

Comparative Sensitivity of Structured Cam Clay Parameters in Predicting the Undrained Behaviour of Cement-Treated Soil

(A parametric assessment of residual sandy clay from Isheri, Nigeria)

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Abstract - The Structured Cam Clay (SCC) model separates intrinsic soil behaviour from structure-dependent effects, making it suitable for interpreting cement-treated soils. This study provides a comparative parametric assessment of four SCC parameters—destructuring index b , additional void ratio at initial yielding Δe_i , intrinsic compression index λ^* , and flow-rule parameter ω —using five sample-specific parameter sets derived from an underlying study of cement-treated residual sandy clay from Isheri, Nigeria. The reported undrained simulations indicate that b mainly changes the deformation trajectory associated with structural degradation; Δe_i affects the magnitude of deviatoric and volumetric deformation; λ^* governs intrinsic plastic compressibility; and ω modifies the plastic-flow/loading trajectory. Terminal deviatoric strength is comparatively insensitive to these four parameters in the reported responses and is more directly associated with the cementation-related cohesion parameter C and critical-state stress ratio M^* . Because the five sample parameter sets vary simultaneously, these observations are treated as comparative parameter-response evidence rather than formal isolated sensitivity coefficients. The study also identifies conflicting source entries that require verification before quantitative sensitivity indices are reported. The resulting framework separates strength-controlling from deformation-controlling parameters and provides a controlled one-at-a-time and global-sensitivity protocol for subsequent SCC calibration and validation.

Keywords - Structured Cam Clay; cement-treated soil; destructuration; additional void ratio; compression index; flow rule; undrained behaviour; constitutive modelling; parametric analysis; Isheri clay.

I. INTRODUCTION

Cement treatment modifies the mechanical response of fine-grained geomaterials through changes in bonding, fabric, stiffness, compressibility and strength. For constitutive modelling, these mechanisms should not be represented solely by an increase in apparent cohesion because cementation can also alter the deformation path and the rate at which initial structure is destroyed.

The Structured Cam Clay (SCC) model provides a critical-state framework for distinguishing intrinsic soil-skeleton behaviour from structure-dependent behaviour. In the underlying study, intrinsic parameters include M^* , e^*_{ic} , λ^* , κ^* and v^* , while b and Δe_i describe important aspects of structural behaviour. Here, λ^* represents intrinsic plastic compression, κ^* the elastic swelling response, b the destructuration-rate parameter, and Δe_i the additional void ratio associated with initial structure.

For cement-treated soil, the strength contribution is represented through a cementation-related cohesion parameter C , with the peak-strength relationship written as $q_{peak} = M^*p' + C$. This distinction is important because C directly contributes to the strength envelope, whereas b , Δe_i , λ^* and ω primarily affect the evolution of deformation, compressibility and plastic flow.

Recent constitutive studies increasingly represent cementation and structure through evolving internal variables, while anisotropic critical-state formulations emphasize the separation of yield-surface evolution from plastic-flow behaviour. The present paper therefore focuses on a narrower methodological question: which SCC parameters are primarily associated with strength, and

which primarily control the deformation path of cement-treated soil?

A. Research Gap

Existing SCC application to the Isheri materials provides sample-specific parameter values and simulated responses, but the comparison does not constitute a statistically controlled sensitivity experiment because several parameters change simultaneously between samples. The methodological gap is therefore the absence of a clearly separated interpretation of parameter effects and sample variability, together with a reproducible protocol for controlled sensitivity analysis.

B. Objectives

- Examine the reported effect of b , Δe_i , λ^* and ω on the undrained SCC response.
- Distinguish parameters primarily associated with strength from those associated with deformation and volume change.
- Identify limitations in interpreting sample-to-sample parameter differences as isolated sensitivity effects.
- Establish a controlled sensitivity-analysis protocol for subsequent SCC calibration and extension to cement-treated Isheri soil.

II. CONSTITUTIVE FRAMEWORK

The SCC framework represents the total void ratio as the sum of intrinsic and structure-related components:

$$e = e^* + \Delta e$$

where e^* is the intrinsic or reconstituted response and Δe is the additional void-ratio contribution associated with soil structure. The destructuring parameter b controls the rate at which the structure-related component changes during loading.

For cemented soil, the source formulation represents strength through the cementation-related cohesion parameter C :

$$q_{peak} = M^* p' + C$$

where q_{peak} is peak deviatoric stress, p' is mean effective stress, M^* is the intrinsic critical-state stress ratio, and C is the cementation-related strength contribution. The four parameters investigated here are therefore interpreted primarily through their reported influence on deformation and structural response rather than as direct strength increments.

A. Physical Interpretation of the Parameters

Parameter	Physical role in SCC	Primary response expected
b	Rate of destructuration	Stress-strain trajectory and structural degradation
Δe_i	Magnitude of initial structural void-ratio contribution	Deviatoric and volumetric deformation
λ^*	Intrinsic plastic-compression slope	Plastic compressibility and deformation
ω	Structure-related flow-rule modifier	Plastic-strain direction and loading trajectory
C	Cementation-related strength contribution	Peak/undrained strength
M^*	Critical-state stress ratio	Critical-state strength relationship

TABLE I. PHYSICAL INTERPRETATION OF THE SCC PARAMETERS

III. MATERIALS AND METHODS

A. Study Material

Five soil samples (S1–S5) obtained from the Isheri area of Ogun State, Nigeria, form the basis of the analysis. The underlying thesis reports disturbed and undisturbed sampling and physical/classification testing. The present paper uses the sample-level parameter sets reported in that work and does not introduce additional laboratory values.

B. Sample-Specific Parameter Sets

Sample	b	Δe_i	λ^*	κ^*	ω
S1	0.5	0.288	0.16	0.45	0
S2	0.6	0.408	0.22	0.43	1
S3	0.6	0.377	0.23	0.28	2
S4	5.0	0.309	0.30	0.28	4
S5	1.0	0.390	0.16*	0.39	5

TABLE II. SAMPLE-SPECIFIC SCC PARAMETER SETS USED IN THE COMPARATIVE ASSESSMENT

* The source material contains a conflicting λ^* value for S5 in another table. The value shown here is the one used in the present interpretation and must be verified against the original thesis calculation before submission.

C. Undrained Simulation Procedure

The source simulations evaluate deviatoric stress q against deviatoric strain ϵ_d and volumetric strain ϵ_v against ϵ_d for the

reported parameter sets. The analysis begins from the stress state specified in the underlying parametric study and follows the corresponding undrained loading path. The present manuscript retains the source simulation values for comparative interpretation rather than presenting new numerical simulations.

D. Definition of Sensitivity

Because S1–S5 do not vary one SCC parameter while all other parameters remain fixed, the present results are not reported as formal sensitivity coefficients. They are interpreted as comparative parameter-response observations. For a response R and parameter P , a normalized local sensitivity coefficient may be expressed as:

$$S_P = (\Delta R/R) / (\Delta P/P)$$

where R may represent peak q , deviatoric strain, volumetric strain or stiffness. Such a coefficient requires controlled perturbation of P around a common baseline.

E. Recommended Controlled Sensitivity Design

Stage	Procedure	Purpose
Baseline	Select one physically calibrated SCC parameter set	Reference response
Local OAT	Vary one parameter while all others remain fixed	Isolate individual influence
Range check	Use physically justified lower and upper bounds	Avoid nonphysical sensitivity
Interaction study	Use factorial or Latin-hypercube sampling	Quantify parameter interaction
Global analysis	Compute normalized/variance-based indices	Identify dominant parameters
Validation	Compare sensitive parameters with independent tests	Establish physical identifiability

TABLE III. RECOMMENDED CONTROLLED SENSITIVITY-ANALYSIS PROTOCOL

IV. RESULTS AND PARAMETRIC INTERPRETATION

A. Destructuring Index b

The reported b values range from 0.5 to 5.0. The simulations indicate that b mainly modifies the deformation trajectory associated with structural degradation rather than producing a direct systematic change in terminal deviatoric strength. Sample S4, with $b = 5.0$, exhibits a substantially different trajectory from samples with lower b . Because S4 also has different Δe_i , λ^* , κ^* and ω values, however, this observation cannot be treated as an isolated b effect.

B. Additional Void Ratio Δe_i

The reported Δe_i values range from 0.288 to 0.408. Larger Δe_i values are associated in the source simulations with greater deviatoric and volumetric deformation. The parameter therefore represents the magnitude of the initial structural contribution and is particularly important when the modelling objective is deformation or settlement rather than peak strength alone.

C. Intrinsic Compression Index λ^*

The reported λ^* values used in the parametric interpretation range from 0.16 to 0.30. Increasing λ^* is associated with greater plastic and volumetric deformation, while terminal deviatoric stress is comparatively insensitive in the reported responses. This

is consistent with λ^* being an intrinsic plastic-compressibility parameter rather than a direct critical-state strength parameter.

D. Flow-Rule Parameter ω

The reported ω values range from 0 to 5. The source simulations indicate that ω mainly modifies the loading trajectory and stiffness/flow response, with limited change in terminal strength and terminal volumetric strain. Its calibration should therefore be tied to stress-strain and volumetric response rather than peak strength alone.

E. Comparative Response

Parameter	Dominant reported effect	Effect on terminal q	Calibration implication
b	Structural degradation/deformation path	Limited	Tests sensitive to destructuration
Δe_i	Magnitude of structural deformation	Limited	Compression/volume-change response
λ^*	Intrinsic plastic compressibility	Limited	Intrinsic/reconstituted compression
ω	Plastic-flow/deformation trajectory	Limited	Stress-strain and volumetric response
C	Cementation-related strength	Direct	Strength response

TABLE IV. SUMMARY OF REPORTED PARAMETER EFFECTS AND CALIBRATION IMPLICATIONS

The principal constitutive observation is a separation between strength control and deformation control. The source results associate cementation-related cohesion C with strength, whereas b, Δe_i , λ^* and ω predominantly modify the deformation response. This separation can reduce parameter compensation during inverse calibration.

V. DATA QUALITY AND REPRODUCIBILITY

Three source-data issues require explicit resolution before submission. First, one source table reports a volumetric strain of 428.0% for S2 at $p' = 0.06 \text{ kN/m}^2$, whereas the corresponding structural-parameter table reports a substantially different value. Second, the source contains conflicting κ^* entries for S3. Third, λ^* for S5 is reported differently in separate tables. These entries should be checked against the original thesis calculations, laboratory records and numerical output.

The anomalous S2 value is not used to support a constitutive conclusion in this revised manuscript. To preserve reproducibility, the final submission should contain one verified parameter table, identify the exact simulation input associated with each response curve, and archive the numerical data used to generate the final figures.

VI. DISCUSSION

A. Strength versus Deformation Control

The reported responses suggest that SCC calibration should not attempt to determine all parameters from peak-strength data. Cementation-related C and M^* are associated primarily with strength, whereas b, Δe_i , λ^* and ω govern aspects of the deformation path. Consequently, a calibration strategy based only on matching peak q may produce non-unique combinations of structural and compressibility parameters.

B. Parameter Identifiability

The sample-to-sample comparison demonstrates why parameter identifiability is essential. The wide range in b, for example, cannot be attributed solely to destructuration because other material parameters also differ between samples. The same principle applies to Δe_i , λ^* and ω . Controlled numerical perturbation around a common calibrated baseline is therefore required to establish partial parameter effects.

C. Implications for Subsequent Anisotropic SCC Development

The present results provide a parameter hierarchy for the broader SCC development programme. Intrinsic compressibility should be constrained independently of structure; cementation should be calibrated from strength and bonding response; destructuration should be constrained from tests capable of resolving structural degradation; and the flow rule should be constrained using volumetric and directional strain response. Once these components are independently constrained, fabric anisotropy and stress-induced rotation can be introduced without allowing anisotropy parameters to compensate for poorly identified structural parameters.

VII. LIMITATIONS

- The available results are based on five sample-specific parameter sets rather than a statistically independent global sensitivity design.
- The present manuscript does not claim new experimental measurements or a new numerical constitutive implementation.
- The anomalous and conflicting source entries identified in Section V require verification before quantitative sensitivity indices are reported.
- The available simulations are principally undrained and therefore do not independently constrain all aspects of compressibility and flow-rule behaviour.
- Formal sensitivity indices and parameter-interaction measures require additional controlled simulations.

VIII. CONCLUSIONS

- The reported SCC simulations indicate that the destructuring index b primarily affects the rate and trajectory of structural degradation and deformation.
- The additional void ratio Δe_i has a pronounced influence on the magnitude of simulated deviatoric and volumetric deformation.
- The intrinsic compression index λ^* strongly affects plastic compressibility and deformation while showing limited influence on terminal deviatoric strength in the reported simulations.
- The flow-rule parameter ω primarily affects the deformation/loading trajectory rather than terminal strength.
- The four investigated parameters should not be treated as interchangeable strength parameters; cementation-related C is more directly associated with the cementation-induced strength contribution.
- Because the five source samples vary in several parameters simultaneously, the results should be regarded as comparative parametric evidence rather than formal isolated sensitivity coefficients.
- A controlled one-at-a-time and/or global sensitivity analysis, supported by verified input data and independent experimental validation, is required for a definitive quantitative sensitivity study.

IX. DATA AVAILABILITY

The numerical values analysed in this manuscript are derived from the author's thesis dataset. The complete verified laboratory dataset, constitutive-model input files and simulation output used to generate the final figures should be retained and, where permitted, deposited in an appropriate repository in accordance with journal requirements.

X. DECLARATIONS

A. Funding

No specific funding was received for this work.

B. Conflict of Interest

The author declares no conflict of interest.

C. Ethics Approval

Not applicable.

D. Author Contribution

Alhassan A. I. Conception, and interpretation of parameter dataset, performed the comparative parametric analysis, and prepared the manuscript.

Stephen A. O. laboratory testing and data compilation

Omenaimen Ikhide: Data Compilation and paper administration

REFERENCES

- [1] Z. Chen, "Experimental study on the evaluation in thermal-hydraulic-mechanical-chemical properties of cement-stabilized clay," PLOS ONE, vol. 19, no. 11, e0313760, 2024, doi: 10.1371/journal.pone.0313760.
- [2] H. Dejaloud and M. Rezaia, "Adaptive anisotropic constitutive modeling of natural clays," International Journal for Numerical and Analytical Methods in Geomechanics, vol. 45, no. 12, pp. 1756–1790, 2021, doi: 10.1002/nag.3223.
- [3] T. O. Ho, W. B. Chen, J. H. Yin, P. C. Wu, and D. C. W. Tsang, "Stress-strain behaviour of cement-stabilized Hong Kong marine deposits," Construction and Building Materials, vol. 274, 122103, 2021, doi: 10.1016/j.conbuildmat.2020.122103.
- [4] W.-F. Huang, Z.-J. Ruan, D.-B. Song, D.-L. Wang, and M.-Y. Cheng, "Experimental investigation of mechanical and microstructural properties of re-cemented clay," Acta Geotechnica, vol. 20, pp. 5113–5137, 2025, doi: 10.1007/s11440-025-02669-w.
- [5] A. Shirmohammadi and M. Hajialilue-Bonab, "Simulation of the behavior of structured clay using nonassociated constitutive model with and without anisotropic fabric at critical state," Journal of Engineering Mechanics, vol. 149, no. 3, 2023, doi: 10.1061/JENMDT.EMENG-6769.
- [6] J. Wu, L. Liu, Y. Deng, G. Zhang, A. Zhou, and Q. Wang, "Distinguishing the effects of cementation versus density on the mechanical behavior of cement-based stabilized clays," Construction and Building Materials, vol. 271, 121571, 2021, doi: 10.1016/j.conbuildmat.2020.121571.
- [7] S. Yamada, T. Sakai, M. Nakano, and T. Noda, "Method to introduce the cementation effect into existing elastoplastic constitutive models for soils," Journal of Geotechnical and Geoenvironmental Engineering, vol. 148, no. 5, 04022013, 2022, doi: 10.1061/(ASCE)GT.1943-5606.0002727.
- [8] Z. Zhang, M. Feng, G. Zhou, and Z. Xu, "A thermodynamic constitutive model for structured and destructured clays," Computers and Geotechnics, vol. 166, 105969, 2024, doi: 10.1016/j.compgeo.2023.105969.