Disturbed state concept as unified constitutive modeling approach

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A R T I C L E  I N F O

Article history:
Received 28 January 2016
Received in revised form 29 January 2016
Accepted 30 January 2016
Available online 1 April 2016

Keywords:
Disturbed state concept (DSC)
Constitutive model
Parameters
Soils
Interfaces
Validations

A B S T R A C T

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.

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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
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 over-consolidated 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

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**Fig. 1.** Schematics of DSC. $D_c, D_f$ and $D_u$ denote initiation of fracture, failure and ultimate disturbance, respectively.
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 micromechanics); 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).

Behavior 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. 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:

$$\sqrt{J_{2D}^c} = m_1 f$$ (1a)

$$e^c = e_0^c - \lambda \ln(f/j/3p_a)$$ (1b)

where superscript “c” denotes the critical state, $J_{2D}$ is the second invariant of the deviatoric stress tensor, $m$ is the slope of the critical state line (Fig. 5), $f_1$ is the first invariant of the stress tensor, $e$ is the void ratio, $e_0$ is the initial void ratio, $\lambda$ 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 ($\bar{\sigma}$) vs. time or number of cycles (Fig. 3d). Fig. 4 shows the schematic of the disturbance (D) as function of $\xi_D$ 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 $\xi_D$.

2.3.1. Disturbance from measurements

From measurements, for example, we have:

$$D_e = \frac{\sigma^e - \sigma^a}{\sigma^e - \sigma^i} \quad \text{(stress – strain behavior)}$$ (2a)

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

where $\sigma^e$ is the measured stress; $V^i$ is the measured nondestructive velocity; and $i$ and $c$ represent RI and FA responses, respectively.
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 \( (xi_D) \) or plastic work:

\[
D = D_u \left[ 1 - \exp \left( -A x_i D \right) \right] 
\]  

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):
\[
d\sigma_{ij}^0 = (1 - D)\sigma_{ij}^0 + Dd\sigma_{ij}^0 + dD\left(\sigma_{ij}^c - \sigma_{ij}^0\right) \tag{4a}
\]

or

\[
d\sigma_{ij}^0 = (1 - D)C_{ijkl}^C d\varepsilon_{kl}^i + DC_{ijkl}^C d\varepsilon_{kl}^c + dD\left(\sigma_{ij}^c - \sigma_{ij}^0\right) \tag{4b}
\]

where \(\sigma_{ij}\) and \(\varepsilon_{ij}\) 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

\[
d\sigma_{ij}^0 = C_{ijkl}^C d\varepsilon_{kl}^c \tag{5}
\]

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):

\[
F = J_{2D} - \left(-\frac{\sigma_{ij}^0}{J_1} + \frac{\sigma_{ij}^C}{J_1}\right) (1 - \beta S_t)^{-0.5} = 0 \tag{6}
\]

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

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**Fig. 4.** Disturbance vs. \(\xi_0\) (or number of cycles of time).

**Fig. 5.** Stress–strain behavior of loose and dense materials, and critical state.
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 also been used by Lade and coworkers (e.g. Lade and Kim, 1988), based on prior open yield surfaces (Matsuoka and Nakai, 1974).

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 $\sqrt{I_2}$, $J_1$ space, in which $\tau$ would denote the tensile strength. In both cases, the extension of yield surfaces in the negative $J_2$-axis is not relevant; they are usually shown for convenience of plotting. Sometimes, the extended yield surfaces in the negative $J_2$-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)**

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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), viscoelastic-plastic (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, $v$ (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, $\phi$, or (c) HISS plasticity: ultimate yield, $\gamma$ and $\beta$; phase change (transition from compaction to dilation), $n$; continuous yielding, $a_1$ and $\eta_1$; and cohesive strength intercept, $\tau$ ($R$).

(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, $\beta$ 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
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, \( \tau \) 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):

\[
F = \tau^2 + \alpha \sigma_n^0 - \gamma \sigma_n^g = 0
\]

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

![Fig. 9. Test data for contact (interface or joint).](image)

![Fig. 10. HISS yield surfaces for interfaces and joints.](image)

![Fig. 11. FA behavior of interface/joint at critical state.](image)
transition from compressive to dilative response; \( q \) governs the slope of the ultimate envelope (if the ultimate envelope is linear, \( q = 2 \)); and \( \alpha \) is the growth or yield function given by

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

(11)

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

\[
\xi = \int (du_r^p dt_r^p + dv_r^p dt_r^p)^{1/2} = \xi_D + \xi_V
\]

(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 (\( \sigma_n \)). 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):

\[
\tau^c = c_0 + c_1 \sigma_n^{(c)G}
\]

(13a)

where \( c_0 \) is related to the adhesive strength and denotes the critical value of \( \tau^c \) when \( \sigma_n = 0, \sigma_n^{(G)} \) 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, \( \sigma_n \), and the relative normal displacement at the critical state, \( v^c_r \), was proposed by Schneider (1976) (Fig. 11b):

\[
v^c_r = \frac{v_0^r}{\lambda} \exp(-\lambda \sigma_n)
\]

(13b)

where \( \lambda \) 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
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


By other researchers


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

By author and coworkers


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

By other researchers
Pan YW, Wang HJ, Ng CWW. Effective stress-based dynamic analysis and centrifuge simulation of earth dam. Powerpoint Presentation, Hong Kong University of Science and Technology, China, 2013.
Pan J. A disturbed state concept model of granular material
Syed SM, Maheshwari BK. Evaluation of DSC parameters for solar sand.
Yu XJ, Shi JY, Xu YB. Modelling disturbed state and anisotropy of dark green silty clay in Shanghai with disturbed state concept model.
By other researchers
Geiser F, Laloui L, Vulliet L, Desai CS. Disturbed state concept


(3) Unsaturated or partially saturated soils

By author and coworkers

By other researchers

By other researchers

(4) Reinforced, stabilized soils

By author and coworkers

By other researchers

(5) Structured soils

By author and coworkers

By other researchers

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

By author and coworkers

By other researchers


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

By author and coworkers


By other researchers


Prochazka P. Inelastic and damage modeling of tunnel face surrounded by discrete elements. In: Proceedings of the 19th International Mining Congress and Fair of Turkey, Izmir, Turkey, 2005.


(8) Concrete and masonry

By author and coworkers


By other researchers


(9) Pavement materials

By author and coworkers


By other researchers


(10) Polymers, asphalt

By other researchers


(11) Interfaces, joints, soil-structure interaction

By author and coworkers


By other researchers


(12) Ceramics, silicon with impurities

By author and coworkers


(13) Numerical analysis

By other researchers


(14) Load transfer function of piles

By other researchers


(15) Earth pressures, seepage, consolidation, anisotropy

By author and coworkers


By other researchers


(16) DSC, critical state (CS), and self-organized criticality (SOC)

By author and coworkers


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.

References


Chandrakant S. Desai obtained M.S. and Ph.D. degrees from the Rice University, Houston, Texas and the University of Texas, Austin Texas, USA, respectively. He is a Regents’ Professor (Emeritus) at the University of Arizona, AZ, USA. He has been involved in teaching, research, consulting and professional activities over four decades. He has been author/editor of 22 books, over 335 papers in journals and conferences, founding and Editor-in-Chief of two international journals in Geomechanics, Advisory Editor of International Journal of Geomechanics, ASCE, and founding President of the IACMAG. Dr. Desai has received a number of awards and recognitions, e.g. The Distinguished Member Award by the American Society of Civil Engineers (ASCE); The Nathan M. Newmark Medal, by Structural Engineering and Engineering Mechanics Institute, ASCE; The Karl Terzaghi Award, by Geo Institute, (ASCE); Honorary Professor, University of Nottingham, U.K.; Diamond Jubilee Honor, Indian Geotechnical Society; Suklje Award/Lecture, Slovenian Geotechnical Society; Meritorious Civilian Service Award by the U.S. Corps of Engineers; Alexander von Humboldt Stiftung Prize by the German Government; Outstanding Contributions Medal by the International Association for Computer Methods and Advances in Geomechanics; Outstanding Contributions Medal in Mechanics by the Czech Academy of Sciences; Clock Award for outstanding Contributions for Thermomechanical Analysis in Electronic Packaging by the Electrical and Electronic Packaging Division, ASME; Five Star Faculty Teaching Finalist Award and the El Paso Natural Gas Foundation Faculty Achievement Award, at the University of Arizona, Tucson, Arizona.