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# Numerical Simulations on Triaxial Strength of Silty Sand in Drained Conditions

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## ABSTRACT

*Silty sand deposits exhibit low bearing capacity at different density levels and depths. It may be due to low frictional values and non-plastic behaviour in nature. This study focuses on response of silty sand under drained conditions of triaxial testing using hypoplastic model. The influence of soil state parameters i.e. void ratio/relative density, and consolidation pressure level on drained response of silty sands is examined from the model simulations. The model results are displayed graphically in terms of stress-strain curves, stress paths and volume change-strain plots. The results reveal that the response of soil is dependent on both the combination of density and consolidation pressure levels.*

**Keywords:** *Silty sand, Hypo plastic model, drained response, volume change, consolidation, density, stress ratio*

## I. INTRODUCTION

In general, well graded sand and gravel deposits provide good stability and adequate drainage to support the overlying structures. However, such soil types are not available. At present, there is large demand to construct civil infrastructures on silty or clayey sands due to spread of such soils in abundance. Studies on such silty sands are necessary to analyse the behavior and stabilize the soils to improve its bearing capacity. The soils existing nearby any water bodies are mainly consisting of fine grained sands to silty sands. Most natural and artificial (e.g., hydraulic fills) sand deposits contain some amount of silt may possess less shear strength and susceptible to liquefaction during earthquake events. A few numerical studies were carried out to examine the factors affecting the mechanical behavior of silty soils. The constitutive model plays a major role in predicting the mechanical response of granular material and several models are available to analyses the geotechnical problems. The constitutive model formulated based on the theory of hypoplasticity has been proven to more advance over the other models [1, 2, and 3]. The present paper was attempted to run the hypoplastic model simulations to analyses the drained response of silty sands under static triaxial loading. The influence of soil state parameters i.e. void ratio/relative density, and consolidation pressure level on the drained response of silty sands under static triaxial loading is investigated in terms of stress-strain characteristics, stress paths and volume change response.

## II. HYPOPLASTIC MODEL

Today, several constitutive models are available to simulate the real behavior of soils irrespective of type of soil, loading and drainage conditions. However, new advanced models are emerging to simulate even more complex soil behaviour. In recent past, hypoplastic constitutive model is developed based on simple mathematical formulations of critical state concept. It was gaining more popularity after successful validation with different geotechnical applications. It is an incrementally nonlinear constitutive model, which requires only a single tensorial equation contains both the elastic and plastic regions. This model simulates equally good for both the loading and unloading. In contrast to other elasto-plastic models, the formulations of Hypoplastic model are very simple and the model parameters can be easily determined from standard laboratory experiments. The mathematical formulations of Hypoplastic model have been well described in the past published literature [1, 2, and 3].

The first version of model contains only a single state variable, i.e. current Cauchy stress $T_s$. But that model was quite limited in its applicability. It was only recommended for cohesionless granular materials consisting of not too soft grains. The cyclic loading and creep effects were not included in this model. Therefore later versions are improved in such a way that a general formulation is then developed for describing the irreversible and rate-independent response of materials with the stress tensor as a single state variable [1]. The void ratio was added as an additional state variable in improved model. The hypoplastic constitutive equation in general form is given by:

$$T_s^o = F\left(T_s, e, D\right) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Herein $T_s^o$ represents the objective stress rate tensor as a function of the current void ratio $e$, the Cauchy granulates stress tensor $T_s$ and the stretching tensor of the granular skeleton $D$. Bauer (1996) proposed to separate the above equation into two parts:

$$T_s^o = A\left(T_s, e, D\right) + B(T_s, e)\|D\| \qquad \ldots\ldots\ldots\ldots\ldots \ (2)$$

The first part A ($T_s$, e, D) is linear in D to represent the particular case where the soil behaviour is in elastic nature, while the second part B (e,Ts) $\|D\|$ is nonlinear in D. $\|D\|$ stands for the Euclidian norm $\sqrt{\mathrm{tr}D^2}$. The operators A and B are factorised in such a way that the pressure-dependency of the material response can be easily modeled by introducing two dimensionless factors i.e. relevant density and pycnotropy factors [1, 3]. The factors are arrived based on pressure dependent void ratios. The mathematical formulations are well developed to determine the constitutive material parameters those requires basic experimental tests data.

The past studies carried out by Gudehus (1996) and Bauer (1996) have been proved the applicability of hypoplastic model equation for a wide range of stresses in both the loose and dense sands by using a single set of material parameters. Further, Wolffersdorff (1996) improved a model after considering the effect of cyclic loads and deformations by incorporating a predefined limit stress condition into the model. The software code has been developed in FORTRAN language by using the formulations of hypoplastic constitutive model relations for different loading/drainage conditions and implemented to attain the numerical simulations of the present study.

## III. CONSTITUTIVE MODEL PARAMETERS

For the present study, silty sand is artificially prepared after mixing naturally available fine sand with non plastic stone dust powder in dry condition, 15% by weight. Initially basic routine laboratory soil properties tests including soil gradation, specific gravity, boundary void ratios, angle of repose, consolidation and direct shear tests were conducted as per IS codes to determine the required model parameters. The index and basic properties of silty sand are given in Table 1. The gradation curve for the processed silty sand is shown in Fig. 1.

**Table1.** Index and basic properties of Silty Sand

| | |
|---|---|
| Specific Gravity, $G$ | 2.64 |
| Effective size, $D_{10}$ | 0.07 *mm* |
| $D_{50}$ | 0.20 *mm* |
| $C_u$ | 3.14 |
| $C_c$ | 1.99 |
| $e_{max}$ | 0.94 |
| $e_{min}$ | 0.555 |

**Table 2** Hypoplastic parameters for silty sand

| | |
|---|---|
| $\phi_c$ | $35^0$ |
| $e_{do}$ | 0.55 |
| $e_{co}$ | 0.94 |
| $e_{io}$ | 1.13 |
| $h_s$ | 75 MPa |
| $n$ | 0.55 |
| $\alpha$ | 0.085 |
| $\beta$ | 0.621 |

The model requires only a limited number of eight material parameters include critical state friction angle $\varphi_c$, granulate hardness $h_s$, limit void ratios $e_{i0}$, $e_{d0}$ and $e_{c0}$, and exponents n, β and α. The calibration procedure and mathematical expressions to determine the model parameters for granular soils is described in [4]. For the present study, the procedure given by [4] is followed to calibrate the model parameters and the obtained hypoplastic parameters for processed silty sand soil are listed in Table 2.

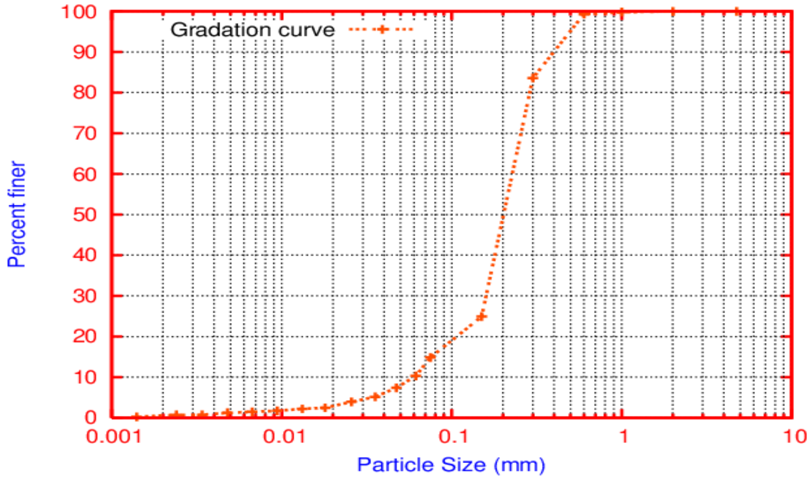


**Fig.1** Gradation curve for processed silty sand

## IV. VALIDATION OF THE MODEL

The Hypoplastic model simulations were performed on oedometric compression of both the loose and dense silty sands and compared with experimental data of oedometric compression as shown in Figs. 2-3. The resulting plots of e-log σ curves shown in Figs. 2-3 indicating that the numerical model data is well coinciding with experimental data in both the loading and unloading. The model is validated for both the loading and extension loading cases. The model is performs well in both the cyclic as well as statically repeated loading and unloading stages. After validating the model, further the numerical simulations were performed on triaxial shear strength response of silty sands subjected to loading in drained conditions.

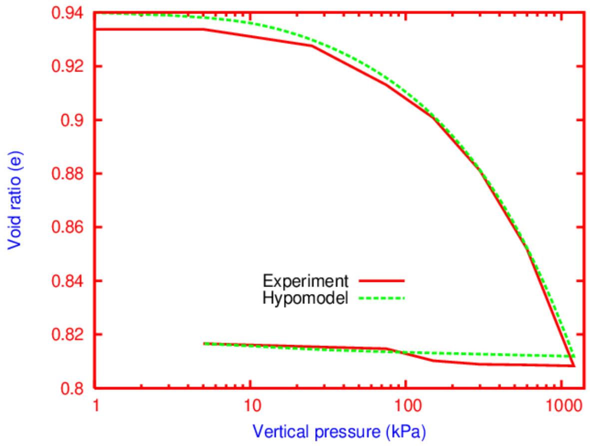


**Fig. 2** Validation of e-log σ curves for loose silt sand

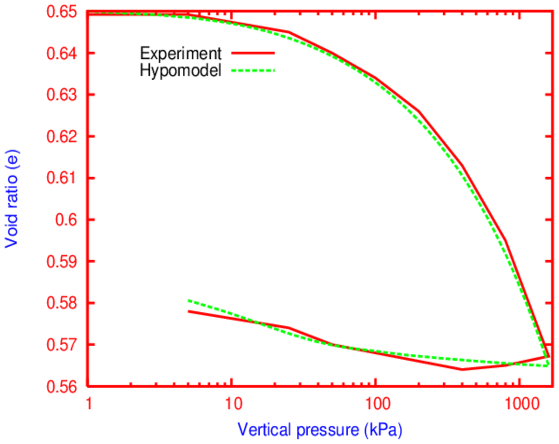


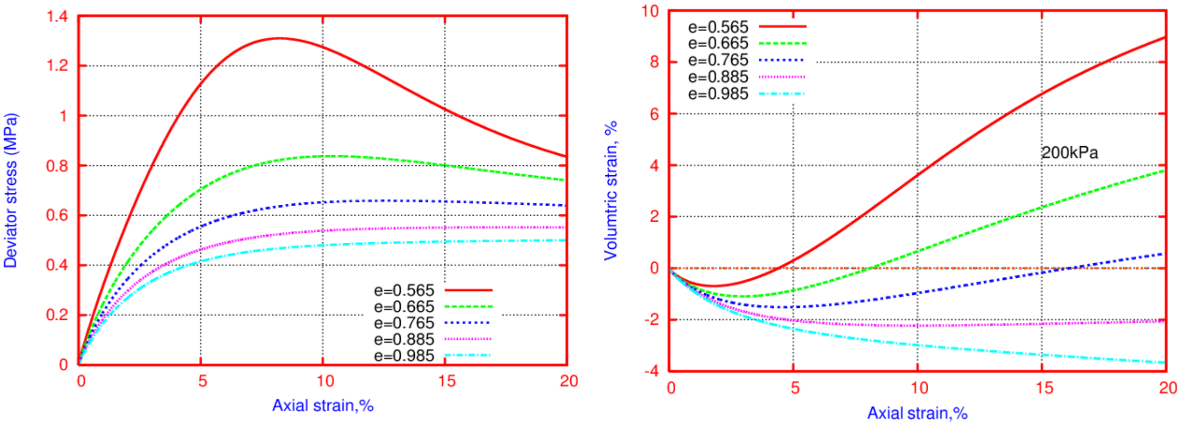
**Fig. 3** Validation of e-log σ curves for dense silt sand

## V. RESULTS AND DISCUSSION

The influence of soil state parameters i.e. void ratio/relative density, and consolidation pressure level on drained response of silty sands under static triaxial loading is examined from the hypoplastic model simulations. The model results are displayed graphically in terms of stress-strain curves, stress paths and volume change-strain plots.

### 5.1 Effect of density

Static triaxial test simulations were performed on silty sand subjected to a particular consolidation pressure of 200 kPa. In order to study the effect of void ratio on drained response of silty sands, the void ratios are varied in the range of 0.565 to 0.985. The ranges of void ratios were chosen in such a way that the soil state has to change from very loose to dense condition. The effect of void ratio on drained response of consolidated silty sand is shown in Figs. 4 (a)-(b). It can be observed from the figures that the dense silty sand experiences the dilation behaviour by indicating the sharp peak deviator stress and increase in volume of soil i.e. undergo a sudden expansion. However loose silty sand experience the contraction behaviour that shows the continuous decrease in volume i.e. compression. The tendency of dilation is increasing with decrease in void ratio of silty sand. It is also interesting to note that the silty sand exhibit initial contraction up to certain axial strain limit irrespective of dense or loose condition. The reason may be due to the re-adjustment of solid particles. The trends are very similar to experimental trends observed from the past published papers.



**(a)** **(b)**

**Fig. 4 (a)** Stress- strain characteristics, and **(b)** Volume change response of silty sand at different void ratios

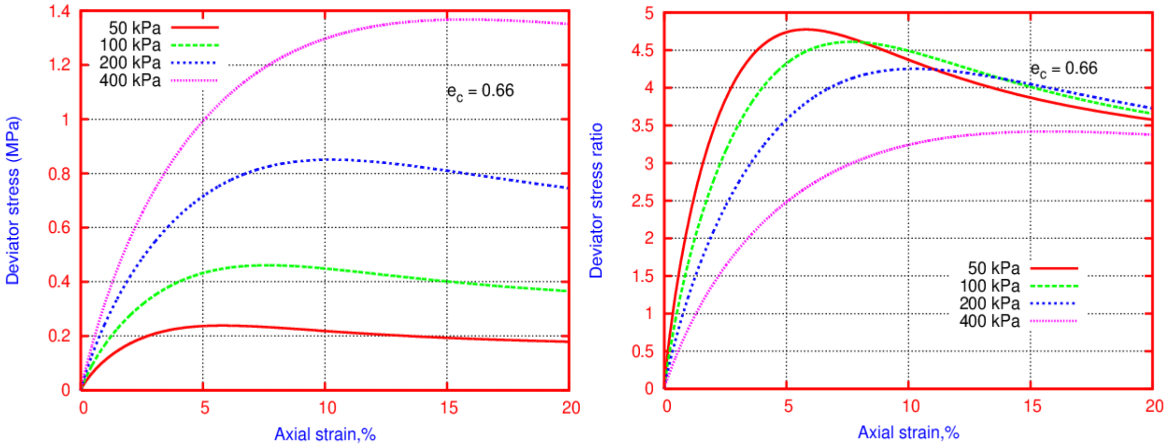
Figure 4(a) shows the stress-strain characteristics of silty sand consolidated at different void ratios. It can be seen that the deviator stresses are increasing with decrease in void ratios at the same axial strain level. However, a sharp peak stress was observed only for dense silty sand at the low void ratio of 0.565. For loose silty sands ($e_c$=0.985~0.885), the constant ultimate stress is reached at the critical state strain levels. Herein, the critical state indicates where the deviator stress is becomes constant. For the medium dense silty sands, ($e_c$=0.765~0.665), a slight peak deviator stress is observed at low strain levels and further decreased to residual values. Fig. 4(b) presents the volume change response of silty sand consolidated at different void ratios. It demonstrate that the loose silty sands ($e_c$=0.985~0.885) exhibiting fully contraction behavior i.e. volume reduction. However, the dilative behavior i.e. volume expansion is increasing with decrease in the void ratios from 0.765 to 0.565 representing the state of soil changes from medium dense to dense state. In summary the result conclude that the drained response i.e. either contraction or dilation is dependent on density/void ratio of the soils consolidated at a particular pressure.

### 5.2 Effect of consolidation pressure

In order to study the effect of consolidation pressure on triaxial drained response of medium dense silty sands, the numerical simulations were performed on silty sands consolidated at different pressures in the range of 50 kPa to 400 kPa. The pressures are chosen in such a way that the soils are to be characterized into low, medium and highly consolidated soils. The effect of consolidation pressure on drained response of medium dense silty sands is shown in Figs. 5(a)-(c). The response curves are illustrating that the dilation tendency is increases with decrease in consolidation pressures. The silty sands consolidated at low consolidation pressures behave as dilative and vice versa.

Figure 5(a) shows the stress-strain characteristics of silty sand consolidated at different pressures. It can be inferred from figure that the deviator stresses are increases with increase in applied consolidation pressures. It is also observed that the slight peak stress occur at low strains of about 5-10% and further the stresses are reduces to constant values at high strain values in the case of silty sand consolidated at pressures in the range of 50 to 200 kPa. However, ultimate residual stress is arrived at high strain values in the case of silty sand consolidated at high pressure of 400 kPa and behave contractive even the shear strength values are more. The drained response of silty sands can be easily visualized after normalizing the deviator stresses in dimensionless ratios. Therefore, the normalized stress-strain characteristics of silty sand consolidated at different pressures are depicted in Fig. 5(b). Herein, the deviator stress values are normalized with the corresponding applied consolidation pressures to obtain static stress ratios. It can be seen from Fig. 5 (b) that the normalized stress ratios are decreasing with increase in consolidation pressures. Peak deviator stress ratios are observed for the silty sands subjected to low consolidation pressures of 50 kPa to 200 kPa. For highly consolidated silty sands ($\sigma_c$=400 kPa), the constant ultimate stress ratio is reached at the high strain levels.

Fig. 5(c) presents the volume change response of silty sand consolidated at different pressures. It demonstrate that the highly consolidated silty sands ($\sigma_c$=400 kPa) exhibiting fully contraction behavior i.e. volume reduction. However, the dilative behavior i.e. volume expansion is increasing with decrease in applied pressures from 200 kPa to 50 kPa. The result concludes that the low consolidated silty sand behaves as highly dilative behavior and vice versa. The dilation may cause due to the sliding of the particles and contraction takes place due to the crushing of particles under the application of high pressures. The dilated soils are more stable. Similar trends are also observed in the past studies on drained response of silty sands.



**(a)** **(b)**

**Fig. 5 (a)** Stress-strain and **(b)** Stress ratio characteristics of silt sand consolidated at different pressures

Fig. 6 shows the stress path at different pressures propagate towards the modified failure envelope. The modified failure envelope is developed after connecting the points corresponding to maximum mean normal stress and mean shear stress values. The apparent shear strength parameters were obtained from MFE and the actual parameters are derived by using the well-established relations. The cohesion value and friction angle obtained from the plot are 0 and 38° respectively.

## VI. CONCLUSIONS

Based on the drained triaxial test simulations, the following important conclusions are arrived at:

- The silty sand subjected to medium consolidation pressures may behave dilative at higher densities and contractive at low density levels.
- The medium dense soil behaves more dilative at low consolidation pressures and more contractive at high consolidation pressures.
- Normalised stress ratios are decreasing with increase in consolidation pressures at the same axial strain level even though the deviator stresses are increasing with increase in pressures.
- The drained response of soil is dependent on both the combination of density and consolidation pressure levels.

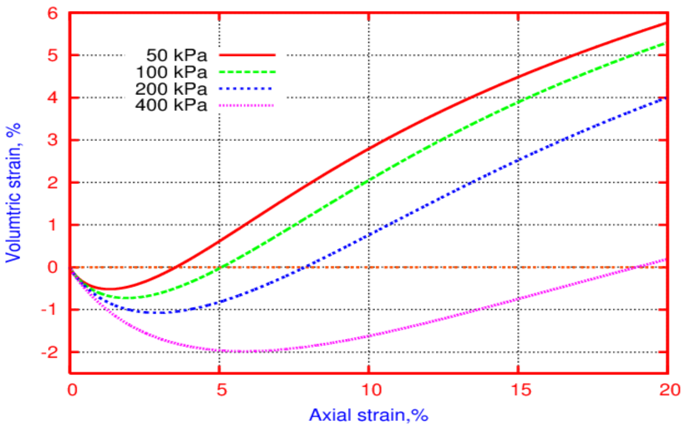


**Fig. 5(c)** Volume change response of silty sand consolidated at different pressures

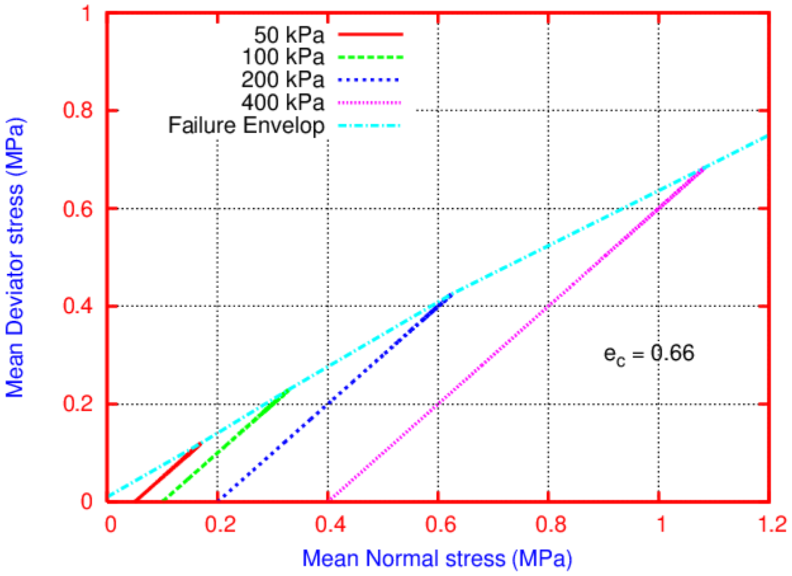


**Fig.6** Stress Path and modified failure envelope for medium dense silty sand

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