

Influence of contact intensity fabric on sand mechanical response and its incorporation in a constitutive model

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ABSTRACT: The mechanical behavior of uncemented sand in in-situ and reconstituted states often exhibit distinct mechanical properties. The source of these differences has rarely been quantified and incorporated in constitutive modeling. Based on element tests and X-ray computed tomography (XRCT) scans on an intact and reconstituted sand, this study proposes a fabric scalar I to characterize the contact interlocking between particles. It is assumed that interlocking evolves towards a unique critical state value for the same sand under the same mean effective stress, irrespective of its initial state. This fabric scalar can thus be incorporated into the state parameter within the critical state theory to reflect the role of interlocking in continuum scale behavior. A specific constitutive model SANISAND-I is developed and is validated against laboratory tests on intact and reconstituted sand samples, highlighting its capability to reflect the influence of the interlocking in in-situ sand. The proposed theory provides a solution to unify the constitutive modeling of uncemented in-situ and reconstituted sand.

KEYWORDS: Intact sand, Fabric, Constitutive model, Contact intensity, Critical state.

1 INTRODUCTION

It has been widely recognized that there are distinct differences between naturally deposited intact sand and laboratory reconstituted sand in terms of both static and dynamic properties (e.g., Goto et al., 1992; Cuccovillo and Coop, 1999; Ghionna and Porcino, 2006; Ventouras and Coop, 2009). Compared with reconstituted sand of the same density, intact sand typically exhibits higher stiffness (Cuccovillo and Coop, 1997; Cresswell and Powrie, 2004), more pronounced dilatancy (Goto et al., 1992), and greater liquefaction resistance (Kiyota et al., 2009).

The origin of these differences is often attributed to the general concept of structure of the soil (Cuccovillo and Coop, 1999), which can be categorized based on whether it results from cementation between the particles (bonded structure) or from particle interlocking (fabric structure) (Cresswell and Powrie, 2004). Although numerous studies have been conducted on the mechanical properties and constitutive modeling of cemented sand (e.g., Coop and Atkinson, 1993; Zhang et al., 2023; Rossi et al., 2024), research on the fabric of uncemented sand is relatively limited due to the challenges in preserving its state.

In recent years, techniques have been developed for intact sand sampling and X-ray tomography imaging of geomaterials, making direct observation of uncemented intact sand fabric possible. Existing X-ray scanning test results indicate that there are clear differences in void structure and particle arrangement between intact and reconstituted sand (Fonseca et al., 2013a; Quinteros and Carraro, 2023), and notably, a distinction in the coordination number and the average contact area for intact and reconstituted sand has been reported, indicating interlocking within the intact sand (Fonseca et al., 2013b; Garcia et al., 2024). These studies have significantly advanced the understanding of the fabric of intact sand. However, the connection between these fabric characteristics and macroscale mechanical properties has not yet been established, which has limited the constitutive modeling of intact sand.

The objective of this study is to associate the microstructure characteristics of uncemented intact sand with its macroscale mechanical behavior, and establish a constitutive model that can account for its interlocking characteristics. To this end, the macro and micro behaviors of intact sand are analyzed. An interlocking variable I is proposed and utilized to formulate the Critical State Theory accounting for Interlocking (CST-I). It is then incorporated into the SANISAND model (Dafalias and Manzari, 2004), resulting in an improved model

referred to as SANISAND-I. The model is employed to simulate a series of element tests on both uncemented intact and reconstituted sand, highlighting its capability for unified modeling of intact and reconstituted sand.

2 MACRO AND MICRO CHARACTERISTICS OF AN INTACT SAND

To understand the macro mechanical behavior of intact sand, a series of drained triaxial tests were conducted on uncemented frozen intact sand samples (IS) from a river-lake sedimentary layer and their reconstituted counterparts (RS). The intact sand was obtained using blocking sampling and frozen transport methods to preserve its in-situ structure, and the sand is characterized by minimal fines (less than 0.5%) and no indication of cementation. The reconstituted sand was prepared using the air pluviation method to match the density and grading of the intact sand. Details of the material and test procedures can be found in the work of Yang et al. (2025).

The test results provide clear evidence of structural characteristics in intact sand, as depicted in Figure 1. Under varying confining pressures, intact sand consistently exhibits a markedly greater initial shear modulus and more pronounced dilation than reconstituted sand. However, at relatively large strains, the responses of intact and reconstituted sands tend to converge. These observations indicate that the fabric of intact sand significantly governs its early-stage mechanical behavior, yet this fabric is progressively degraded during loading, leading to a critical state identical to that of reconstituted sand.

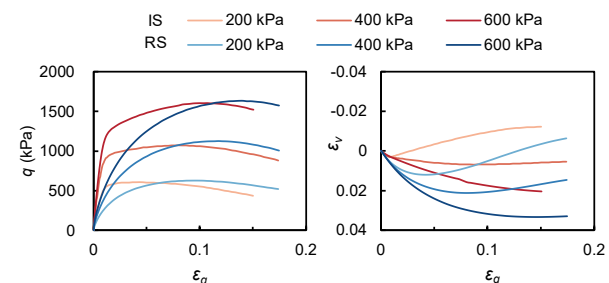


Figure 1. Drained triaxial tests under different confining pressures for intact sand (IS) and reconstituted sand (RS). ($e=0.75$)

To elucidate the microscale origins of these differences, X-ray tomography was also performed on the same batch of intact and reconstituted sand, at their initial states. The scanning images were carefully processed to identify individual particles

and characterize their contact fabric (see Zhang et al. (2025) for details). A clear interlocking contact structure is identified within scanning images of intact sand samples (Figure 2), similar to that observed by Garcia et al. (2024). This interlocking structure, commonly attributed to aging effect, increases the energy required for particle sliding and rotation, thereby enhancing the soil modulus and inducing more pronounced dilation (Liu et al., 2024).

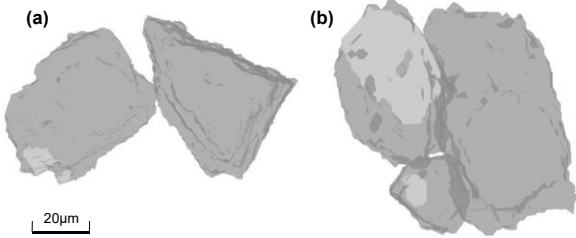


Figure 2. 3-D rendering of two different contact structures: (a) point contact, and (b) interlocking contact.

To quantitatively describe the interlocking between particles, a contact intensity fabric scalar CI is adopted, following the definition of Fonseca et al. (2013b):

$$CI = \frac{1}{N_p} \sum_{i=1}^{N_p} \frac{1}{S_{a_i}} \sum_{j=1}^{N_{c,i}} S_{c_{a_j}} \quad (1)$$

where N_p is the number of particles in the calculated region, $N_{c,i}$ is the number of contacts involving particle i , S_{a_i} is the surface area of particle i , and $S_{c_{a_j}}$ is the area of contact j . CI is a measurable microscale quantity that reflects the proportion of the contact area relative to the total surface area. Figure 3 presents the frequency histogram of contact intensity for each individual particle. In intact sand, particles with higher contact intensity ($CI > 0.3$) are more prevalent than in reconstituted sand, whereas particles with lower CI are less common. The average CI for intact sand is 0.336, compared to 0.302 for reconstituted sand. These findings further confirm the significant differences in interlocking between intact and reconstituted sands. However, how this interlocking influences the mechanical response at the continuum scale remains to be elucidated.

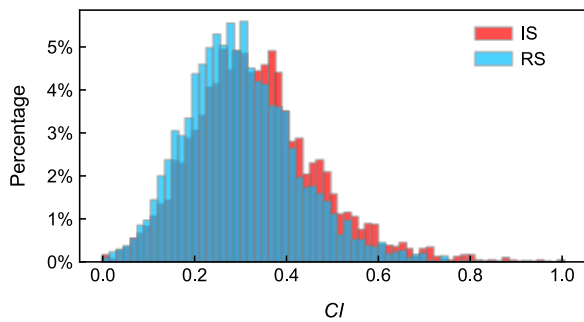


Figure 3. Frequency histogram of contact intensity (CI) for intact sand (IS) and reconstituted sand (RS).

3 INCORPORATION OF INTERLOCKING IN A CONSTITUTIVE MODEL

3.1 Critical State Theory accounting for Interlocking

Based on the aforementioned microscale analysis, interlocking is a crucial internal variable distinguishing the fabric of intact and reconstituted sands. However, it is not included in the classical Critical State Theory (Roscoe et al., 1958; Schofield

and Wroth, 1968). Therefore, we propose to consider the interlocking structure as a state of the soil and incorporate it into the state parameter (Been and Jefferies, 1985).

First, to characterize interlocking from a continuum scale, an interlocking variable I using contact intensity as an indicator for interlocking is introduced by:

$$I = CI/CI_c \quad (2)$$

where CI_c is the contact intensity value at critical state. A larger I indicates stronger interlocking. It should be noted that the choice of I is not necessarily tied with the definition of contact intensity. Rather, it is a general concept that reflects the interlocking structure, and could also incorporate the influence of other fabric quantities, such as the coordination number. The framework proposed here is flexible and can accommodate other indicators or combinations of indicators in future research.

This study further assumes that the contact intensity CI of the same sand evolves towards a unique critical state value CI_c under the same mean effective stress p , regardless of its initial state. This results in $I = 1$ at the critical state. In this sense, the interlocking variable I can serve as an internal variable reflecting the fabric state of the soil and can be incorporated into the state parameter ζ_I . Here, a simple form that satisfies critical-state requirements is adopted:

$$\zeta_I = e - e_c - \hat{e}_I(e, p) \ln(I) \quad (3)$$

where $\hat{e}_I(e, p)$ is a positive function reflecting the extent of the material state change due to variations in the interlocking variable. In the most simplified case, it can be taken as a constant. At the critical state, $I = 1$, $\hat{e}_I(e, p) \ln(I) = 0$, which implies $\zeta_I = 0$, satisfying the compatibility with the critical state.

In the e - p space, $\zeta_I = 0$ represents a Dilatancy State Line (DSL), similar to that by Li and Dafalias (2012). The distance between DSL and the current (p, e) quantifies the material's dilatancy (or contraction) tendency (Figure 4). A higher interlocking degree I , according to Equation (3), shifts the DSL upward, indicating a state further away from the critical state. As deformation progresses and $I \rightarrow 1$ (i.e., full degradation of interlocking), the last term in Equation (3) vanishes, and the DSL gradually coincides with the CSL, explaining why both intact and reconstituted sands converge to the same critical state at large strains.

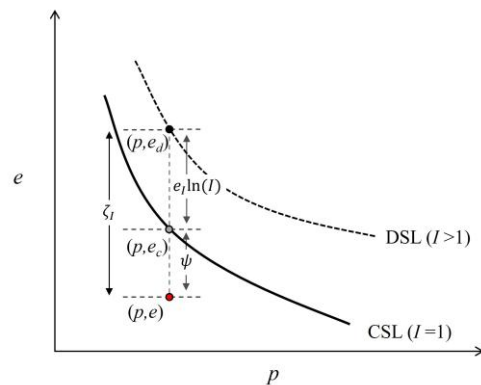


Figure 4. Illustration of the effect of interlocking variable I on the DSL in e - p space.

Based on the above rationale, the state parameter ζ_I can replace the original state parameter $\psi = e - e_c$ proposed by Been and Jefferies (1985) and be applied to any state-dependent constitutive model to reflect the influence of interlocking. This framework is hence referred to as the Critical State Theory accounting for Interlocking (CST-I).

3.2 The SANISAND-I model

To achieve unified constitutive modeling of intact and reconstituted sand, this study applies the above CST-I framework to a specific model named SANISAND (Dafalias and Manzari, 2004), referred to as SANISAND-I. The original SANISAND model is well-known, and this study only presents the three modifications made using the CST-I framework.

Firstly, the SANISAND-I model replaces the original state parameter ψ with the newly proposed ζ_I , which enables the model to account for the dilatancy changes caused by interlocking. Its impact on the model is primarily reflected in the size of the bounding surface and dilatancy surface:

$$\alpha_\theta^b = \sqrt{2/3}[g(\theta)M_c \exp(-n^b \zeta_I) - m]\mathbf{n} \quad (4)$$

$$\alpha_\theta^d = \sqrt{2/3}[g(\theta)M_c \exp(n^d \zeta_I) - m]\mathbf{n} \quad (5)$$

Here, θ is the Lode angle, M_c is the critical stress ratio under triaxial compression, m is a parameter that affects the size of the yield surface, n^b and n^d are model constants, and \mathbf{n} is the loading direction tensor. According to Equations (4) and (5), soils with a smaller state parameter (i.e., intact sand) will have a larger bounding surface and a smaller dilatancy surface, thereby exhibiting a higher plastic modulus and stronger dilation. The function $g(\theta)$, the critical state surface, the mapping rule, and the formulations for plastic modulus and dilatancy are the same as in the original SANISAND model.

The second modification targets the small-strain stiffness, as some studies have shown that the small-strain stiffness of intact sand is higher than that of reconstituted sand (Ventouras and Coop, 2009; Quinteros and Carraro, 2025). This difference at small strains is difficult to capture solely within a plasticity framework. Therefore, the interlocking variable I is also introduced in the calculations of the elastic shear modulus G and the hardening function b_0 :

$$G = G_0 I^k p_{at} \frac{(2.97 - e)^2}{1 + e} \left(\frac{p}{p_{at}}\right)^{1/2} \quad (6)$$

$$b_0 = G_0 I^k h_0 (1 - c_h e) \left(\frac{p}{p_{at}}\right)^{-1/2} \quad (7)$$

where p_{at} is atmospheric pressure, G_0 , k , h_0 , and c_h are model constants. Compared with the original model, the newly added I^k reflects the effect of interlocking on modulus and can better capture the difference in small-strain stiffness between intact and reconstituted sand. Typical data from laboratory tests (e.g., Ventouras and Coop, 2009; Fonseca et al., 2013b) indicate that the initial shear modulus of intact sand is approximately 1.5 to 3 times higher than that of reconstituted sand at the same void ratio and confining pressure. For the values of $k = 5.3$ and $I_{in}^{IS} = 1.22$ used in the present study, the initial shear modulus of intact sand is increased by a factor of approximately 2.9 compared to reconstituted sand.

The final modification to the model is the introduction of an evolution equation for the interlocking variable I :

$$dI = -c_1(I - 1)\langle L \rangle \quad (8)$$

where L is the loading index, and c_1 is a model constant that controls the rate of interlocking evolution. This equation assumes that the interlocking variable evolves from its initial value towards the critical state value $I = 1$, with the evolution process depending solely on the plastic shear strain. It can generally describe the changes in contact area observed in existing scanning experiments (Fonseca et al., 2013b; Garcia et al., 2024), but its applicability under different stress paths still requires further validation.

The three modifications described above introduce three additional parameters e_I , k , c_1 and enable the model to reflect the mechanical response caused by interlocking. The model can simulate intact and reconstituted sand using the same set of parameters without the need for re-calibration, and the differences between intact and reconstituted sand are reflected only in their initial fabric values. It should be noted that, according to the above modifications, the model will revert to SANISAND when $I = 1$, which is beneficial for parameter calibration and model comparison.

4 MODEL VALIDATION

4.1 Determination of model parameters

To validate the effectiveness of the SANISAND-I model, this study conducted parameter calibration and simulation based on the triaxial test results presented in Figure 1. The calibration methods for the original parameters in SANISAND model are well documented in the literature (e.g., Dafalias and Manzari, 2004; Taiebat et al., 2010). Moreover, as cyclic loading is not considered in the present simulations, the fabric tensor \mathbf{z} in the original SANISAND model is not employed. The following sections focus on the calibration methods for the newly introduced 3 parameters and the initial fabric values. All the parameters and initial interlocking variables used are summarized in Table 1.

Table 1. Model constants of SANISAND-I used in this study. (The superscripts *IS* and *RS* denote Intact Sand and Reconstituted Sand.)

Description	Symbol	Value	Description	Symbol	Value
Elasticity	G_0	125	Dilatancy	n^d	1.3
	ν	0.05		A_d	0.85
Critical state	M_c	1.4	Plastic modulus	k	5.3
	c	0.75		n^b	1.2
	e_0	0.91		h_0	2.3
	λ_c	0.0424		c_h	0.9
State parameter	e_I	0.2	Fabric evolution	c_1	12
			Initial fabric value	I_{in}^{IS}	1.22
Yield surface	m	0.01	Initial fabric value	I_{in}^{RS}	1

The parameter e_I reflects the influence of interlocking on the state parameter and can be estimated based on the difference in void ratio between intact and reconstituted sand at phase transformation point. The parameter k controls the influence of interlocking on the initial shear modulus and can be calculated by comparing the shear modulus of intact and reconstituted sand under small-strain conditions. Finally, the parameter c_1 controls the evolution rate of the interlocking variable and can be determined through a trial-and-error process.

Due to the lack of fabric information at the critical state, the initial value of interlocking variable is calculated as follows: The initial interlocking variable for reconstituted sand I_{in}^{RS} can be set to 1, indicating the absence of interlocking. Given the assumption that intact and reconstituted sand have the same critical state fabric, the normalized initial fabric value for intact sand can be calculated based on the proportional relationship from the initial fabric scanning results of coarse particles (Zhang et al., 2025), yielding $I_{in}^{IS} = 1.22$ for intact sand.

4.2 Model performance

The simulation results of triaxial drained tests are presented in Figure 5. The model is capable of simulating the higher initial

shear modulus of intact sand under different confining pressure. Additionally, the model effectively captures the more pronounced dilation of intact sand and the increasing contraction with the increase of confining pressure. As strain increases, the influence of interlocking gradually diminishes, and intact and reconstituted sand tend towards an identical critical state, consistent with the experimental observations.

Overall, the good agreement between simulation and test data demonstrates SANISAND-I's ability to capture the modulus and dilation differences between intact and reconstituted sand. However, further validation under varied densities and stress paths is required.

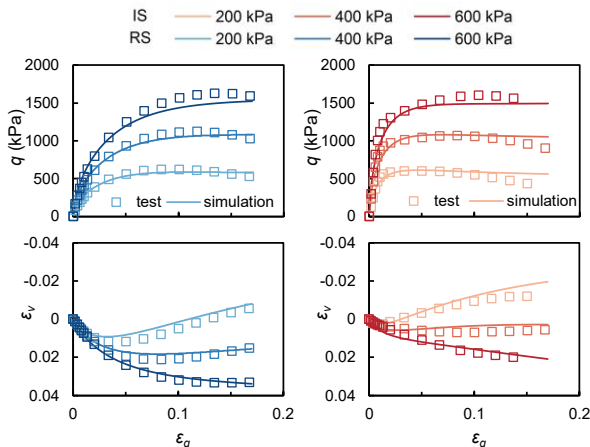


Figure 5. Simulation results of drained triaxial tests under different confining pressures for intact sand (IS) and reconstituted sand (RS). ($e=0.75$)

5 CONCLUSIONS

This study compares the macro and micro characteristics of an uncemented intact sand and its reconstituted counterpart through triaxial tests and X-ray tomography. Intact sand is found to be stiffer and more dilative than reconstituted sand of the same density. An interlocking fabric is identified in the X-ray scanning images to contribute to these differences. Based on these observations, a contact intensity fabric scalar is proposed and supplemented to the classical critical state theory. The framework is then applied to the SANISAND model by introducing an interlocking variable I and modifying the state parameter. The model successfully reflects the greater shear modulus and more pronounced dilation of intact sand, thereby providing a means to unify the modeling of uncemented intact and reconstituted sand.

It should be mentioned that the proposed model is built upon several assumptions and simplifications, which require further investigation. First, XRCT resolution and image thresholding may influence the accuracy of contact intensity quantification. The assumed uniqueness of CI_c at the critical state is supported by current data from monotonic drained triaxial tests, but its validity under different stress paths, and over wider ranges of void ratio and mean effective stress has yet to be established. Furthermore, factors such as particle crushing, shape evolution, and the presence of fines are not explicitly accounted for in ζ_I and may affect the model's extrapolability to other sand types.

6 ACKNOWLEDGEMENTS

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