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Review

Disturbed state concept as unified constitutive modeling approach

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ABSTRACT

A unified constitutive modeling approach is highly desirable to characterize a wide range of engineering materials subjected simultaneously to the effect of a number of factors such as elastic, plastic and creep deformations, stress path, volume change, microcracking leading to fracture, failure and softening, stiffening, and mechanical and environmental forces. There are hardly available such unified models. The disturbed state concept (DSC) is considered to be a unified approach and is able to provide material characterization for almost all of the above factors. This paper presents a description of the DSC, and statements for determination of parameters based on triaxial, multiaxial and interface tests. Statements of DSC and validation at the specimen level and at the boundary value problem levels are also presented. An extensive list of publications by the author and others is provided at the end. The DSC is considered to be a unique and versatile procedure for modeling behaviors of engineering materials and interfaces.

1. Introduction

Accurate solutions to engineering problems using conventional or advanced methods are dependent significantly on the responses of materials that compose the engineering systems. Hence constitutive modeling of materials such as soils, rocks, concrete, interfaces between structures and soils, and joints in rocks, plays a vital role in reliable solutions to geomechanical problems. A number of constitutive models, from simple to the advanced, have been proposed and available. Most of them account for specific characteristics of the material behavior. However, as stated before, a deforming material may experience simultaneously many characteristics such as elastic, plastic and creep strains, loading (stress) paths, volume change, microcracking leading to failure, strain softening or degradation, liquefaction and healing or strengthening.

Hence, there is a need for unified models that account for such characteristics simultaneously. This review paper presents a unique approach called the disturbed state concept (DSC) that includes a number of available constitutive models for solids and interfaces as special cases, and provides a unified model that allows the above factors simultaneously. The DSC includes models for the behavior of the continuum part of material for which the hierarchical single surface (HISS) plasticity model can be often used for the continuum; hence, the model covered here is called DSC/HISS. Descriptions of various constitutive models and the DSC/HISS are presented in various publications, e.g. Desai (2001).

Computer methods (e.g. Desai and Abel, 1972; Desai, 1979; Desai and Zaman, 2014) with appropriate constitutive models for behavior of geologic materials and interfaces have opened a new era for accurate and economic analysis and design for problems in geomechanics and geotechnical engineering. Such procedures account for many significant factors such as initial or in situ stress or strain; elastic, irreversible (plastic) and creep deformations; volume change under shear and its initiation during loading; isotropic and anisotropic hardening; stress (load) path dependence; inherent and induced discontinuities; microstructural modifications leading to fracture and instabilities like failure and liquefaction; degradation or softening; static, repetitive and cyclic (dynamic) loading; forces like loads, temperature, moisture (fluid) and chemical effects; anisotropy, nonhomogeneities, and strengthening or healing.

The reviews of available models based on elasticity, plasticity, elastoviscoplasticity, damage, fracture, and micromechanics are presented in Desai (2001, 2015a,b); they present details of DSC/HISS for a number of disciplines in engineering. A brief description of the DSC model and applications is given below together with relevant publications.

2. The disturbed state concept (DSC)

The DSC is a general and simple approach that can accommodate most of the forgoing factors including discontinuities that influence the material behavior, and provide a hierarchical

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framework that can include many of the available models as special cases. One of the attributes of the DSC is that its mathematical framework for solids can be specialized for interfaces and joints, thereby providing consistency in using the same model for both solids and interfaces (Desai, 2001).

In the DSC, a deforming material element is considered to be composed of two or more components. Usually, for a dry solid, two components are assumed, i.e. a continuum part called the relative intact (RI) which is defined by using a theory from continuum mechanics, and the disturbed part, called the fully adjusted (FA), which is defined based on the approximation of the ultimate asymptotic response of the material (Fig. 1).

The origin of the DSC constitutive modeling can be traced to the papers by Desai (1974, 1976) on the subject of behavior of overconsolidated soils and free surface flow in porous materials, respectively. The DSC is based on rather a simple idea that the behavior of a deforming material can be expressed in terms of the behaviors of its components. Thus, the behavior of a dry material can be defined in terms of the continuum (called relative intact – RI, *i*) and microstructurally organized, e.g. micro cracked part which approaches, in the limit, to the fully adjusted (FA, *c*) state; the latter can be essentially considered as collection of particles in failure. The behavior of the FA part is unattainable (or unmanifested) in practice because it cannot be measured; therefore, a state, somewhere near the residual or ultimate, can be chosen as approximate FA state (Fig. 1). The space between the RI and FA denoted by (*i*) and (*c*), respectively, can be called the domain of deformation, whose observed or average behavior (can be called manifested) occurs between the RI and FA states (Figs. 1 and 2). The deviation of the observed state from the RI (or FA) states is called *disturbance*, and is denoted by *D*. It represents the difference between the RI and observed behavior or difference between the observed and FA behavior, which can be considered as a parameter.

The observed material behavior is defined in terms of the behavior of RI (continuum) and that of the fully adjusted parts. The disturbance, *D*, acts as the coupling mechanism. The DSC thus provides for the coupling between two parts of the material behavior, rather than on the behavior of particle(s) at the micro level. Thus, the emphasis is on the modeling of the *collective behavior of interacting mechanism in clusters of* RI and FA states, rather than on the particle level processes, thereby yielding a *holistic* model. These comments are similar to those in the self-organized criticality concept (Bak and Tang, 1989), which is used to simulate catastrophic events such as avalanches and earthquakes. In this context, the DSC assumes that as the loading (deformation) progresses, the material in the continuum state

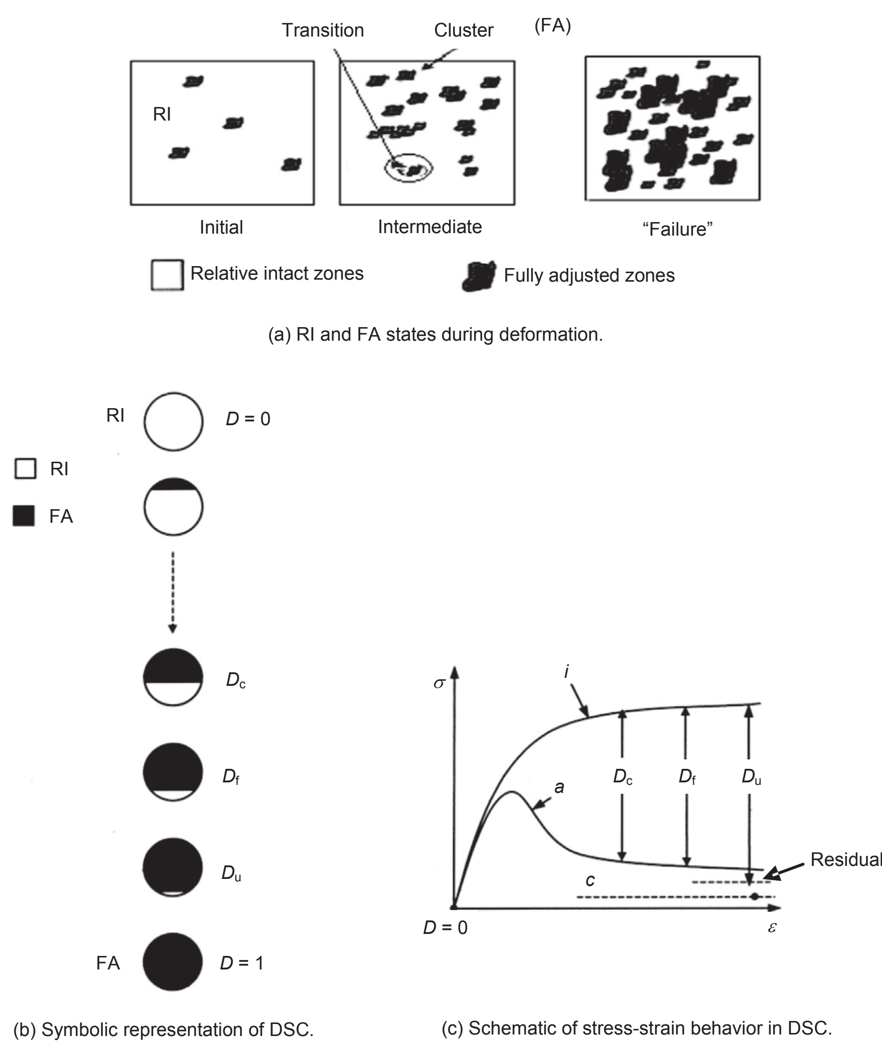


Fig. 1. Schematics of DSC. D_c, D_f and D_u denote initiation of fracture, failure and ultimate disturbance, respectively.

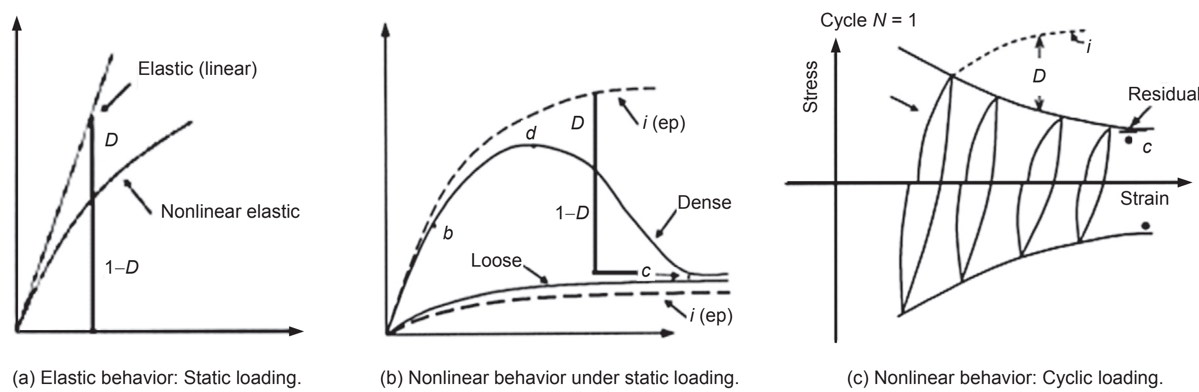


Fig. 2. Schematics of RI (i), FA (c) behavior, and disturbance (D).

tends continuously into the FA state through transformations in the microstructure of the material. The definition of the DSC is not based on the behavior at the microlevel (say, as in micro-mechanics); rather it is based on the definition of the behavior of the material clusters in the RI and FA states defined from the measured behavior in those states (Fig. 2).

Behaviors of the RI and FA can be defined from laboratory or field tests, and the observed behavior is expressed in terms of the behaviors of the RI and FA parts. Assume that the material is continuous in the beginning and remains so during deformation, such a behavior is called that of the RI state, which contains no disturbance. As stated before, the fully adjusted behavior is related to that of the material in the FA state. Some of the ways to define RI and FA responses are given below. Fig. 2a shows the continuum response as linear elastic, which can be considered as the RI state. However, the observed response can be nonlinear (elastic), due to the factors such as existing cracks and cracking. The FA response can be assumed to have a small finite strength. The disturbance can be defined as the difference between linear elastic and nonlinear elastic responses. Fig. 2b shows a strain softening response. Here the RI response can be assumed to be nonlinear elastoplastic and the FA response based on the critical state concept. Fig. 2c shows cyclic response. Here the RI response can be adopted as the extended response of the first cycle. The FA response can be assumed to be asymptotic as the response becomes steady after a number of cycles.

2.1. Relative intact (RI) state

Schematics of RI observed and FA behaviors in terms of various measured quantities: stress vs. strain, volume or void ratio response, nondestructive behavior (velocity), and effective stress (or pore water pressure), are shown in Fig. 3a–d. Fig. 4 shows schematic for disturbance vs. accumulated plastic strain ξ_D or number of cycles or time. In some cases, the RI behavior can be assumed to be linear elastic defined by the initial slope. However, such an assumption may not be valid if the material behavior is nonlinear and is affected by factors such as coupled volume change behavior, e.g. volume change under shear loading. Hence, very often, conventional or continuous yield or HISS plasticity is adopted as the RI response.

2.2. Fully adjusted (FA) state

As a simple approach, it can be assumed that the material in the FA state has no strength, just like in the classical damage model (Kachanov, 1986). This assumption ignores interaction between RI and FA states, may lead to *local* models, and may cause computational difficulties. The second assumption is to consider that the material in the FA state can carry hydrostatic stress like a *constrained liquid*, in which case the bulk modulus (K) can be used to define the FA state. The FA material can be considered as of *liquid–solid* like in the critical state (Roscoe et al., 1958; Desai, 2001), when after continuous yield, the material approaches a state at which there is no change in volume or density or void ratio under increasing shear stress. The equations for the strength of the material in the critical state (FA) are given below:

$$\sqrt{J_{2D}^{c}} = \overline{m}J_1^{c} \tag{1a}$$

$$e^{c} = e_0^{c} - \lambda \ln\left(J_1^{c}/3p_a\right) \tag{1b}$$

where superscript “c” denotes the critical state, J_{2D} is the second invariant of the deviatoric stress tensor, $\overline{m}$ is the slope of the critical state line (Fig. 5), J_1 is the first invariant of the stress tensor, e is the void ratio, e_0 is the initial void ratio, λ is the slope of the consolidation line (Fig. 5), and p_a is the atmospheric pressure constant. A description of the DSC for FA state of such partially saturated materials is given in Desai (2001).

2.3. Disturbance

As stated before, disturbance defines the coupling between the RI and FA states, and is represented by the deviation (disturbance) of the observed behavior from the RI or FA state. It can be determined based on the stress-strain behavior (Fig. 3a), void ratio vs. strain (Fig. 3b), nondestructive behavior for P- and S-wave velocities (Fig. 3c), fluid (pore) water pressure or effective stress ($\overline{\sigma}$) vs. time or number of cycles (Fig. 3d). Fig. 4 shows the schematic of the disturbance (D) as function of ξ_D or number of cycles (N) or time (t).

The disturbance can be defined in two ways, i.e. (1) from measurements (Fig. 3) as stated before, and (2) by mathematical expression in terms of internal variables such as ξ_D.

2.3.1. Disturbance from measurements

From measurements, for example, we have:

$$D_\sigma = \frac{\sigma^i - \sigma^a}{\sigma^i - \sigma^c} \quad (\text{stress} - \text{strain behavior}) \tag{2a}$$

$$D_v = \frac{V^i - V^a}{V^i - V^c} \quad (\text{nondestructive velocity}) \tag{2b}$$

where σ^a is the measured stress; V^a is the measured nondestructive velocity; and i and c represent RI and FA responses, respectively.

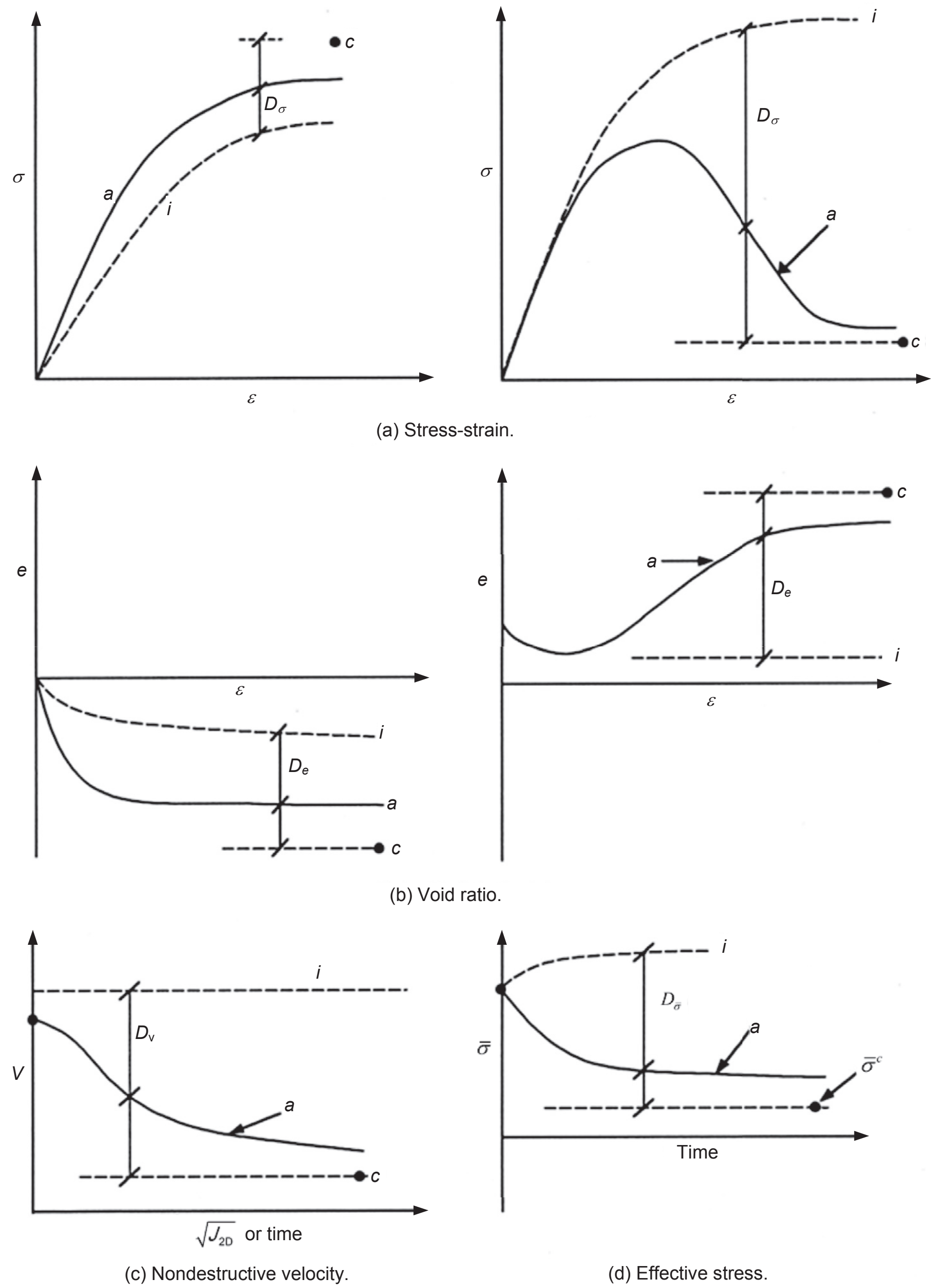


Fig. 3. Various test behaviors to define disturbance.

2.3.2. Mathematical expression for D

Disturbance, D, can be expressed using the (Weibull) function in terms of internal variable such as accumulated (deviatoric) plastic strains (ξ_D) or plastic work:

$$D = D_u\left[1 - \exp\left(-A\xi_D^Z\right)\right] \tag{3}$$

where A, Z and D_u are the parameters. The value of D_u is obtained from the ultimate FA state (Fig. 2). Eqs. (2a) and (2b) are used to find the disturbance (Fig. 3) at various points on the response curves, which are substituted in Eq. (3) to find the parameters. Note that the expression in Eq. (3) is similar to that used in various areas such as biology to simulate birth to death, or growth and decay, and in engineering to define damage in classical damage mechanics, and disturbance in the DSC. However, the concept of disturbance is much different from damage; the former defines deviation of observed response from the RI (or FA) state, in the material treated as a mixture of interacting components, while the latter represents physical damage or cracks.

2.4. DSC equations

Once the RI and FA states and disturbance are defined, the incremental DSC equations based on equilibrium of a material element can be derived as (Desai, 2001):

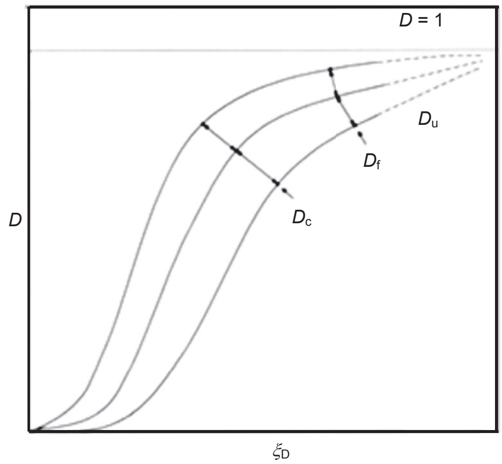


Fig. 4. Disturbance vs. ξ_D (or number of cycles of time).

$$\mathrm{d}\sigma_{ij}^{a} = (1-D)\mathrm{d}\sigma_{ij}^{i} + D\mathrm{d}\sigma_{ij}^{c} + \mathrm{d}D\left(\sigma_{ij}^{c} - \sigma_{ij}^{i}\right) \tag{4a}$$

or

$$\mathrm{d}\sigma_{ij}^{a} = (1-D)C_{ijkl}^{i}\mathrm{d}\varepsilon_{kl}^{i} + DC_{ijkl}^{c}\mathrm{d}\varepsilon_{kl}^{c} + \mathrm{d}D\left(\sigma_{ij}^{c} - \sigma_{ij}^{i}\right) \tag{4b}$$

where σ_{ij} and ε_{kl} denote the stress and strain tensors, respectively; C_{ijkl} is the constitutive tensor; and dD is the increment or rate of Eqs. (4a) and (4b) that represents DSC equation from which conventional continuum (elasticity, plasticity, creep, etc.) models can be derived as special cases by setting $D = 0$, as

$$\mathrm{d}\sigma_{ij}^{a} = C_{ijkl}^{i}\mathrm{d}\varepsilon_{kl}^{i} \tag{5}$$

in which the observed and RI behaviors are the same, and the constitutive tensor can be based on the appropriate continuum model. If $D \neq 0$, Eq. (4) accounts for microstructural modifications in the material leading to fracture and instabilities like failure and liquefaction (in saturated materials, D_c, in Fig. 4).

A major advantage of the DSC approach is that it is hierarchical and unified. Hence, one can extract available models as special cases from Eq. (4). When the RI behavior is modeled by using the HISS plasticity, various conventional and continuous yield plasticity models can also be derived as specialization of the HISS model (Desai, 2001).

2.5. Hierarchical single surface (HISS) plasticity

The need for a unified and general plasticity model that can account for the factors mentioned before was the driving force for the development of the HISS plasticity model (Desai, 1980, 2001; Desai et al., 1986a); it is based on the continuum assumption, hence, it cannot account for discontinuities.

The yield surface, F, in HISS associative plasticity is expressed as (Fig. 6a):

$$F = \bar{J}_{2D} - \left(-\alpha\bar{J}_1^{n} + \gamma\bar{J}_1^{2}\right)(1-\beta S_r)^{-0.5} = 0 \tag{6}$$

where $\bar{J}_{2D} = J_{2D}/p_a^2$ is the non-dimensional second invariant of the deviatoric stress tensor; $\bar{J}_1 = (J_1 + 3R)/p_a$ is the non-dimensional first invariant of the total stress tensor; R is the term related to

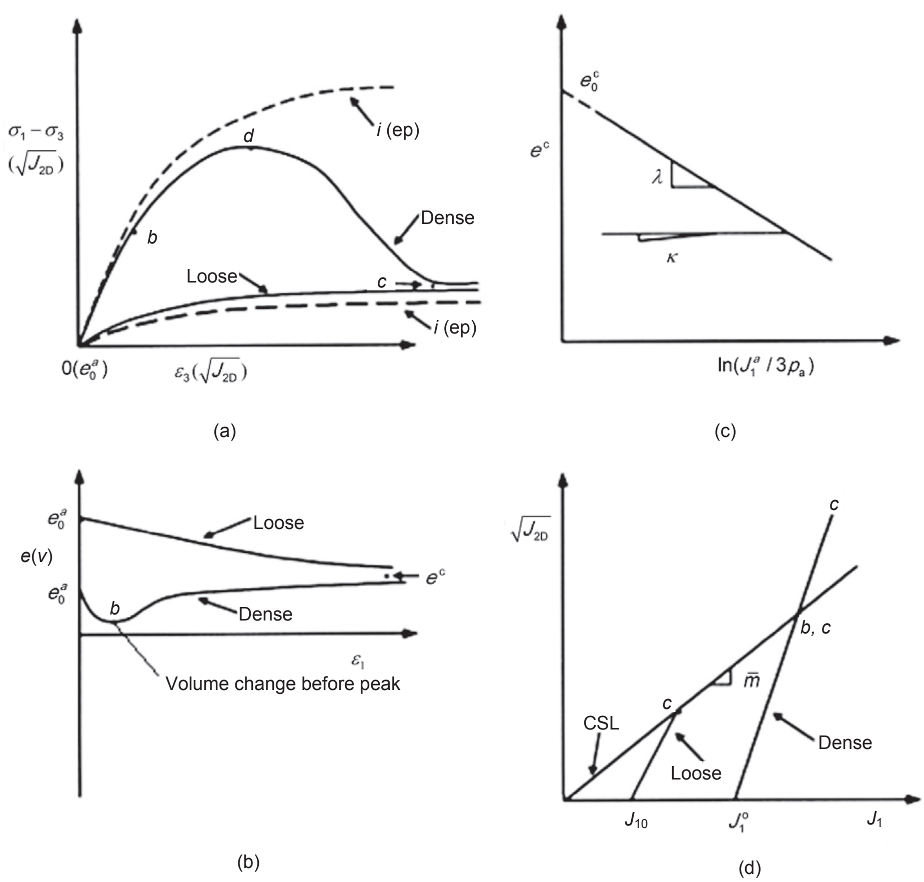
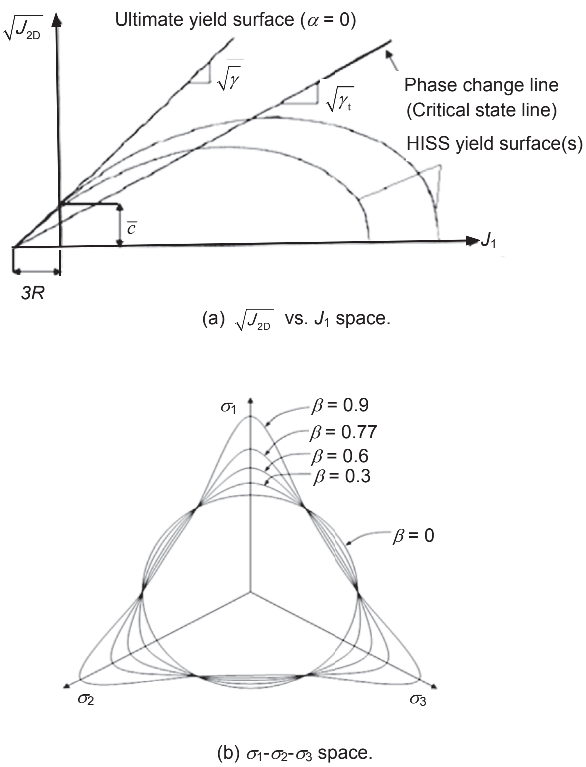


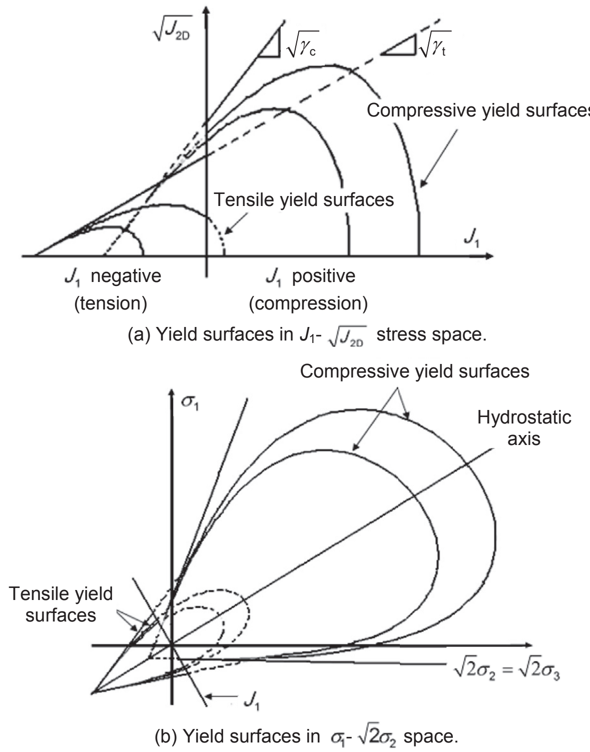
Fig. 5. Stress–strain behavior of loose and dense materials, and critical state.



(a) $\sqrt{J_{2D}}$ vs. J_1 space.

(b) σ_1-σ_2-σ_3 space.

Fig. 6. HISS yield surfaces in two stress spaces.



(a) Yield surfaces in J_1- $\sqrt{J_{2D}}$ stress space.

(b) Yield surfaces in σ_1- $\sqrt{2}\sigma_2$ space.

Fig. 7. HISS yield surfaces for compressive and tensile yielding.

the cohesive (or tensile) strength, $\bar{c}$ (Fig. 6a); $S_r = \sqrt{27}J_{3D}/2J_{2D}^{1.5}$; n is the parameter related to the transition from compressive to dilative volume change (Fig. 5); γ and β are the parameters associated with the ultimate surface (Fig. 6a); and α is the hardening or growth function, in a simple form, it is given by

$$\alpha = \frac{a_1}{\xi^{\eta_1}} \tag{7}$$

where a_1 and η_1 are the hardening parameters, and ξ is the accumulated or trajectory of plastic strains, given by

$$\xi = \xi_v + \xi_D \tag{8}$$

Here the accumulated volumetric plastic strain is given by

$$\xi_v = \frac{1}{\sqrt{3}}|\varepsilon_{ii}^p| \tag{9a}$$

and the accumulated deviatoric plastic strain is given by

$$\xi_D = \int \left(d\varepsilon_{ij}^p d\varepsilon_{ij}^p\right)^{1/2} \tag{9b}$$

where ε_{ii}^p is the plastic volumetric strain, and $d\varepsilon_{ij}^p$ is the increment of plastic shear strain. In the HISS model, the yield surface grows continuously and approaches the *ultimate* yield (Fig. 6); it can include, as special cases, other conventional and continuous yield plasticity models (Desai, 2001).

For compression intensive materials (e.g. geologic, concrete, powders), the model and the yield surfaces (Fig. 6) are relevant for compressive yield only in the positive $\sqrt{J_{2D}} - J_1$ space, in which $\bar{c}$ will be the compressive strength. Similarly, for tension intensive materials (e.g. metals and alloys), the model and yield surfaces are relevant for tensile yield only in the positive $\sqrt{J_{2D}} - J_1$ space, in which $\bar{c}$ would denote the tensile strength. In both cases, the extension of yield surfaces in the negative J_1-axis is not relevant; they are usually shown for convenience of plotting. Sometimes, the extended yield surfaces in the negative J_1-axis have been used with an *ad hoc* model for materials experiencing tensile conditions, which may not be realistic. As discussed below (HISS-CT model), for example, when a material experiences tensile stress (during deformation), it would be realistic to use the model (e.g. HISS) defined on the basis of tensile tests, and vice versa.

2.6. HISS for compression and tension (HISS-CT)

For some problems, the material can be subjected to both compressive and tensile stress conditions. To develop and use the *same* model for both conditions is difficult, and perhaps not possible. However, the same model like HISS can be formulated for both conditions by obtaining parameters from separate compression and tension (extension) tests. Details are given in Desai (2007, 2009) and Akhaveissy and Desai (2013).

The HISS plasticity model allows for continuous yielding, volume change (dilation) before the peak, stress path dependent strength, effect of both volumetric and deviatoric strains on the yield behavior, and it does not contain any discontinuities in the yield surface. The HISS surface (Eq. (6)) represents a unified plastic yield surface, and most of the previous conventional and continuous yield surfaces can be derived from it as special cases (Desai, 2001). Also, the HISS model can be used for nonassociative and anisotropic hardening responses, etc. The idea of the single yield surface has been also used by Lade and coworkers (e.g. Lade and Kim, 1988), based on prior open yield surfaces (Matsuoka and Nakai, 1974).

2.7. Creep behavior

Many materials exhibit creep behavior, increasing deformations under constant stress or stress relaxation under constant strain (displacement). A number of models have been proposed for various types of creep behavior, e.g. viscoelastic (ve), viscoelasticplastic (vep) and viscoelastic-viscoplastic (vevp); they are also based on the assumption of continuum material. A generalized creep model has been proposed under the DSC (Desai, 2001). It is called multicomponent DSC (MDSC) which includes ve, vep and vevp versions as special cases. Details of the creep models are given in Desai and Zheng (1987) and Desai (2001).

Models based on theories of elasticity, plasticity and creep assume that the material is initially continuous and remains continuous during deformation. However, it is realized that many materials contain discontinuities (microcracks, dislocations, etc.), initially and during loading. During deformations, they coalesce and grow, and separate, resulting in microcracks and fractures, with consequent failure. Since the stress at a point implies continuity of the material, theories of continuum mechanics may not be valid for such discontinuous materials.

2.8. Discontinuous materials

There are a number of models available to consider discontinuities in a deforming material. Chief among those are considered to be fracture mechanics, damage mechanics, micromechanics, microcrack interaction, gradient and Cosserat theories (Mühlhaus, 1995). Most of them combine the effect of discontinuities and microcracks, with the continuum behavior. Descriptions of these models are presented in Mühlhaus (1995), Desai (2001, 2015a,b).

3. Parameters

The basic DSC model contains the following parameters.

(1) Relative intact (RI)

Elasticity: Young's modulus, E, and Poisson's ratio, ν (or shear modulus, G, and bulk modulus, K), and **Plasticity:** (a) von Mises: tensile yield/cohesion, c, or (b) Mohr-Coulomb: cohesion, c and angle of internal friction, φ, or (c) HISS plasticity: ultimate yield, γ and β; phase change (transition from compaction to dilation), n; continuous yielding, a_1 and η_1; and cohesive strength intercept, $\bar{c}$ (R).

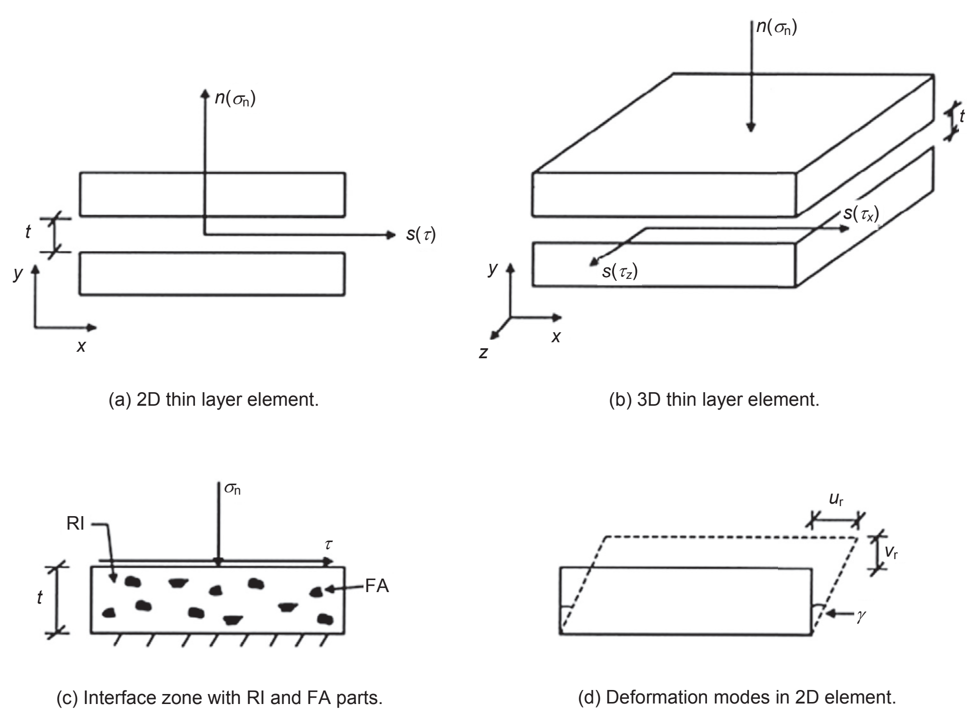
(2) Fully adjusted (FA)

For the critical state, the parameters are shown in Eq. (1).

(3) Disturbance

The parameter D_u can be obtained from Fig. 1; often a value near unity can be used. Parameters A and Z are obtained by first determining various values of D from the test data by using Eqs. (2a) and (2b), and then plotting logarithmic form of Eq. (3).

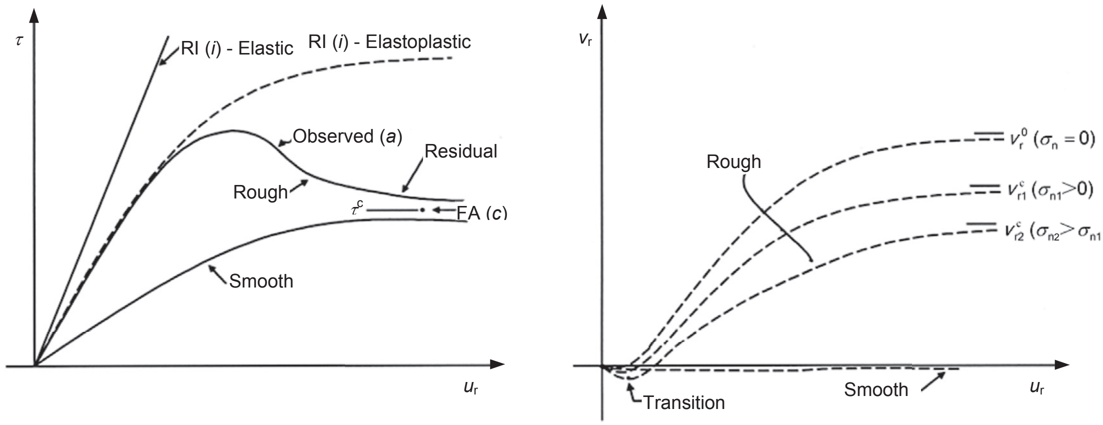
Most of the above parameters in the DSC have physical meanings, i.e. almost all are related to specific states in the material response, e.g. elastic modulus to the unloading slope of stress-strain behavior, β to the ultimate state, and n to the transition from compactive to dilative volume change (Fig. 5). Their number is equal to or lower than that of previously available model of comparable capabilities. They can be determined from standard laboratory tests such as uniaxial, shear, triaxial and/or multiaxial. The procedures for the determination of the parameters are provided in



(a) 2D thin layer element. (b) 3D thin layer element.

(c) Interface zone with RI and FA parts. (d) Deformation modes in 2D element.

Fig. 8. Schematics of 2D and 3D interface elements and DSC.



(a) τ vs. u_r.   (b) v_r vs. u_r.

Fig. 9. Test data for contact (interface or joint).

various publications (e.g. Desai, 2001). Details of the softening and stiffening behaviors are given in various publications (Desai, 1974, 2001; Desai et al., 1998; Shao and Desai, 2000).

4. Interfaces and joints

Behavior at interfaces between two (different) materials and joints plays a significant role in the overall response of an engineering system (Desai et al., 1986b; Samtani et al., 1996; Fakharian and Evgin, 2000). One of the main advantages of the DSC is that its mathematical framework for solids can be applied also for interfaces (see Fig. 7).

4.1. Relative intact (RI) response

Schematics of two- (2D) and three-dimensional (3D) interfaces, disturbed states, and deformation modes are shown in Fig. 8. A 2D interface is considered in Fig. 8a. In the same way as was assumed in the solid material, an element for the (thin) interface is considered to be composed of RI and FA states (Fig. 8c). The RI behavior in the interface can be simulated by various models such as nonlinear elastic and plastic (conventional or continuous yield). Here, the HISS plasticity model is adopted for the RI part, as the specialized form of Eq. (6) for solids. It can be calibrated from laboratory tests in terms of shear stress, τ vs. relative shear (horizontal) displacement, u_r, and relative normal (vertical) displacement v_r vs. u_r (Fig. 9a and b), respectively.

The yield function specialized from Eq. (6) for 2D interface is given by (Fig. 10):

$$F = \tau^2 + \alpha\sigma_n^n - \gamma\sigma_n^q = 0 \tag{10}$$

where σ_n is the normal stress, which can be modified as $\sigma_n + R$, R is the intercept along σ_n- axis which is proportional to the adhesive strength, c_0; n is the phase change parameter, which designates

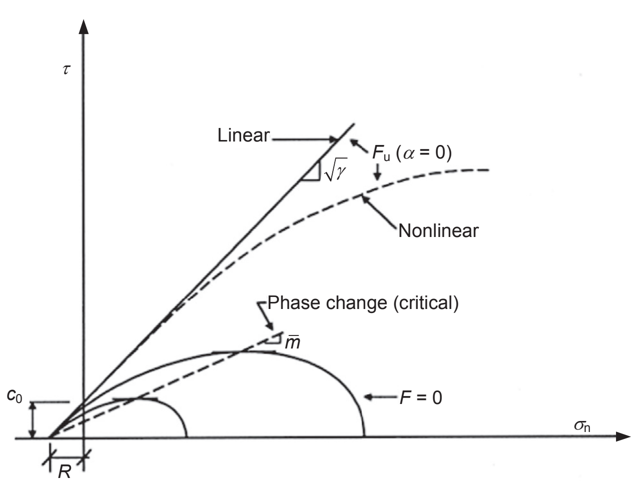
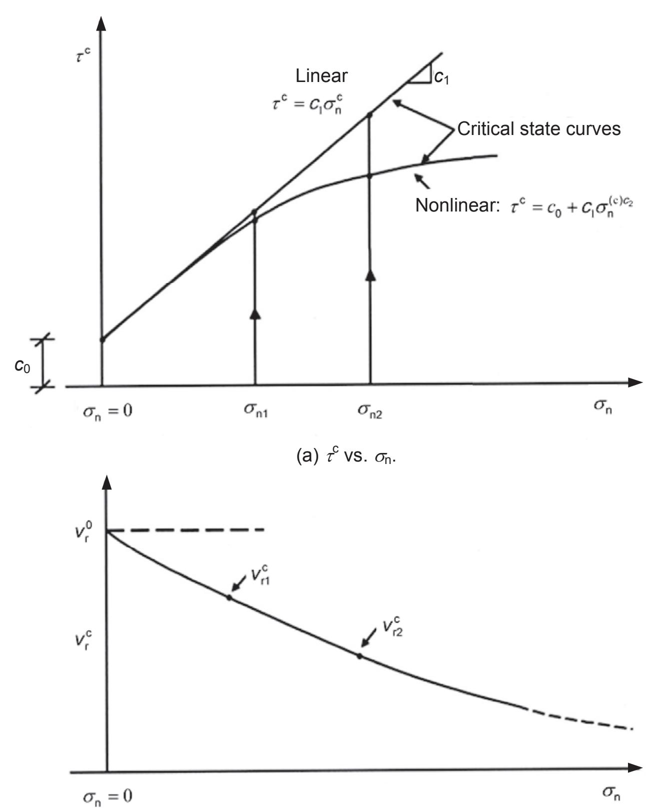


Fig. 10. HISS yield surfaces for interfaces and joints.



(b) v_r^c vs. σ_n.

Fig. 11. FA behavior of interface/joint at critical state.

transition from compressive to dilative response; q governs the slope of the ultimate envelope (if the ultimate envelope is linear, $q = 2$); and α is the growth or yield function given by

$$\alpha = \frac{h_1}{\xi^{h_2}} \tag{11}$$

where h_1 and h_2 are the hardening parameters, and ξ is the trajectory of plastic relative horizontal (u_r) and vertical (normal) (v_r) displacements, given by

$$\xi = \int \left(\mathrm{d}u_r^p \mathrm{d}u_r^p + \mathrm{d}v_r^p \mathrm{d}v_r^p\right)^{1/2} = \xi_D + \xi_v \tag{12}$$

where the superscript "p" denotes plastic.

As in the case of solids, the interface can reach the critical state, irrespective of the initial roughness and normal stress (σ_n). At that state, the relative normal displacement v_r tends to a steady state (Fig. 9b). The equation for the material at the critical state, proposed by Archard (1957) is given by (Fig. 11a):

$$\tau^c = c_0 + c_1 \sigma_n^{(c)c_2} \tag{13a}$$

where c_0 is related to the adhesive strength and denotes the critical value of τ^c when $\sigma_n = 0$, $\sigma_n^{(c)}$ is the normal stress at the critical state, and c_1 and c_2 are parameters related to the critical state.

The relation between the normal stress, σ_n, and the relative normal displacement at the critical state, v_r^c, was proposed by Schneider (1976) (Fig. 11b):

$$v_r^c = v_r^0 \exp(-\lambda \sigma_n) \tag{13b}$$

where λ is a parameter and other quantities are shown in Fig. 11.

Eqs. (11a) and (11b) for modeling interfaces/joints are similar to Eqs. (1a) and (1b) for solids.

4.2. Disturbance

Like in the case of solids, the disturbance for interfaces can be obtained from measured quantities as shown in Fig. 12.

The DSC has been published in a number of papers and books, only a few are cited here (Desai, 2001, 2015a, b); these works include application of the DSC by the author and coworkers, and other researchers for materials such as soils, structured soil, masonry, concrete, asphalt concrete, fully and partially saturated materials, rock and rockfills, pavement materials, metals, alloys, ceramics, polymers and silicon, and interfaces and joints. It has been used for applications beyond material behavior, e.g. developing expressions for earth pressures (Zhu et al., 2009), computation of pile capacity (Desai, 2013), and free surface fluid flow (Desai, 1976; Desai and Li, 1983).

A constitutive model including discontinuities should satisfy properties such as mesh dependence and localization. The DSC has

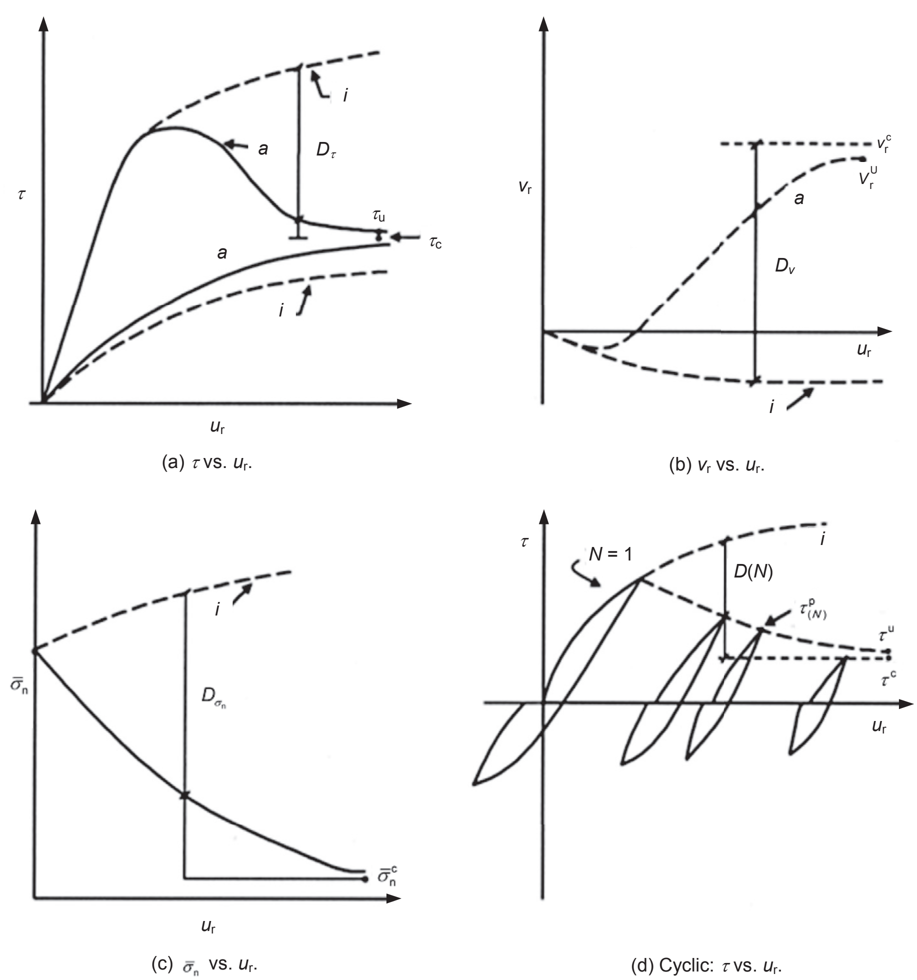


Fig. 12. Disturbance from various test data for interfaces.

been analyzed for localization and mesh dependence and details are presented in Desai (2001, 2015a,b), and Desai and Zhang (1998).

5. Validations and applications

The DSC and its special versions like HISS plasticity have been used by the author, coworkers, and other researchers, to model a wide range of materials such as geologic (sands, clays, rocks and concrete), asphalt concrete, metals, alloys (e.g. leaded and unleaded solders), polymers and silicon, and interfaces/joints; they are covered in various publications, e.g. Desai (2001). It has been implemented in computer (finite element, FE) methods for nonlinear static and dynamic problems in structural- and geomechanics, coupled flow through porous media and composites in electronic packaging.

The DSC models are used successfully for a wide range of materials and interfaces. Here, specimen level validations are performed for tests data from which the material parameters were determined, and independent test data not used for finding parameters. The DSC models are implemented in nonlinear FE procedures for solution to static and dynamic problems in dry and saturated materials. The FE procedures are used to perform boundary value problem level validation in which the predictions are compared with measurements in the field and/or simulated problems in the laboratory. Details of such validations and applications are given in a number of publications. Examples of only typical materials, particularly those containing complexities that are difficult to model by conventional models, are presented in various publications, in extensive publications provided later (see Appendix).

Conflict of interest

The author wishes to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Appendix. DSC publications

The DSC has been used for a wide range of problems in Geomechanics, geotechnical engineering and other disciplines of engineering. A comprehensive list of publication related to geomechanics and geotechnical engineering is presented in this Appendix.

(1) Basic and related publications

By author and coworkers

Desai CS. Mechanics of materials and interfaces: The disturbed state concept. Boca Raton, FL, USA: CRC Press, 2001.

Desai CS. A consistent numerical technique for work softening behavior of geologic media. In: Proceedings of the International Conference on Computational Methods in Nonlinear Mechanics. Austin, TX, USA: University of Texas Press, 1974.

Desai CS. Finite element residual schemes for unconfined flow. International Journal for Numerical Methods in Engineering 1976; 10(6): 1415–8.

Desai CS, Li GC. A residual flow procedure and application for free surface flow in porous media. Advances in Water Resources 1983; 6(1): 27–35.

Desai CS, Basaran C, Zhang W. Numerical algorithms and mesh dependence in the disturbed state concept. International Journal for Numerical Methods in Engineering 1997; 40(16): 3059–83.

Desai CS, Zhang W. Computational aspects of disturbed state constitutive models. Computer Methods in Applied Mechanics and Engineering 1998; 151(3–4): 361–76.

Desai CS. Constitutive modeling of geologic materials, interfaces and joints: Disturbed state concept. Chapter in Rock Mechanics and Engineering, Feng XT (editor). Boca Raton, FL, USA: CRC Press, 2015 (under preparation).

Desai CS. Constitutive modeling of materials and contacts using the disturbed state concept: Part 1 – Background and analysis. Computers and Structures 2015; 146: 214–33.

Desai CS. Constitutive modeling of materials and contacts using the disturbed state concept: Part 2 – Validations at specimen and boundary problems levels. Computers and Structures 2015; 146: 234–51.

By other researchers

Zheng JY. Disturbed state theory of soil mechanics problems. Beijing, China: China Water Power Press, 2006 (in Chinese).

Zhu W, Zhao J, Hudson JA (editors). Stability analysis and modeling of underground excavations in fractured rocks. Amsterdam, the Netherlands: Elsevier, 2004.

Sousa LR, Olalla C, Grossmann NF (editors). Proceedings of the 11th Congress of the International Society for Rock Mechanics. London, UK: Taylor and Francis Group, 2007.

Springman S (editor). Constitutive and modeling: Two extremes. Lisse: A.A. Balkema, 2002.

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Qian Q, Zhou Y (editors). Harmonising rock engineering and the environment. In: Proceedings of the 12th ISRM Congress on Rock Mechanics. Boca Raton, FL, USA: CRC Press, 2012.

Wu G. Disturbed state constitutive models of engineering material (I) – Disturbed state concept and its theory principium. Chinese Journal of Rock Mechanics and Engineering 2002; 21(6): 759–65 (in Chinese).

Muira S, Ishikawa T, Yoshida N, Hisari Y, Nagato A. Advances in transportation geotechnics II. In: Proceedings of the 2nd International Conference on Transportation Geotechnics, Hokkaindo, Japan, 2012.

Zaman M, Gioda G, Booker J. Modeling in geomechanics. John Wiley and Sons, 2000.

(2) Geological materials (sands and clays), model parameters

By author and coworkers

Wathugala GW, Desai CS. Damage based constitutive models for soils. In: Proceedings of the 12th Canadian Congress on Applied Mechanics. Ottawa, Canada: Carleton University, 1989.

Armaleh S, Desai CS. Modeling and testing of a cohesionless material using the disturbed state concept. Journal of the Mechanical Behavior of Materials 1994; 5(3): 279–96.

Shao C, Desai CS. Implementation of DSC model and application of analysis of field pile load tests under cyclic loading. International Journal for Numerical and Analytical Methods in Geomechanics 2000; 44(6): 601–24.

Desai CS, Wang Z. Disturbed state model for porous saturated materials. International Journal of Geomechanics 2003; 3(2): 260–5.

Desai CS, El-Hoseiny KE. Prediction of field behavior of geosynthetic-reinforced soil wall. Journal of Geotechnical and Geoenvironmental Engineering 2005; 131(6): 209–39.

(Contains DSC modeling for backfill soil and interface between Tensar reinforcement and backfill.)

Sane S, Desai CS, Jenson JW, Contractor DN, Carlson AE, Clark PV. Disturbed state constitutive modeling of two Pleistocene tills. Quarterly Science Reviews 2008; 27(3–4): 267–83.

Minh NH, Suzuki K, Oda M, Tobita T, Desai CS. Numerical simulation using disturbed state concept (DSC) model for softening behavior of sand. Journal of Southeast Asian Geotechnical Society 2008; 34(1): 25–35.

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(3) Unsaturated or partially saturated soils

By author and coworkers

Geiser F, Laloui L, Vulliet L, Desai CS. Disturbed state concept for constitutive modeling of partially saturated porous materials. In: Proceedings of the 6th International Symposium on Numerical Models in Geomechanics, Montreal, Canada, 1997.

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By author and coworkers

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(6) Liquefaction-microstructural instability, strain localization, softening

By author and coworkers

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(7) Rocks, rockfill materials, coal, rock salt

By author and coworkers

Varadarajan A, Sharma KG, Desai CS, Hashemi M. Analysis of a powerhouse cavern in the Himalayas. International Journal of Geomechanics 2001; 1(1): 109–27.

By other researchers

Wu G. Disturbed state constitutive models of engineering material (I): Disturbed state concept and its theory principium and (II) DSC-based numerical simulation of finite element method. Chinese Journal of Rock Mechanics and Engineering 2002; 21(6): 759–65 (in Chinese).
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By author and coworkers

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Note: The connections between the DSC, CS and SOC are discussed in this Appendix. It is shown that CS and SOC can be considered to be special cases of the DSC. A number of applications and comparisons for behavior of geologic materials are also presented in the Appendix.

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