Evaluation of DSC Parameters for Solani Sand

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ABSTRACT

In the present work, Disturbed State Concept (DSC) has been used for the characterization of the liquefaction behavior of saturated Solani river sand (near Roorkee) by studying its laboratory behavior. DSC provides a unified constitutive modeling approach for the characterization of the stress-strain behavior of soil under cyclic loading as well as identification of liquefaction in saturated sand samples. For the present study, the saturated Solani sand was tested using cyclic triaxial device. The relative intact (RI) behavior has been characterized by using the $d_0$-version in the hierarchical single-surface (HiSS) plasticity concept whereas the fully adjusted (FA) state has been characterized by using critical state concept. Various elasticity parameters, the parameters of the HiSS $d_0$-model, parameters needed for critical-state representation and that for defining disturbance $D$, have been evaluated from the obtained laboratory test results.

1. INTRODUCTION

Loose saturated sand deposits liquefy when subjected to ground shaking, causing damage to the structures founded on such soil. Liquefaction related damages to the structures in past earthquakes such as Niigata, El Centro, Mexico, and Kobe had led to the appreciation of the liquefaction potential assessment of sites prior to the construction of structures on such sites. Along with the conventional and empirical procedures for the assessment of liquefaction potential such as SPT-N method, those based on equivalent uniform shear stress and leading cycles on laboratory specimens under simulated cyclic loading, such as cyclic simple shear, torsion shear device and cyclic triaxial tests are also used (Kramer, 1996). Among the laboratory methods, cyclic triaxial tests are widely practiced.

Development of numerical tool to predict earthquake response and large deformation of liquefied ground is gaining importance widely. Use of such numerical tools for the analysis purpose require appropriate constitutive modelling of dynamic behaviour of saturated soil in order to simulate liquefaction phenomenon realistically. A new method based on unified constitutive modelling approach, called the Disturbed State Concept (DSC), as proposed by Desai (2001), is a simplified procedure for the assessment of initial liquefaction. The parameters involved in the DSC can be found from relatively simple test conducted on soil specimens using cyclic triaxial device (Desai, 2001).

This paper describes DSC in brief with the main focus given to the identification of liquefaction. This is followed by the brief description of laboratory tests conducted on soil specimen using cyclic triaxial device in order to define the material parameters involved in DSC. For the cyclic triaxial tests, Solani river sand is used.

2. DISTURBED STATE CONCEPT

The Disturbed State Concept (DSC) is a unified modeling approach that allows, in an integrated manner, for elastic, plastic and stiffening or healing, in a single framework. The DSC is based on the basic physical consideration that the observed response of a material can be expressed in terms of the response of its constituents, connected by the coupling or disturbance function ($D$). In simple words, the observed material state is considered to represent disturbance or deviation with respect to the behavior of the material for appropriately defined reference states i.e. Relatively Intact (RI) state and Fully Adjusted (FA) state.

As shown in Figure 1, an initially relative intact (RI) material modifies continuously, through a process of natural self-adjustment, and a part of it approaches the fully adjusted (FA) state at randomly disturbed locations in the material. The deforming material is considered a mixture of the two interacting material parts in the RI and FA states. The behavior of the RI and FA materials, as well as the disturbance function $D$, needs to be defined from laboratory tests (Desai, 2001).
Relative Intact State

The RI behavior can be characterized using an elasticity or plasticity model with an associative response or any other suitable continuum model. The RI state in the present research work is characterized using an elasto-plastic model that includes plastic hardening behavior. Here, the basic DT model in the HiSS family is used to represent the behavior of the elasto-plastic material in the RI state. When the elasto-plastic theory is used, the incremental stress-strain equation is expressed as,

\[ \sigma^{ijkl} = C^{ijkl}_{ep(i)} \varepsilon^{ijkl} \]  

where \( \sigma^{ijkl} \) is the incremental stress tensor, \( \varepsilon^{ijkl} \) is the incremental strain tensor and \( C^{ijkl}_{ep(i)} \) is the elasto-plastic constitutive tensor, which will be a function of Young’s modulus \( E \) and Poisson’s ratio \( \nu \).

In HiSS model, the single yield surface function \( F \) for the case when parameter \( \beta = 0 \) (Fig. 2) is given by (Desai, 2001).

\[ F = (J_{2d}/P_a^2) + \alpha(J/P_a) - \gamma(J/P_a)^2 = 0 \]  

where \( J_1 \) is the first invariant of the stress tensor that includes plastic hardening behavior, \( J_{2d} \) is the second invariant of the deviatoric stress tensor, \( P_a \) is atmospheric pressure with the stress units, \( \gamma \) and \( n \) are material parameters that influence the shape of \( F \) in \( J_1 - J_{2d} \) space, \( \gamma \) being related to ultimate yield behavior, \( n \) is phase change parameter and \( \alpha \) is the hardening function.

The hardening function \( \alpha \) is expressed as

\[ \alpha = \frac{h_1}{\xi h_2} \]  

where \( h_1 \) and \( h_2 \) are the hardening parameters and \( \xi \) is the trajectory of plastic strains such that \( \xi = \int \sqrt{\sigma_{ijkl}^p \sigma_{ijkl}^p} \) and \( \sigma_{ijkl}^p \) is the increment of plastic strain tensor.

Fully Adjusted State

In this study, the FA state is modeled using the critical state concept. In the critical state, the material with a given initial mean pressure continues to deform under the constant shear stress reached up to that state without further change in its volume. Such critical state often lies on a straight line called critical state line (CSL) with the slope \( \bar{m} \) (Schofield & Wroth, 1968):

\[ \sqrt{J_{2d}^c} = \bar{m} J_1^c \]  

The super-script \( c \) is for the critical state.

The void ratio at the critical state \( e^c \) is given by

\[ J_1^c = 3P_a \times e^c_{\lambda} \]  

where \( e^c \) is the void ratio at critical state corresponding to \( J_1^c \) is the void ratio at critical state. \( e^c \) is equal to \( D_e \) (\( D_a = 1 \)).

The disturbance function, \( D \), is given by (Armaleh & Desai, 1990),

\[ D = D_a \left[ 1 - e^{-\frac{J_1^c}{\lambda}} \right] \]  

where \( A, Z, \) and \( D_a \) are material parameters and \( \xi \) is the trajectory of plastic deviatoric strain such that

\[ \xi_D = \int \sqrt{\sigma_{ijkl}^p \sigma_{ijkl}^p} \cdot dE_{ij}^p \]  

where \( dE_{ij}^p \) is the tensor of incremental deviatoric plastic strains. Fig. 3 shows a typical shape of the disturbance function curve in terms of disturbances and deviatoric plastic strain trajectories.

Table 1 summarizes the DSC parameters to be determined from the laboratory test. As evident from Table 1, the total number of parameters required to be determined...
are 13 out of which 8 parameters, consisting of 2 elastic parameters and 6 plastic parameters, are required to define RI state and 3 parameters are required to define FA state.

**Table 1: Summary of DSC Parameters**

<table>
<thead>
<tr>
<th>Material State</th>
<th>Group</th>
<th>DSC Para.</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative Intact (RI)</td>
<td>Elastic</td>
<td>E</td>
<td>Young’s modulus</td>
</tr>
<tr>
<td>Plastic</td>
<td>v</td>
<td>Poisson’s ratio</td>
<td></td>
</tr>
<tr>
<td></td>
<td>γ</td>
<td>Ultimate parameter</td>
<td></td>
</tr>
<tr>
<td></td>
<td>β</td>
<td>Ultimate parameter</td>
<td></td>
</tr>
<tr>
<td></td>
<td>n</td>
<td>Phase change parameter</td>
<td></td>
</tr>
<tr>
<td></td>
<td>m</td>
<td>Plastic parameter</td>
<td></td>
</tr>
<tr>
<td></td>
<td>h₁</td>
<td>Hardening</td>
<td></td>
</tr>
<tr>
<td></td>
<td>h₂</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fully Adjusted (FA)</td>
<td>Ultimate State</td>
<td>$m\sqrt{\frac{J_2^{ζ}D}{\lambda}} = mJ_1^c$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\varepsilon_n^1$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$J_1^c = 3P^*\varepsilon_n^1 \sqrt{\frac{\lambda^{c\varepsilon_n^1}}{\lambda}}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Observed Disturbance Function</td>
<td>Z</td>
<td>D = $D_o\left[1 - \varepsilon_n^1 \left(\frac{A}{\lambda^{c\varepsilon_n^1}}\right)^{1/n}\right]^{1/2}$</td>
<td></td>
</tr>
</tbody>
</table>

**Table 2: Index Properties of Solani River Sand**

<table>
<thead>
<tr>
<th>Particulars</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Gravity, G</td>
<td>2.64</td>
</tr>
<tr>
<td>Coeff. of uniformity, C_u</td>
<td>1.769</td>
</tr>
<tr>
<td>Coeff. of curvature, C_c</td>
<td>1.207</td>
</tr>
<tr>
<td>Mean grain size, D_50 (mm)</td>
<td>0.215</td>
</tr>
<tr>
<td>Max. void ratio, $e_{max}$</td>
<td>0.927</td>
</tr>
<tr>
<td>Min. void ratio, $e_{min}$</td>
<td>0.533</td>
</tr>
</tbody>
</table>

**Fig. 3: Disturbance Function Curve Between D and $\xi_D$ (Desai et al. 1998)**

3. LABORATORY TESTS AND EVALUATION OF DSC PARAMETERS

In order to determine the DSC parameters, the saturated Solani river sand was tested using a Cyclic Triaxial System under stress-controlled conditions. Some index properties of the soil are given in Table 2 (Kale S., 2010). The soil samples were prepared by using Water Sedimentation Method (Ishihara, 1993) which can provide the homogenous samples with uniform distribution of void. In this study, tests were conducted with a relative density, $D_r = 60\%$. Figure 4 shows the plot of applied deviatoric stress $\delta'$. The lateral stresses $\sigma_2$ and $\sigma_3$ are kept constant at their initial effective confining stress, $\sigma_0''$, while $\sigma_1$ is increased and decreased by first loading the sample to the required deviatoric stress value and then unloading to zero value.

**Fig. 4: Plot of Deviatoric Stress vs. Time**

**Material Parameters for RI State**

For an isotropic linear elastic material, description of the stress-strain behavior requires two elastic constants, Young’s modulus $E$ and Poisson’s ratio $\nu$. Young’s modulus $E$ can be evaluated from the unloading slope of stress-strain curve. The values of $E$ are 320 MPa under $\sigma_0' = 100$ kPa and 400 MPa under $\sigma_0' = 160$ kPa. Figures 5a and b show the stress-strain behavior for two different initial effective confining pressures ($\sigma_0'$) of value 100 kPa and 160 kPa respectively. In Fig. 5, the octahedral stress $\sigma_{oct}$ is given by,

$$\sigma_{oct} = \sqrt{\left(\sigma_1 - \sigma_2\right)^2 + \left(\sigma_2 - \sigma_3\right)^2 + \left(\sigma_3 - \sigma_1\right)^2} / 3$$

The average value of $E$ considered is 360 MPa. The Poisson’s ratio ($\nu$) value is assumed to be 0.35. In this study, plastic parameter $m$ is adopted as -0.5 (Desai, 2001). The phase change parameter, $n$, is related to the point at which the geological material starts dilating after the initial compression. The expression to calculate $n$ is given by

$$J_{ln} = \left(\frac{2}{n}\right)^{1/n}$$

where $J_{ln}$ is obtained from effective stress path for undrained test on saturated sands and $J_{ln}$ is obtained from the initial effective confining pressure, $J_{lm} = 3 \times \sigma_0'$. The ratio of $J_{ln} / J_{lm}$ for the tests can be calculated and corresponding $n$ can be obtained from the plot shown in Figure 6.

Based on this procedure, the value of $n$ for Solani river sand is 100.5 which is the average value from two different test data (Table 3). However, for medium dense sands ($D_r = 60\%$), the value of $n$ is around 3 (Desai, 2001). The excessive high value of $n$ obtained from the test results may be attributed to the fact that there was very low rise in excess pore-pressure owing to the small B-value achieved during the saturation stage. Therefore, the $n$ value adopted for the study is 3.

The ultimate parameters, $\gamma$, represent the asymptotic (failure) stress and $\beta$ controls the shape of yield surface in the octahedral plane. Determination of ultimate...
parameters $\gamma$ and $\beta$, hardening parameters $h_1$ and $h_2$, parameters for fully adjusted material and the disturbance function are the part of on-going research work.

Table 3: Phase Change Parameter ($n$)

<table>
<thead>
<tr>
<th>$\sigma_0$ ($\text{kPa}$)</th>
<th>$J_{1u}$</th>
<th>$J_{1m}$</th>
<th>$J_{1u}/J_{1m}$</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>300 kPa</td>
<td>290 kPa</td>
<td>0.966</td>
<td>120.5</td>
</tr>
<tr>
<td>160</td>
<td>480 kPa</td>
<td>458 kPa</td>
<td>0.954</td>
<td>80.5</td>
</tr>
</tbody>
</table>

4. CONCLUSIONS

From literature, the DSC is a realistic constitutive model for saturated sands. In the present paper, some of the parameters required in DSC are found from the laboratory tests using Cyclic Triaxial. These parameters are mainly required to define the RI state which is modeled using basic $\tilde{\sigma}_0$ HiSS model. However, few more tests are required to be performed for further implementation.

REFERENCES


