Assessment of mechanical behavior of granular soils adopting various plasticity models

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ABSTRACT: The mechanical behavior of soils is highly complex due to the heterogeneous behavior of these deposits. There are various experimental and empirical methods followed to assess the behavior of these granular masses. However, field tests, laboratory tests and empirical relationships have inherent uncertainties associated with them. The empirical correlations developed are based on the data collected from various field tests. The quality of the data collected from various field tests like Standard Penetration Test (SPT) and Cone Penetration Test (CPT) depends on the field practices which may be inconsistent due to different test methods followed in the field. Also the quantity of data available for adopting these correlations are not sufficient in some cases. Hence for a sophisticated evaluation of various properties, analytical methods are a must. In addition to this, the behavior of saturated soil during sudden loading is highly influenced by the development of excess pore water pressure. The sudden development of excess pore pressure in soils is directly related to the field condition of that soil deposit. Analytical methods help to understand the gradual accumulation of permanent strain. In this research, various models based on theory of plasticity is adopted for assessing the behavior under drained static conditions. The data obtained from the reported experimental results are collected for various soils and are utilized to obtain the elastic and hardening parameters required for the numerical and analytical models. Numerical modeling of the sample and various loading conditions are simulated using a finite element software. The stress strain relationships which accounts for the accumulation of plastic strain and the subsequent plastic flow is defined and a comparison of the different models considered is reported.

Keywords: Drained Triaxial test, Cam Clay Model, Drucker Prager Model, Shear stress, Strain

1. INTRODUCTION

Granular material is made up of discrete particles. The shape and size of particles influence the mechanical behavior of granular materials. Also it depends upon particle orientation, friction among particles, pore spaces and saturation level of particles. When external forces such as static and cyclic loads act on these materials, deformation takes place by particle sliding leading to changes in mechanical behavior. Therefore, understanding the mechanical behavior is important in designing the structures. Because any changes in behavior of soil affects the structures directly and may cause failure of structure (Brenda, 2003).

When granular material such as sand or silty sand (saturated cohesion less soil) is subjected to rapid rate of loading, positive excess pore pressure is developed. This causes decrease in effective stress leading to the reduction on shear strength of soil and subsequently soil behaves like a liquid. This phenomenon is known as liquefaction which is usually associated with earthquake loads. But liquefaction can occur due to static sudden loads also. This phenomenon is known as static liquefaction. Static liquefaction causes damage to the infrastructure from landslides and bearing capacity failure. So it is important to study the behavior of soil before infrastructure construction. (Ellison & Andrade, 2009). Triaxial tests are generally conducted to understand the the behavior of granular soil. But it is difficult to collect the undisturbed sample of loose sand to conduct triaxial test. To overcome this difficulty, empirical methods are developed based on SPT, CPT and Borehole Penetrometer Test (BPT) (García et.al, 2012). But empirical method depends upon material conditions and is limited to specific topographic conditions. Accuracy of prediction of behavior of soil adopting empirical methods depends on knowledge of soil properties such as strength, stiffness and sampling method (Beaty and Byrne, 2000). These all limitations affect the accuracy of evaluation of shear failure of granular soil under various loading conditions. To overcome the limitations of empirical method, analytical methods are adopted which are simpler, easier and more accurate than traditional empirical methods (Lee, 2009). In this study, Cam Clay model and Drucker Prager models are used to analyze the behavior of granular soil subjected to drained static loading conditions.

2. BACKGROUND STUDY

Jefferies (1993), developed constitutive model for sand based on critical state theory. The study indicated that soil moves to critical state regardless of initial conditions. Khalili et. al (2005), formulated Bounding surface plasticity model for granular soils subjected to static and cyclic loads. They developed the model using the available experimental data from literature. It is reported that the developed model predicts stress softening and dilatancy during drained loading of dense sand. Arvelo (2005) evaluated the behavior of dense granular soil using Modified Cam Clay Model (MCCM). The results of the analytical model are compared to the laboratory drained triaxial test data. The study suggests that MCCM with some modifications, is applicable to dense sands. Thomas Oommen et. al (2010) compared the predictive performance of empirical liquefaction models. Deterministic and probabilistic empirical liquefaction models are developed using SPT and CPT data. But it is found that identifying gaps in data sets is extremely important for improving empirical models. Xilin & Maosong (2014) proposed a model to analyze the stress strain behavior of soil when it is subjected to static liquefaction. Mohr Coulomb elasto-plastic hardening model is proposed to predict static liquefaction. It is concluded that static liquefaction is initiated in loose sands when the undrained stress path occurred along with potentially unstable stress path. If sand is dense, it fails when state of sand becomes potentially unstable. Results show that static liquefaction occurred for selected sample at the hardening stage only before it reaches plastic limit failure. Rani. et al. (2014) studied the prediction accuracy of Mohr-Coulomb and Drucker Prager models in evaluating the behavior of clayey soil. It is reported that the Mohr- Coulomb model showed lower predictions compared to Drucker-Prager model.

3. CAM CLAY MODEL

Cam Clay model is developed to represent the soil behavior based on critical state. This model considers strength, compression and critical state aspects while formulating the behavior under various loading conditions. The basic parameters which describe this model include the effective mean stress, deviatoric stress and specific volume. The initial state of stress is also considered significant in this model which can be considered in terms of over consolidation ratio or pre-consolidation stress.

3.1 Collection of experimental data

The various input parameters required for the model has to be obtained from experimental data. For this, drained triaxial test data reported by Arvelo (2005) is adopted for this study. From this test, material properties and parameters for Cam Clay model are selected to evaluate the stress and strain behavior of the granular material. This data can be used as the input for both numerical and analytical modeling. The properties collected from the triaxial test are given in Table 1. The sand sample is subjected to a confining pressure of 100kPa. Figure 1 shows the variation of shear stress with shear strain for the drained triaxial laboratory test.

Table 1 Material Properties of Dense Sand Obtained from Triaxial Drained Test

Internal friction angle (Φ in degree)	34.96
Initial voids ratio (e_o)	0.28
Swelling index (κ)	0.0021
Slope of critical straight line (M)	1.416
Poisson's ratio (μ)	0.35
Young's modulus (E)	48 MPa
Density of sand (γ)	2700 kg/m^3
Specific gravity (G_s)	2.7

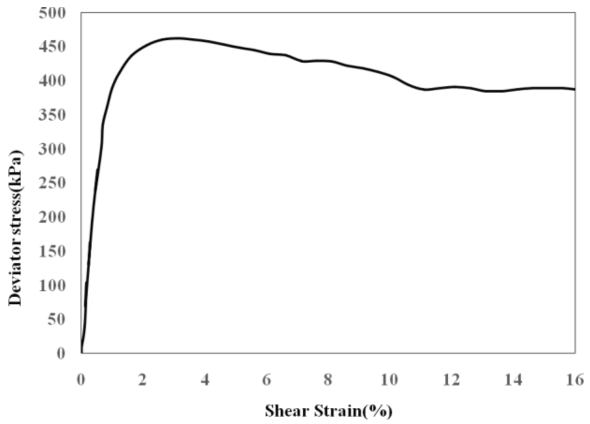


Figure 1 Shear stress vs Shear strain: Experimental results (Arvelo, 2005)

3.2 Analytical modeling adopting Cam Clay Model

The analytical model to predict the mechanical response of granular sand under drained conditions based on Cam Clay theory is developed in MATLAB. The relevant material properties to apply in the constitutive model are obtained from drained triaxial test results (Arvelo, 2005).

3.3 Numerical modeling adopting Cam Clay model

The sand sample is numerically modeled in ANSYS workbench for drained triaxial test adopting Cam Clay model. The cylindrical sand sample having diameter 36mm and height 72 mm is developed using SOLID 185 element in ANSYS (Figure 2). This element is suitable for 3-D modeling of solid structure which is defined by 8 nodes. The material properties given in Table 1 are used for the modeling. To replicate the experimental conditions, fixed base is given at the bottom of sample by selecting the bottom surface as shown in Figure 3. In this study, the gradual application of loads is done by providing 600 load steps. These load steps were sufficient to capture the gradual development of the non-linear behavior of sand.

An isotropic loading condition is imparted to the sample by applying a confining pressure of 100kPa in all directions and is shown in Figure 4(a). After isotropic stage, shear stage is developed by giving vertical displacement at the rate of 2mm per minute throughout the last load step. i.e. up to 600 seconds as shown in Figure 4(b).

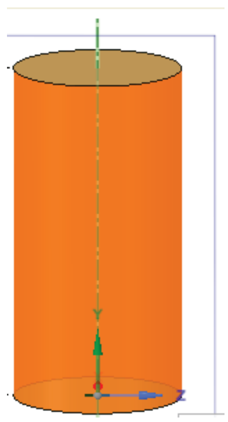


Figure 2 Sand sample for numerical simulation in ANSYS

Figure 3 Fixed support at the bottom of sand sample

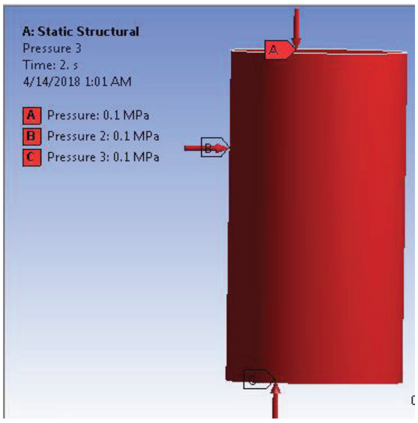


Figure 4 (a) Isotropic loading stage of sand in ANSYS

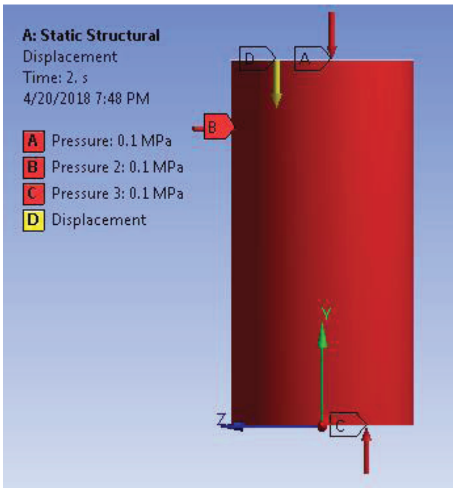


Figure 4 (b) Shear loading stage of sand

3.4 Results and Discussions of Cam Clay model

The loading path followed for the shear test in both numerical and analytical studies is shown in Figure 5. The deformed shape and strain in the sand sample when subjected to drained triaxial test condition in numerical analysis is shown in Figure 6(a) and (b). The formation of shear band is clearly visible in these figures.

Figure 7 shows a comparison of the constitutive behavior of the experimental, numerical and analytical studies. The results indicate the Cam Clay model prediction is fairly accurate in low strains during the strain hardening stage. It can be observed that the initial stiffness is very high and is similar to experimental results in both the numerical and analytical studies. However the peak stress attained by both the models is less than that observed in the experiment. More over the strain softening behavior predicted by Cam Clay model shows much lower residual strength values when compared to experiments. This clearly shows that Cam Clay model can accurately predicts the initial hardening behavior whereas the strain softening on residual strength is not accurately predicted.

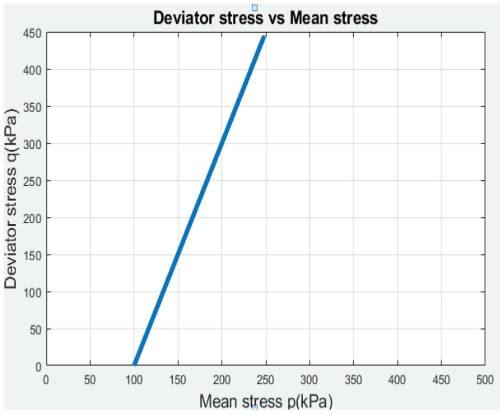
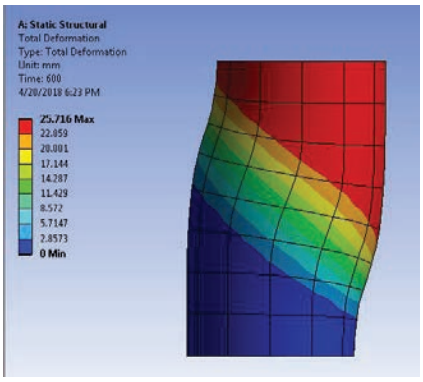
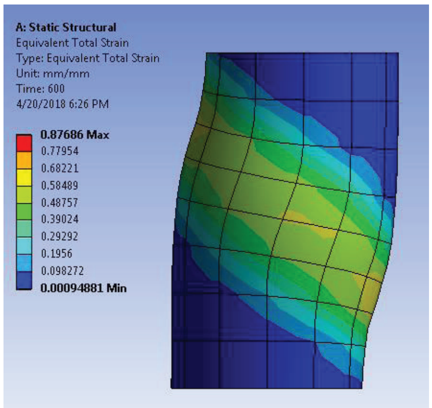


Figure 5 Stress path for drained condition



(a) Deformation



(b) Strain

Figure 6 Shearing stage in sand sample

A comparative study of the maximum shear stress and the corresponding shear strain is shown in Table 2. This table indicates that the strain at which peak shear stress is observed in numerical and analytical solutions is less than that of experimental results. This also points to the fact that this model underestimates the residual value or fails to predict the strain softening behavior.

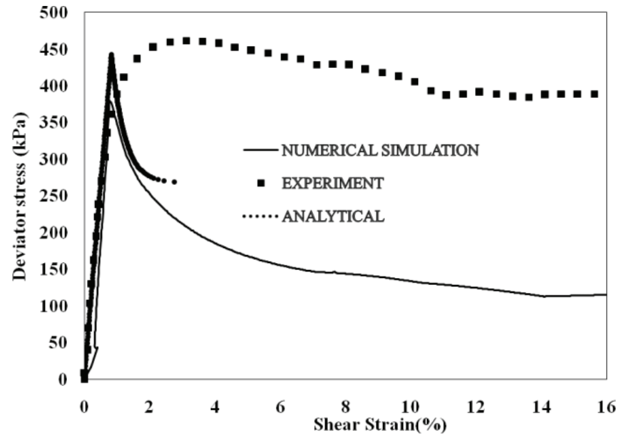


Figure 7 Comparison of shear stress vs. shear strain: Experiment, numerical and analytical methods

Table 2 Comparison of maximum shear stress and corresponding shear strain

Type	Shear stress (MPa)	Shear strain (%)
Experimental results	0.46	2.5
Analytical results	0.44	0.83
Numerical modeling	0.38	0.8

4. DRUCKER PRAGER MODEL

Drucker Prager criterion is a generalization of Mohr-Coulomb criterion for soils. Failure in this model is estimated by assuming that the ultimate shear stress is dependent on octahedral normal stress. However the relation can be used for the estimation of the ultimate strength through a number of material constants. These material constants can be arrived from the various experimental results.

4.1 Collection of experimental data

The various material parameters required for the modeling of the mechanical behavior using Drucker Prager model is collected from Abe et. al (2012). The idea of the paper is to understand the failure patterns and condition of a slope after failure. To evaluate the properties of the soil constituting the slope, drained triaxial test is carried out on the soil sample subjected to a confining pressure of 50kPa. The material properties for modeling the soil sample as collected from the experimental test results are given in Table 3. Figure 8 shows the variation of shear stress with axial strain for the experiment (Abe et. al, 2012).

4.2 Numerical modeling adopting Drucker Prager Model

After the collection of the material data, the sample is modeled similar to that described in the previous section. The cylindrical sample modeled is subjected to an all round confining pressure of 50kPa. This sample is then subjected to shearing.

Table 3 Material properties of Sand

Peak State	Internal friction angle (Φ in degree)	39.5
	Cohesion (kPa)	2.9
Residual state	Internal friction angle (Φ in degree)	36.3
	Cohesion (kPa)	1.7
Soil Properties	Density of the soil (kg/m^3)	1767
	Poisson's ratio	0.214

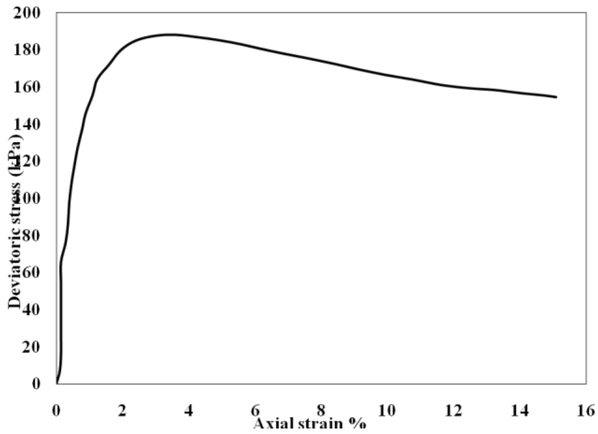
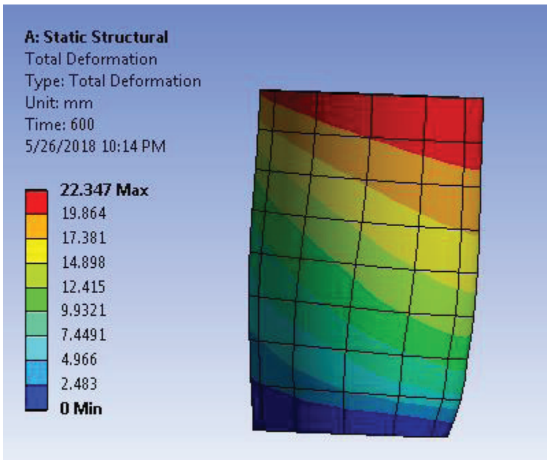


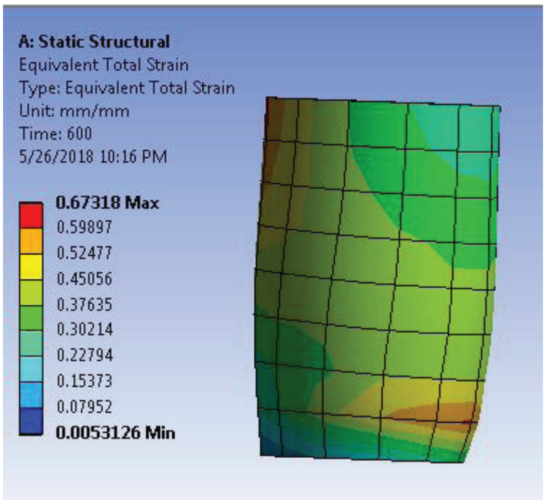
Figure 8 Shear stress vs. axial strain: Experimental results (Arvelo, 2005)

4.3 Results and Discussion of Drucker Prager model

The deformation behavior of the sand sample when subjected to shear loading is shown in Figure 9(a) and (b). The formation of the shear bands in this case also is obvious from these figures. A comparison of the variation of shear stress with axial strain for the numerical and experimental studies is shown in Figure 10. The initial stiffness values predicted by Drucker Prager model are similar to the experimental results. However, even at small strains, the prediction of the stresses varies from that the experiment. Also, the maximum stress predicted by the numerical model is higher than the experimental results and at a much smaller strain. The strain softening behavior indicates that the predicted values are much lesser than the experimental values observed. This is similar to the observations made when Cam Clay model is adopted. However the percentage differences in the predicted residual values are lesser in Drucker Prager model. A comparative behavior of the two models with the corresponding experimental data is given in Table 5 and Table 6.



(a) Deformation



(b) Strain

Figure 9 Shearing stage in sand sample (Drucker Prager model)

6. CONCLUSION

The behavior of granular soil under static drained condition is analyzed numerically and analytically. Numerical results and analytical results are compared with experimental values. Results show that Cam Clay Model does not predict the shear behavior of sand sample adequately. It fails to predict the softening behavior of the sample. It is also observed that the predicted maximum shear stress and the corresponding shear strain is lower than the experimental values. This model is suitable for normally consolidated and lightly over consolidated soil (O-C ratio<=2). But the selected sample is over consolidated sand. So it fails to predict strain softening part. Strain hardening or small strain behavior is captured well in Cam Clay model. But at higher strains it fails to do so. At lower strains, the difference of stress in experiment and numerical results is 8%, whereas at higher strains the percentage difference is high. A comparison of the numerical and analytical studies using Cam clay model shows a difference of only 0.03% in the strains at maximum shear stress. In the case of Drucker Prager Model, the strain softening behavior is not captured properly. It also overestimates the strength at lower strain by 49.46%. However, this model captures softening behavior better than Cam Clay Model. The percentage difference in the observed shear stress at around 5% strain is 29.9% for Drucker Prager model whereas it is around 63% for the Cam clay model.

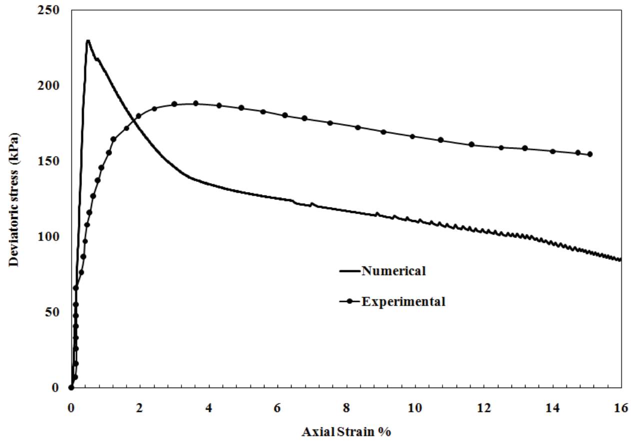


Figure 10 Comparison of experimental and numerical results for Drucker Prager model

Table 5 Comparison of behavior of sand obtained using Cam Clay Model

Behavior	Experiment (Shear Stress kPa)	Numerical (Shear Stress, kPa)	% Difference
Hardening(0.6% strain)	302.54	277.51	8.26 %
Softening(5% strain)	447.7	165	63.14%

Table 6 Comparison of behavior of sand obtained using Drucker Prager Model

Behavior	Experiment (Shear Stress kPa)	Numerical (Shear Stress kPa)	% Difference
Hardening(0.3% strain)	76	150.4	49.46 %
Softening(5% strain)	185	129	43.41 %

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