was applied in each specimen according to the experimental testing of each case. Apart from these two loads the model was fixed arrested at the bottom of the specimen. The results were measured at the middle of the model exactly as per the strain gauges were placed during the experimental test.

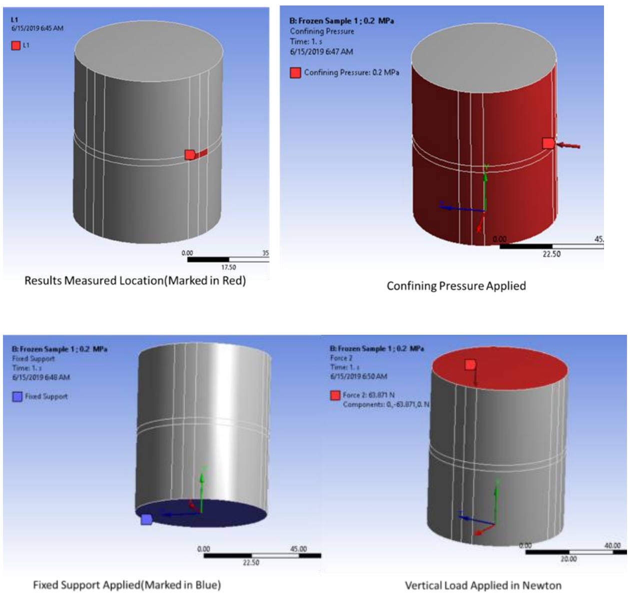


Fig. 8.Loads and Boundary conditions

Due to the complexity of getting the frozen soil's plastic/failure state behavior, this finite element analysis was limited to linear quasi-static analysis. Loads were applied in 14 steps according to the loading information provided. Total 4500+ iterations were needed for properly converging the FEA problem. The material and geometrical Non-Linearity were considered.

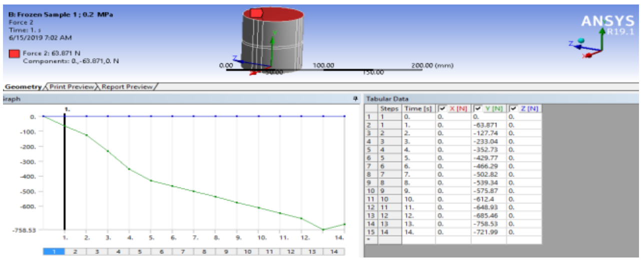
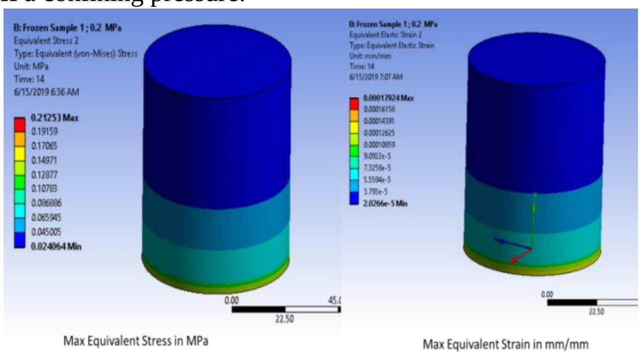


Fig. 9.Load Applied for Sample 1; 0.2 MPa Confining Pressure; -30° C

IV. RESULT AND DISCUSSION

All the results obtained from the finite element analysis were compared against the tested results for both frozen as well as unfrozen condition. Only the linear portion of the results were compared, by checking the slope of each curve obtained. All three samples were tested by maintaining the same experimental conditions. Initially the validation is performed and once satisfactory results are produced, further finite element analysis is done based on the validation. Figure 6.21 show the results for frozen soil sample 1 at -30° C with 0.2 MPa confining pressure.



The results obtained for Frozen Soil Sample 1 at -30° C with 0.2 MPa Confining Pressure.

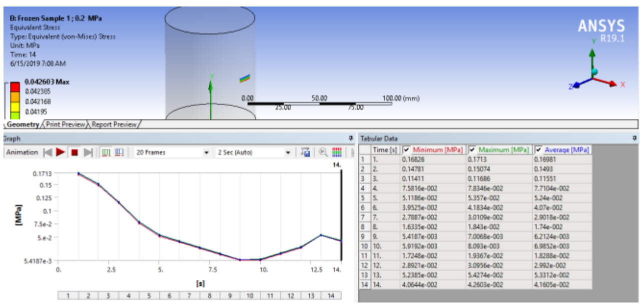


Fig. 10. Max Equivalent Stress (MPa) measured at L1 `

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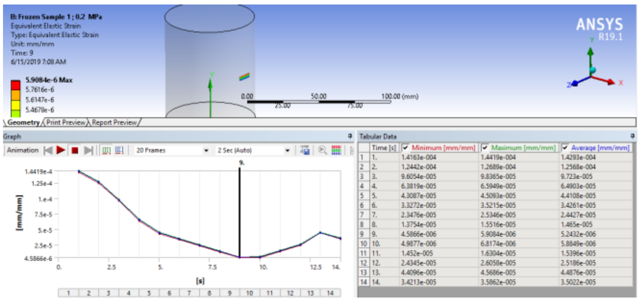

Fig. 11. Max Equivalent Strain (mm/mm) measured at L1 location

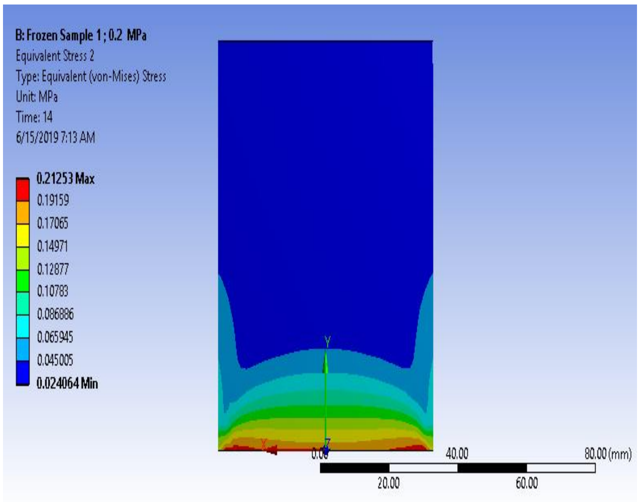

Fig. 12. Max Equivalent Stress (mm/mm) Sectional View

Stress strain curve shown in fig 13 shows the comparison between experiment and finite element results. For the three samples (S1, S2, S3) linear portions of the curves show similar behavior both in experimental and finite element curves. These results were compared with the experimental results and found linear elastic region falls close to experimental results.

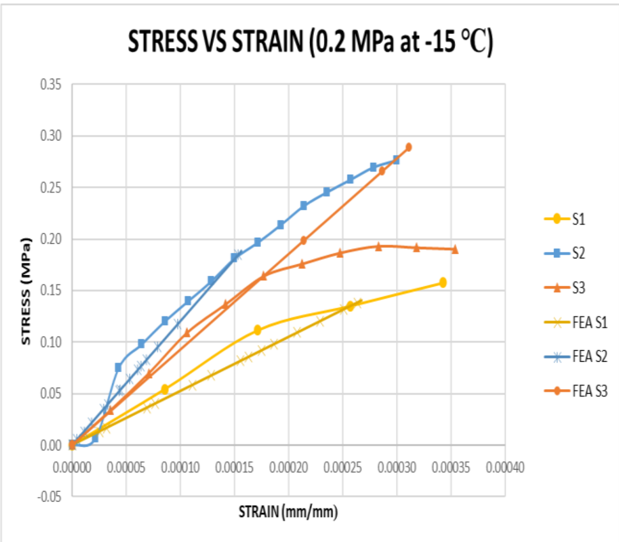

Fig. 13. Stress Strain curves for samples at -15°C

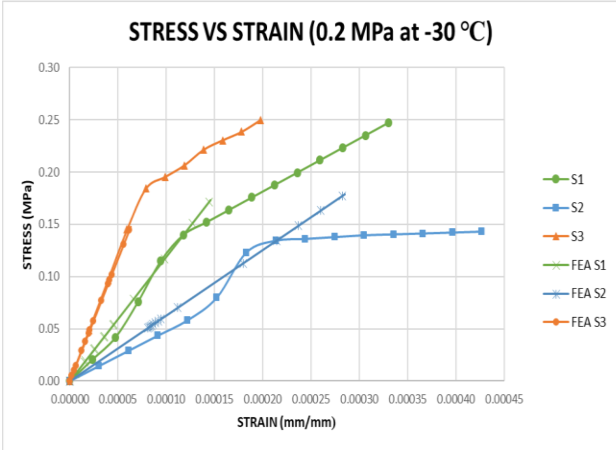

Fig. 14. Stress Strain curves for samples at -30°C

V. CONCLUSION

For the validation of experimentally tested frozen soil, three samples of different characteristics have been modeled in ANSYS 19 using suitable soil model - Mohr coulomb model. Finite element tool ANSYS has been extensively used to provide complex loading conditions that prevail in the experimental triaxial test setup so that loading condition remain the same in finite element analysis as well. FEA will be good tool for large scale analysis of stress behavior of frozen soil condition especially in large scale ground freezing areas. Proper selection of soil model and meshing study helped to have results closer to experimental results. FEA can be thus used as an extensive tool for studying the characteristics of bulk mass of soil which cannot be tested using laboratory test setup.

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