Pertanika J. Sci. & Technol. 34 (4): 2181 - 2211 (2026)

SCIENCE & TECHNOLOGY

Journal homepage: http://www.pertanika.upm.edu.my/

Calibration and Limitations of Hardening Soil and Soft Soil Creep Models for Undrained Behaviour of Tropical Peat

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ABSTRACT

Tropical peat exhibits low shear strength, high compressibility and pronounced strain-softening behaviour, making reliable constitutive modelling essential for the analysis and design of embankments and foundations constructed under short-term undrained conditions. Although the Hardening Soil (HS) and Soft Soil Creep (SSC) constitutive models are widely implemented in PLAXIS, their capability to reproduce the complete undrained stress–strain response of tropical peat has not been systematically evaluated using laboratory-based calibration. This study investigates the performance and limitations of the HS and SSC models through numerical simulation of consolidated undrained (CU) triaxial tests conducted on undisturbed Pontian peat and associated very soft soils obtained from Mukim Rimba Terjun, Johor, Malaysia. Numerical simulations were performed in PLAXIS 2D using laboratory-derived constitutive parameters, followed by iterative calibration and quantitative evaluation using the Mean Absolute Error (MAE), Root Mean Square Error (RMSE) and coefficient of determination (R^2). The HS model successfully reproduced the nonlinear pre-peak stress–strain response and peak deviatoric stress mobilisation but was unable to simulate the progressive post-peak strength degradation observed in the laboratory tests because its constitutive formulation does not incorporate destructuration or damage evolution. In contrast, the SSC model provided a smooth viscoplastic response suitable for representing creep-related behaviour but consistently underestimated peak undrained shear strength. The apparent reduction in deviatoric stress predicted by the SSC model resulted from excess pore-water pressure generation and effective stress redistribution rather than true constitutive strain softening. Sensitivity analyses identified the effective friction angle (φ'), reference secant stiffness modulus (E_{50}, ref) and pre-overburden pressure (POP) as the dominant parameters governing the HS response, whereas the compression index (Cc), swelling index (Cs), secondary compression index (Cα)

ARTICLE INFO

Article history:
Received: 04 September 2025
Accepted: 12 June 2026
Published: 20 August 2026

DOI: https://doi.org/10.47836/pjst.34.4.11

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e-ISSN: 2231-8526

and stress-history parameters controlled the SSC response. The study establishes a laboratory-based constitutive calibration framework that distinguishes parameter-calibration uncertainty from constitutive-model limitations and provides practical guidance for selecting appropriate constitutive models for numerical analyses of tropical peat. The findings demonstrate that the HS model is more suitable for short-term undrained stability analyses, whereas the SSC model is more appropriate for long-term creep and settlement prediction.

Keywords: Consolidated undrained triaxial test, constitutive calibration, hardening soil model, numerical modelling, soft soil creep model, strain softening, tropical peat

INTRODUCTION

Tropical peat and soft clay deposits, which are mostly found in coastal Malaysia, have low shear strength, high compressibility, and considerable strain-softening behaviour (Huat et al., 2014; Mesri & Ajlouni, 2007). These characteristics hamper short-term stability evaluations of embankments, particularly during construction when undrained conditions prevail (Ladd, 1991). Laboratory consolidated undrained (CU) triaxial testing of such organic soils usually displays brittle peak strength mobilisation followed by significant post-peak strength loss (Leroueil et al., 1983; Leroueil & Vaughan, 1990). This strain-softening behaviour is associated with the progressive degradation of soil fabric, bonding, and organic constituents that impart structured or sensitive characteristics to the soil (Burland, 1990).

Newer constitutive models in PLAXIS, especially the Hardening Soil (HS) and Soft Soil Creep (SSC) models, provide a more realistic representation of nonlinear stress-strain behaviour than conventional elastic-perfectly plastic models (Brinkgreve et al., 2023; Schanz et al., 1999). Advanced constitutive soil models capture nonlinear stress-strain response, stress dependency and plastic hardening mechanisms beyond standard elastic-perfectly plastic formulations (Schanz et al., 1999; Brinkgreve et al., 2023). The HS model incorporates shear hardening and stress-dependent stiffness, whereas the SSC model primarily represents creep deformation under drained conditions (Vermeer & Neher, 1999). The applicability of these models for reproducing peak undrained shear strength and post-peak strain softening in tropical peat, however, remains an important practical and scientific issue (Potts & Zdravković, 1999; Wood, 1990).

Although the HS and SSC models have been widely applied in geotechnical analyses of soft soils, most previous studies have concentrated on settlement prediction, consolidation behaviour, or long-term field performance. Recent peat-specific research likewise emphasises the distinct time-dependent stages of one-dimensional creep consolidation (Peng et al., 2024). Comparatively few investigations have systematically calibrated these constitutive models against laboratory CU triaxial responses to evaluate their capability to reproduce peak strength mobilisation, post-peak strain softening, and residual strength behaviour of tropical peat. Consequently, the influence of key constitutive parameters governing undrained shear behaviour has not been comprehensively assessed using controlled laboratory data, limiting confidence in constitutive model selection for short-term stability analyses.

The scientific novelty of this study lies in establishing a laboratory-based constitutive calibration framework for evaluating the performance of the HS and SSC models using consolidated undrained triaxial test results obtained from tropical peat. Rather than focusing solely on matching numerical and experimental stress-strain curves, the study systematically evaluates the ability of each constitutive model to reproduce the governing deformation mechanisms associated with peak strength mobilisation, strain softening, and residual strength development. Furthermore, a comprehensive parameter sensitivity analysis is undertaken to identify the dominant constitutive parameters controlling the simulated undrained shear response, thereby providing a more rigorous understanding of constitutive model behaviour for tropical peat.

Accordingly, the objectives of this study are to (i) evaluate the capability of the HS and SSC constitutive models to simulate the undrained stress-strain behaviour of Pontian tropical peat using laboratory CU triaxial test results, (ii) establish a systematic laboratory-based calibration methodology for both constitutive models, (iii) investigate the sensitivity of the principal constitutive parameters governing peak strength mobilisation and stiffness response, and (iv) identify the practical capabilities and limitations of the HS and SSC models for short-term geotechnical engineering applications involving tropical peat. The findings are expected to provide practical guidance for constitutive model selection and calibration in finite element analyses of embankments and other infrastructure founded on tropical peat and very soft clay deposits.

MATERIALS AND EXPERIMENTAL PROGRAMME

Site Description, Soil Sampling and Peat Characterisation

The study area is located at Mukim Rimba Terjun, Pontian, Johor, Malaysia, where extensive deposits of tropical peat overlie extremely soft clay. The geological conditions, groundwater profile and laboratory testing programme were established through a site investigation undertaken by Sejati Teguh Engineering Sdn. Bhd (2023). The location of the study area is shown in Figure 1.

Undisturbed soil samples were recovered from boreholes BH1 and BH2 at depths ranging from 4.0 to 5.0 m using thin-walled sampling tubes to minimise disturbance.

These samples were subsequently used for laboratory determination of the physical, index and engineering properties, as well as for the consolidated undrained (CU) triaxial and incremental loading (IL) oedometer tests presented in this study.

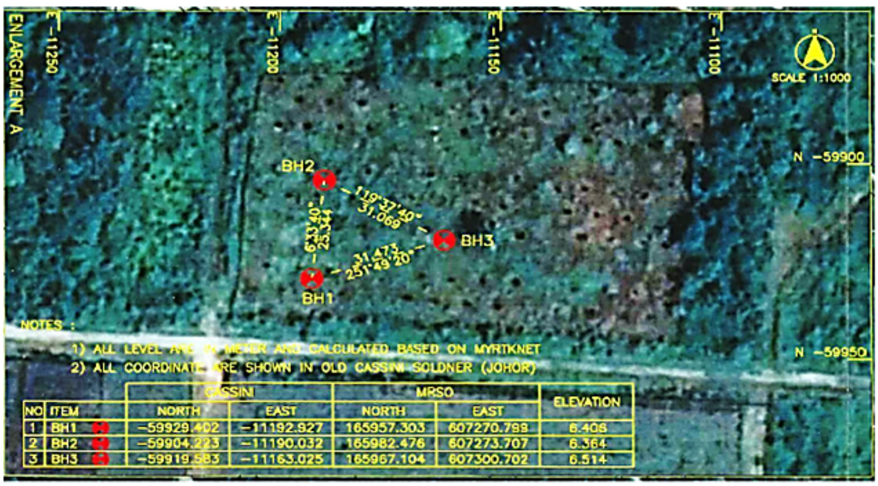

Figure 1. Location of the study area at Mukim Rimba Terjun, Pontian, Johor

The Pontian deposit consists predominantly of highly organic peat with a loose fibrous structure, very high natural water content, high void ratio and low bulk density. These characteristics result in low shear strength, high compressibility and significant deformation under relatively small, applied stresses, making tropical peat one of the most challenging geomaterials for engineering construction. Classification testing followed BS 1377-2:1990 (British Standards Institution, 1990a). Based on the Unified Soil Classification System (USCS), the material is classified as highly organic soil (Pt), while the underlying clay is classified as CH. The measured physical and index properties are summarised in Table 1.

Consolidated Undrained (CU) Triaxial Testing

CU triaxial compression tests on undisturbed Pontian peat samples were conducted to determine the short-term undrained shear behaviour and strain-softening characteristics. The laboratory testing programme was performed by Soilpro Technical Services Sdn. Bhd. in accordance with BS 1377-8:1990 (British Standards Institution, 1990c), Clauses 4-7, using undisturbed specimens obtained from boreholes BH1 and BH2 at depths of 4.0 m (BH1-UD4) and 5.0 m (BH2-UD5), respectively.

Table 1
Physical, index and classification properties of representative Pontian peat and soft soil specimens

Specimen	Borehole	Depth (m)	Soil Type	Natural Water Content, w (%)	Bulk Density (Mg/m^3)	Dry Density (Mg/m^3)	Organic Matter (%)	Liquid Limit, LL (%)	Plastic Limit, PL (%)	Plasticity Index, PI (%)	Initial Void Ratio, e_0	USCS
BH1-UD1	BH1	0.00	Peat	379	1.02	0.21	85.25	–	–	–	11.75	Pt
BH1-UD2	BH1	1.50	Peat	550	0.97	0.15	80.22	–	–	–	11.49	Pt
BH1-UD3	BH1	3.00	Peat	688	1.06	0.13	43.03	–	–	–	10.23	Pt
BH1-UD4	BH1	4.00	Silty Clay	133	1.28	0.55	2.55	95	35	60	5.57	CH
BH1-UD6	BH1	6.45	Silty Clay	126	1.32	0.71	7.62	96	34	64	6.08	CH
BH2-UD4	BH2	4.00	Silty Clay	104	1.23	0.54	2.29	97	37	60	5.91	CH
BH2-UD5	BH2	5.00	Peat/Silty Clay	126	1.30	0.64	–	–	–	–	3.85	OH–CH

Note. Pt = Peat; CH = Inorganic clay of high plasticity (USCS); OH–CH = Transitional organic clay/high-plasticity clay. Bulk density, dry density, moisture content, Atterberg limits, organic matter content, and initial void ratio were obtained from the Pontian Site Investigation laboratory records and laboratory testing programme. Missing values (-) indicate that the corresponding test was not performed for that specimen

Cylindrical specimens measuring 50 mm in diameter and 100 mm in height, corresponding to a height-to-diameter ratio of 2:1, were prepared for testing. Tests were performed under isotropic effective confining pressures of 30, 60 and 120 kPa, representing stress levels commonly encountered beneath shallow embankments and foundation systems constructed on tropical soft soils.

Before consolidation, the specimens were fully saturated using a back-pressure saturation procedure. The degree of saturation was assessed using Skempton's pore-pressure parameter (B-value), with measured values ranging from approximately 0.91 to 1.00, indicating that essentially full saturation had been achieved before isotropic consolidation. The specimens were subsequently isotropically consolidated to the target effective confining pressures according to conventional laboratory procedures (Ladd & DeGroot, 2003; Lade, 2005). During the consolidation stage, pore-water pressure dissipation and specimen volume changes were continuously monitored until equilibrium conditions were reached. Following consolidation, undrained axial compression was applied under strain-controlled loading while axial deformation, deviator stress, pore-water pressure and effective stresses were continuously monitored throughout the shearing stage. Although the laboratory reports did not explicitly specify the applied axial strain rate, the testing programme followed the loading procedures prescribed in BS 1377:1990 for consolidated undrained triaxial compression testing. The tests were continued to approximately 20% axial strain, enabling both peak strength mobilisation and post-peak behaviour to be captured for subsequent numerical calibration.

Figures 2 and 3 present the measured stress–strain responses of specimens BH1-UD4 and BH2-UD5, respectively. Peak deviatoric stress was mobilised at relatively small axial strains (approximately 2-6%), followed by a progressive reduction in shear resistance with continued deformation towards a residual strength. This response is characteristic of structured and relatively sensitive tropical soils, where progressive degradation of soil fabric and interparticle bonding during undrained shearing produces strain-softening behaviour (Leroueil

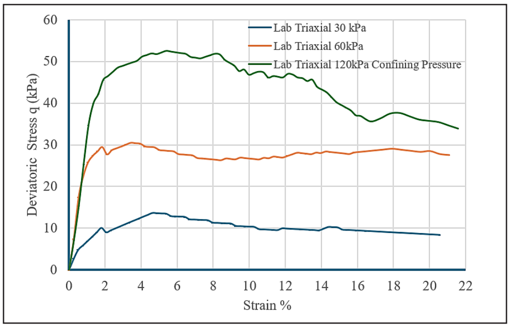

Figure 2. Consolidated undrained (CU) triaxial stress-strain response of Pontian soil sample BH1-UD4 under confining pressures of 30, 60, and 120 kPa. Peak deviatoric stress is mobilised at approximately 2-5% axial strain, followed by progressive post-peak strength reduction, indicating strain-softening behaviour characteristic of structured tropical soft soils

et al., 1983; Tavenas et al., 1983). The laboratory responses shown in Figures 2 and 3 constitute the reference datasets used throughout this study for calibration and evaluation of the Hardening Soil (HS) and Soft Soil Creep (SSC) constitutive models.

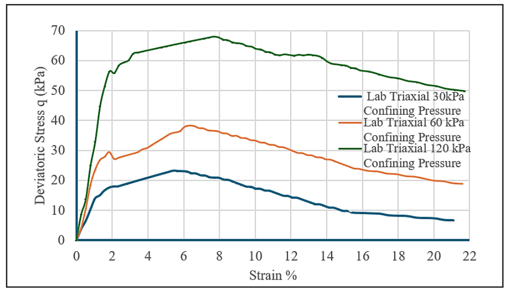

Figure 3. Consolidated undrained (CU) triaxial stress-strain response of Pontian soil sample BH2-UD5 under confining pressures of 30, 60, and 120 kPa. Distinct peak strength mobilisation is followed by gradual degradation towards residual strength, providing the experimental benchmark for calibration and evaluation of the Hardening Soil (HS) and Soft Soil Creep (SSC) constitutive models

NUMERICAL MODELLING FRAMEWORK

Constitutive Model Calibration Strategy

The numerical simulation of tropical peat presents a significant challenge because its mechanical behaviour is governed by nonlinear stress-strain behaviour, stress history, compressibility and, in some cases, time-dependent deformation. Consequently, constitutive model parameters cannot be adopted directly from empirical correlations or generic databases without verification against laboratory observations (Duncan & Chang, 1970; Kulhawy & Mayne, 1990; Wood, 1990). Instead, a laboratory-based calibration strategy was adopted to ensure that the numerical models accurately represented the measured behaviour of the Pontian tropical peat investigated in this study.

The calibration strategy was developed to establish physically meaningful constitutive parameters for the Hardening Soil (HS) and Soft Soil Creep (SSC) models using laboratory-derived soil properties as the primary source of input. Rather than relying solely on empirical parameter fitting, the approach sought to preserve the engineering significance of the measured soil properties while achieving satisfactory agreement between the numerical predictions and the observed laboratory responses. Such an approach improves both the transparency and reproducibility of constitutive model calibration and is widely recommended for advanced geotechnical numerical analyses (Brinkgreve et al., 2023; Potts & Zdravković, 1999).

The HS and SSC constitutive models were selected because they represent two complementary aspects of soft soil behaviour. The HS model incorporates stress-dependent stiffness, nonlinear elasticity and plastic hardening, making it suitable for simulating the short-term undrained stress-strain response and peak strength mobilisation observed during consolidated undrained (CU) triaxial testing (Schanz et al., 1999). In contrast, the SSC model extends the Soft Soil formulation by incorporating time-dependent viscoplastic deformation, enabling the simulation of creep and long-term compression behaviour (Vermeer & Neher, 1999). Although the SSC model was originally developed for consolidation and creep analyses, its response under undrained loading was also evaluated to examine its capability and limitations in reproducing the laboratory triaxial behaviour of tropical peat.

The calibration strategy focused on reproducing the principal features of the laboratory CU triaxial response, including the initial stiffness, peak deviatoric stress mobilisation, overall stress–strain behaviour and post-peak response. Emphasis was placed on identifying the constitutive parameters that exert the greatest influence on the simulated undrained behaviour through systematic sensitivity analyses. Because constitutive parameters are influenced by soil type, stress history, sampling disturbance and depositional environment, the calibrated parameter values presented in this study are considered representative of the investigated Pontian tropical peat and should not be transferred directly to other sites without appropriate verification (Ladd, 1991; Lade, 2005). Nevertheless, the calibration methodology itself provides a systematic and transferable framework for constitutive model selection and parameter calibration using laboratory test data.

Based on this calibration strategy, an axisymmetric finite element model was developed in PLAXIS 2D to reproduce the laboratory CU triaxial testing conditions. The numerical model configuration is described in the following section.

Numerical Model Development

Axisymmetric finite element models created in PLAXIS 2D replicated the cylindrical configuration of triaxial specimens (Figure 4). The dimensions of the specimens, including height and diameter, were aligned with laboratory measurements to maintain consistency in stress paths. The discretisation utilised 15-node triangular elements for quadratic displacement interpolation, ensuring an accurate nonlinear response. A refined mesh was implemented within the specimen to facilitate stable stress redistribution while keeping computational demands manageable.

The boundary conditions were designed to reflect laboratory constraints: the bottom was fixed in all directions, lateral boundaries were constrained radially to uphold confining pressure while permitting vertical deformation, and the axis of symmetry was restrained radially. Axial loading was applied by enforcing a prescribed vertical displacement at the top boundary, which effectively simulated strain-controlled shearing.

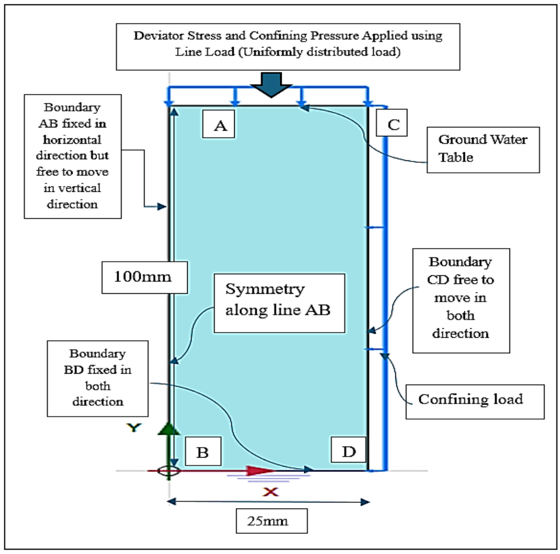

Figure 4. Axisymmetric finite element model adopted for the consolidated undrained (CU) triaxial simulation in PLAXIS 2D, showing specimen geometry, loading configuration and boundary conditions

Drainage boundaries permitted flow during consolidation to achieve the desired effective stress; these boundaries were then closed during shearing to impose undrained conditions, thereby facilitating appropriate pore pressure generation and maintaining volume constancy. Parameters used in the model were sourced from laboratory index and mechanical tests (Table 1) and further refined through calibration. Key parameters of focus included:

- Effective friction angle (φ′)
- Cohesion (c′)
- Pre-overburden pressure (POP)
- Stress dependency exponent (m)
- Reference secant stiffness modulus (E_{50}ref)

Calibration Procedure

The calibration of the Hardening Soil (HS) and Soft Soil Creep (SSC) constitutive models was carried out using a systematic laboratory-based procedure integrating laboratory testing, constitutive parameter interpretation, numerical simulation, sensitivity analysis and iterative back-analysis.

Unlike automated optimisation techniques, the calibration adopted in this study was performed through sequential manual refinement of constitutive parameters to preserve their physical meaning while achieving satisfactory agreement between laboratory observations and numerical predictions. Figure 5 illustrates the overall calibration workflow.

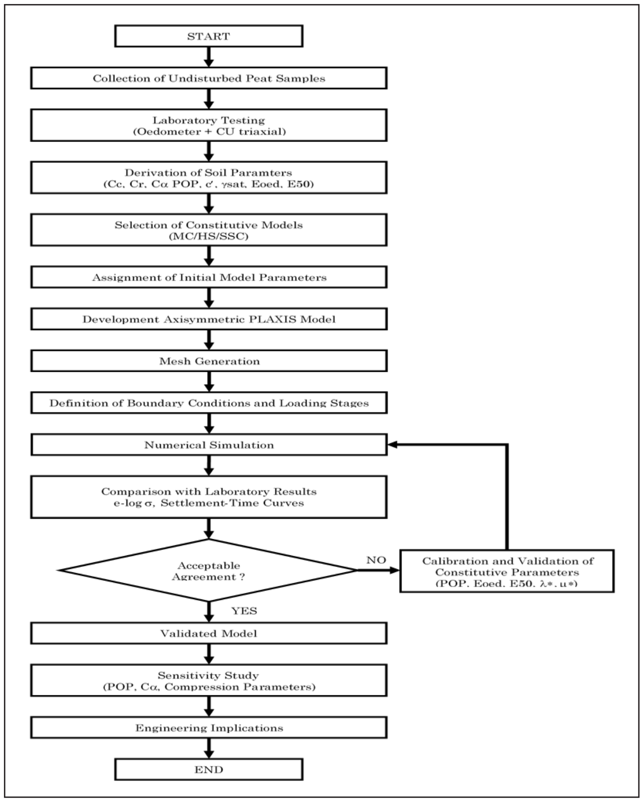

Figure 5. Calibration procedure adopted

The primary objective of the calibration procedure was to establish constitutive parameter sets capable of reproducing the measured laboratory behaviour while maintaining consistency with the physical properties of the tested Pontian tropical peat and associated soft soils. Initial constitutive parameters were derived directly from laboratory testing rather than empirical databases or published parameter ranges. Effective shear strength parameters, namely effective cohesion (c′) and effective friction angle (φ′), were interpreted from the consolidated undrained (CU) triaxial compression tests. The HS stiffness parameters, including the reference secant stiffness modulus (E_{50},ref), reference oedometer stiffness (Eoed,ref) and unloading–reloading stiffness modulus (Eur, ref), were obtained from the triaxial and incremental loading (IL) oedometer tests. For the SSC model, the compression index (Cc), swelling index (Cs), secondary compression index (Cα), initial void ratio (e_0) and pre-overburden pressure (POP) were interpreted from IL oedometer tests conducted in accordance with BS 1377-5:1990 (British Standards Institution, 1990b), while the permeability coefficients (kx and ky) were obtained from laboratory measurements and site investigation data where available.

The laboratory-derived parameter sets were subsequently implemented in PLAXIS 2D using an axisymmetric finite element model that replicated the laboratory specimen geometry, loading conditions and drainage conditions. Numerical simulations were performed for both the CU triaxial and IL oedometer tests, enabling direct comparison between the measured laboratory responses and numerical predictions. For the CU simulations, the calibration focused primarily on reproducing the nonlinear stress–strain response, peak deviatoric stress mobilisation and post-peak behaviour. For the IL oedometer simulations, calibration focused on reproducing the void ratio–log effective stress relationship, compressibility characteristics and stress-history behaviour.

Calibration was performed using a sequential one-at-a-time parameter adjustment strategy. Only those constitutive parameters identified through preliminary sensitivity analyses as having a significant influence on the numerical response were modified during each calibration stage. For the HS model, calibration concentrated principally on the reference stiffness parameters (E_{50}, ref and Eoed, ref) together with the pre-overburden pressure (POP), while maintaining the laboratory-derived effective strength parameters. For the SSC model, refinement focused mainly on the compression index (Cc), swelling index (Cs), secondary compression index (Cα), permeability coefficients (kx and ky) and POP. Parameters exhibiting relatively low sensitivity were retained at their laboratory-derived values to minimise unnecessary adjustment and preserve the physical significance of the constitutive models.

The calibration process was evaluated quantitatively using the Mean Absolute Error (MAE), Root Mean Square Error (RMSE) and coefficient of determination (R^2). Numerical predictions were interpolated to the same strain levels as the laboratory measurements, thereby ensuring direct point-by-point comparison between measured and simulated deviatoric stresses. MAE was used to quantify the average magnitude of prediction error, whereas RMSE provided greater sensitivity to larger deviations between the laboratory and numerical responses. The coefficient of determination (R^2) was used to assess the overall ability of each constitutive model to reproduce the observed stress–strain behaviour.

Calibration convergence was achieved when no physically reasonable one-at-a-time adjustment of the sensitive constitutive parameters produced a further reduction in RMSE without compromising agreement with the measured pre-peak stiffness, peak deviatoric stress mobilisation or the overall stress–strain response. This convergence criterion ensured that the final constitutive parameter sets remained physically realistic while avoiding unnecessary parameter adjustment solely to improve numerical curve fitting. Consequently, the final calibrated parameters represent the optimum balance between numerical accuracy and engineering realism.

The MAE and RMSE were calculated using Equation 1:

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n}\left|q_{\mathrm{exp},i} - q_{\mathrm{num},i}\right|$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(q_{\mathrm{exp},i} - q_{\mathrm{num},i}\right)^2} \qquad [1]$$

where $q_{\mathrm{exp,i}}$ is the experimentally measured deviatoric stress, $q_{\mathrm{num,i}}$ is the corresponding numerical prediction, and n is the total number of measurement points considered during calibration.

The present study is limited to laboratory-scale calibration and does not include independent field validation. Transfer of the calibrated parameters to instrumented embankments or foundations without numerical re-tuning is therefore identified as an essential next step in the Future Research section.

Summary of Model Input Parameters

The constitutive parameters adopted for the Hardening Soil (HS) and Soft Soil Creep (SSC) models were established primarily from laboratory testing and subsequently refined through the calibration procedure described in the preceding Calibration Procedure subsection. The selected parameters represent the engineering characteristics governing the short-term stress-strain behaviour, compressibility, stress-history effects and time-dependent deformation of the Pontian soft soil.

Table 2 summarises the principal constitutive parameters adopted for the numerical simulations together with their corresponding sources. The HS model parameters were primarily derived from the Consolidated Undrained (CU) triaxial compression tests and Incremental Loading (IL) oedometer tests. In contrast, the SSC model utilised laboratory-derived compressibility, creep and stress-history parameters interpreted from the oedometer tests. Where direct laboratory measurements were unavailable, selected parameters were estimated using established geotechnical correlations and subsequently refined through iterative numerical calibration, while maintaining consistency with observed laboratory behaviour.

The parameter ranges presented in Table 2 reflect the values investigated during the calibration process rather than fixed material properties. Final parameter selection was based on achieving satisfactory agreement between the measured and simulated laboratory responses while preserving the physical significance of each constitutive parameter. Parameters identified through sensitivity analyses as having limited influence on the numerical response were retained at their laboratory-derived values to minimise unnecessary adjustment during calibration.

For the CU triaxial simulations, undrained shearing was modelled under axisymmetric conditions using effective stress analysis. Since drainage was not permitted during shearing, permeability had a negligible influence on the predicted stress-strain response. Consequently, isotropic permeability was assumed, with the horizontal and vertical permeability coefficients set equal (kx = ky). This assumption is considered appropriate for reproducing the short-term undrained behaviour investigated in this study.

Table 2
Summary of soil parameters used in HS and SSC model calibration

Parameter	Symbol	Model	Source	BH1-UD4	BH2-UD5
Saturated unit weight (kN/m³)	γsat	HS / SSC	Index tests	12.8	13.2
Initial void ratio	e_0	SSC	IL oedometer	4.10	3.85
Compression index	Cc	SSC	IL oedometer	2.10-3.45	1.95-3.10
Swelling (recompression) index	Cs	SSC	IL oedometer	0.12-0.25	0.10-0.22
Secondary compression index	Cα	SSC	IL oedometer	0.015-0.030	0.014-0.028
Pre-overburden pressure	POP	HS / SSC	Casagrande method	15-25 kPa	18-28 kPa
Reference secant stiffness	E50, ref	HS	CU triaxial	2918 kPa	2375 kPa
Reference oedometer stiffness	Eoed, ref	HS	IL oedometer	817 kPa	910 kPa
Reference unloading-reloading stiffness	Eur, ref	HS	Calibration	8750-12500 kPa	7125-11875 kPa
Effective cohesion	c'	HS	CU triaxial	3-5 kPa	2-4 kPa
Effective friction angle	φ'	HS	CU triaxial	10-19°	10-24°
Poisson's ratio	v	HS / SSC	Calibration	0.47-0.55	0.46-0.57
Stress dependency exponent	m	HS	Calibration	0.65-1.00	0.70-0.95
Vertical permeability	ky	SSC	Falling-head test	Same as kx	Same as kx
Horizontal permeability	kx	SSC	Assumed isotropic	Same as ky	Same as ky

Note. It was assumed that permeability is isotropic ($k_x = k_y$) since the consolidated undrained (CU) triaxial simulations were conducted under conditions where drainage does not occur, and the magnitude of the permeability does not affect the anticipated shear stress-strain behaviour. During each simulation, parameter values were chosen from the specified ranges through a process of iterative calibration to accurately reflect the laboratory stress-strain response

RESULTS AND DISCUSSION

HS versus SSC Triaxial Response

The consolidated undrained (CU) triaxial tests demonstrated a characteristic response of tropical peat and associated very soft soils consisting of nonlinear stress-strain behaviour, distinct peak deviatoric stress mobilisation and progressive post-peak strength degradation with increasing axial strain. Numerical simulations using the Hardening Soil (HS) and Soft Soil Creep (SSC) constitutive models were evaluated against the laboratory results to assess their capability to reproduce these deformation mechanisms under effective confining pressures of 30, 60 and 120 kPa, as shown in Figures 6 and 7.

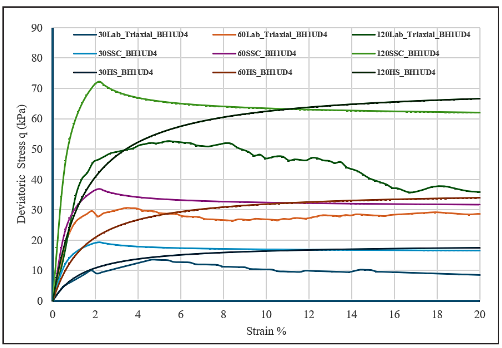

Figure 6. Comparison between laboratory and HS-SSC simulated CU triaxial stress-strain responses for sample BH1-UD4 (20% axial strain)

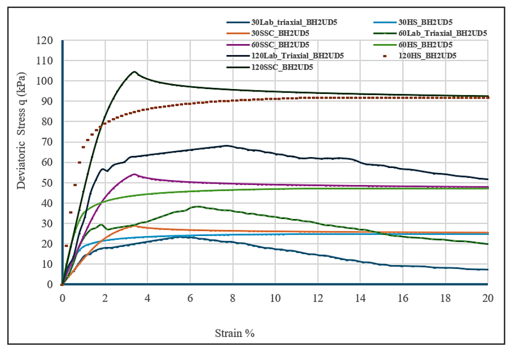

Figure 7. Comparison between laboratory and HS-SSC simulated CU triaxial stress–strain responses for sample BH2-UD5 (20% axial strain)

The HS model reproduced the initial nonlinear stiffness and peak deviatoric stress with good agreement for all confining pressures. The increasing peak strength observed experimentally with increasing confining pressure was also captured satisfactorily by the numerical simulations, indicating that the stress-dependent stiffness and isotropic hardening formulation incorporated within the HS model provides a realistic representation of pre-peak undrained behaviour. These characteristics are consistent with the constitutive framework developed by Schanz et al. (1999), in which stiffness evolves as a function of stress level while plastic strains accumulate progressively before failure. Consequently, the HS model provides reliable prediction of peak strength mobilisation and initial stiffness, both of which are critical for short-term stability analyses of embankments and foundations.

The SSC model exhibited a fundamentally different constitutive response. Rather than reproducing a distinct peak strength, the numerical simulations produced a comparatively smooth and ductile stress-strain relationship characterised by continuous viscoplastic deformation. Peak deviatoric stresses were consistently lower than those measured in the laboratory, particularly under higher confining pressures, confirming that the SSC model is not formulated to simulate rapid undrained strength mobilisation. Instead, the constitutive formulation emphasises time-dependent compression and creep through viscoplastic volumetric strains, making the model more suitable for long-term settlement analyses than short-term undrained loading.

Although both constitutive models generated reductions in deviatoric stress at larger strains, the underlying mechanisms differed fundamentally. In the HS model, the response stabilised after peak strength because the constitutive formulation contains only hardening mechanisms and no constitutive law describing progressive degradation of soil structure. In contrast, the gradual stress reduction predicted by the SSC model resulted from continued viscoplastic contraction under undrained conditions. As excess pore-water pressure accumulated, the mean effective stress decreased, and the effective stress path progressively approached the failure envelope, producing an apparent reduction in deviatoric stress through effective stress redistribution rather than through degradation of the soil skeleton itself (Vermeer & Neher, 1999). Consequently, superficially similar reductions in deviatoric stress predicted by the two models represent fundamentally different constitutive mechanisms.

The constitutive responses observed in the present study are consistent with previous investigations of peat and advanced creep models. Muraro and Jommi (2021) demonstrated that peat exhibits a strongly nonlinear triaxial response governed by stress path and evolving soil structure, reinforcing the need for laboratory-based constitutive calibration. Bhattarai et al. (2025) showed that the isotropic SSC formulation lacks the anisotropy and destructuration mechanisms incorporated in more advanced creep models. The present findings therefore support the view that HS and SSC represent different deformation mechanisms rather than providing a universal constitutive description of tropical peat.

Overall, the comparative assessment demonstrates that the HS and SSC models should be regarded as complementary constitutive formulations because each captures different deformation mechanisms relevant to tropical peat rather than providing a universal constitutive description. The HS model is more appropriate for analyses requiring realistic prediction of stiffness and peak undrained shear strength, whereas the SSC model is more suitable for problems governed by long-term creep, consolidation and settlement. Constitutive model selection should therefore be based on the dominant engineering mechanism controlling the problem under consideration.

Strain Softening and Residual Strength

The laboratory triaxial tests consistently exhibited progressive post-peak strength degradation following mobilisation of the peak deviatoric stress, ultimately approaching a residual-strength condition. Such behaviour is characteristic of structured tropical peat, in which shear resistance is progressively reduced through degradation of the organic soil fabric during continued undrained shearing. Unlike inorganic mineral soils, tropical peat derives much of its strength from its fibrous structure, organic bonding and the interaction between plant fibres and mineral particles. Progressive destruction of these structural components causes the soil skeleton to lose its ability to sustain peak shear resistance, resulting in constitutive strain softening and eventual mobilisation of residual strength.

Although the HS model accurately reproduced the initial stress-strain response and peak strength mobilisation, it was unable to simulate the subsequent post-peak degradation observed experimentally. This limitation arises from the constitutive formulation rather than from parameter calibration. The HS model incorporates stress-dependent stiffness together with isotropic shear hardening but contains no constitutive variables describing destructuration, bond degradation, fibre breakage, strain localisation or progressive damage evolution. Consequently, once peak strength has been mobilised, the numerical response either stabilises or exhibits only limited stress reduction. Further refinement of constitutive parameters may improve agreement before the peak but cannot generate true strain softening because the governing constitutive equations do not permit progressive reduction of material strength.

The behaviour predicted by the SSC model should likewise be interpreted carefully. Although gradual reductions in deviatoric stress occurred at larger strains, these do not represent constitutive strain softening. The SSC formulation was developed to describe time-dependent compression through viscoplastic volumetric deformation. Under undrained loading, continued viscoplastic contraction generates excess pore-water pressure because drainage is prevented. The resulting reduction in mean effective stress causes the effective stress path to migrate progressively towards the failure envelope, producing an apparent decrease in deviatoric stress. Consequently, the observed response originates from pore-pressure evolution and effective stress redistribution rather than degradation of the soil skeleton or progressive loss of constitutive strength.

The present observations agree with recent peat testing and creep-model comparisons. Muraro and Jommi (2021) showed that peat response is nonlinear and strongly dependent on the stress path and evolving structure. Bhattarai et al. (2025) further demonstrated that advanced creep formulations incorporate anisotropy and destructuration mechanisms that are absent from the isotropic SSC model. The present results extend these observations to Pontian tropical peat-associated soft soils: the inability of HS to reproduce strain softening and the apparent post-peak response of SSC arise from their constitutive formulations rather than from parameter calibration alone.

These findings demonstrate that the limitations identified in the present study cannot be eliminated simply through improved calibration. Laboratory-derived parameters may reduce prediction errors associated with stiffness and peak strength, but they cannot compensate for constitutive mechanisms that are absent from the mathematical formulation. Consequently, numerical analyses involving progressive failure, strain localisation or residual-strength mobilisation should consider more advanced constitutive models capable of representing anisotropy, destructuration, bond degradation and damage evolution. The laboratory-based calibration framework developed in this study, therefore, provides a practical means of distinguishing between parameter-calibration uncertainty and constitutive-model inadequacy, enabling more informed selection of constitutive models for geotechnical analyses involving tropical peat.

Quantitative Evaluation of Constitutive Model Calibration Performance

To complement the qualitative comparison between the laboratory and numerical oedometer responses, a quantitative evaluation of the Hardening Soil (HS) model calibration was performed using the Mean Absolute Error (MAE) and Root Mean Square Error (RMSE). These statistical indicators provide an objective assessment of the agreement between the measured and simulated one-dimensional compression behaviour. The MAE represents the average absolute deviation between the laboratory measurements and numerical predictions, whereas the RMSE assigns greater weight to larger discrepancies and is therefore more sensitive to local deviations in the compression curve. Lower values of both indices indicate closer agreement and a more reliable constitutive calibration.

Table 3 summarises the laboratory-derived pre-overburden pressure (POP), calibrated best-fit POP, percentage differences, and the corresponding MAE and RMSE values obtained for each oedometer specimen. The results demonstrate that the HS model successfully reproduced the measured compression behaviour for most of the tested specimens. Nine of the ten specimens achieved either Excellent or Very Good calibration performance, with an overall average MAE of 0.133 and RMSE of 0.188, corresponding to an overall Very Good classification. These results indicate that the laboratory-derived constitutive parameters required only limited refinement to achieve satisfactory agreement with the experimental compression curves.

Table 3
Quantitative performance assessment of hardening soil (HS) model calibration based on incremental loading (IL) oedometer tests

Sample	POPLab (kPa)	POPBest Fit (kPa)	POP Difference (%)	MAE	RMSE	Performance
BH1-UD1	27	23	-14.8	0.130	0.260	Very Good
BH1-UD2	19	5	-81.0	0.440	0.670	Good
BH1-UD3	12	6	-50.0	0.230	0.280	Very Good
BH1-UD4	9	5	-44.4	0.080	0.090	Excellent
BH1-UD5	12	7	-41.7	0.210	0.240	Very Good
BH1-UD6	22	27	+18.5	0.013	0.017	Excellent
BH1-UD7	20	25	+20.0	0.041	0.053	Excellent
BH1-UD8	14	17	+17.6	0.069	0.087	Excellent
BH1-UD9	24	20	-17.0	0.060	0.082	Excellent
BH2-UD4	15	7	-53.0	0.070	0.100	Excellent
Average	-	-	−24.6	0.133	0.188	Very Good

The highest calibration accuracy was obtained for specimens BH1-UD6, BH1-UD7, BH1-UD8, BH1-UD9, and BH2-UD4, all of which recorded MAE values below 0.07 and RMSE values below 0.10. Specimen BH1-UD6 exhibited the smallest prediction errors, with an MAE of 0.013 and an RMSE of 0.017, indicating excellent agreement between the laboratory measurements and the numerical simulation. These results demonstrate that the proposed calibration procedure is capable of accurately reproducing the one-dimensional compression characteristics of tropical peat and very soft clay.

In contrast, specimen BH1-UD2 produced the largest prediction errors, with an MAE of 0.440 and an RMSE of 0.670, together with an 81.0% reduction in the calibrated POP relative to the laboratory-derived value. Although this specimen exhibited the poorest agreement among the dataset, the numerical model nevertheless reproduced the overall shape of the compression curve within an acceptable engineering tolerance. The larger adjustment required for this specimen is attributed to uncertainties associated with stress-history interpretation and the inherent variability of tropical peat, where the determination of yield stress from oedometer tests is often influenced by sample disturbance, natural heterogeneity and the subjective interpretation of the Casagrande construction.

Comparison between the laboratory-derived and calibrated POP values further demonstrates that calibration adjustments were not uniform among the investigated specimens. Several specimens required reductions in POP, whereas others required modest increases to reproduce the measured compression response. This behaviour confirms that POP should not be regarded as a fixed laboratory value, but rather as a constitutive parameter that may require limited calibration within physically realistic bounds to accurately represent stress-history effects in numerical analyses. The relatively small deviations observed for most specimens indicate that the laboratory-derived POP values provide a sound initial basis for constitutive parameter selection.

Overall, the quantitative evaluation confirms that the proposed laboratory-based calibration methodology provides a reliable framework for determining HS model parameters from oedometer testing. The consistently low MAE and RMSE values obtained for most specimens demonstrate that the calibrated model successfully reproduces the principal features of one-dimensional compression behaviour while preserving the physical significance of the laboratory-derived parameters. Consequently, the calibrated parameter sets provide a robust foundation for subsequent finite element analyses and field-scale simulations involving tropical peat and very soft clay deposits.

Parameter Sensitivity Analysis

A methodological parameter sensitivity of the governing parameters of undrained shear response controlling Pontian peat in consolidated undrained (CU) triaxial models was determined through a systematic parameter sensitivity analysis. This part of the investigation analyses both the Soft Soil Creep (SSC) and Hardening Soil (HS) models, comparing them to their laboratory stress-strain patterns.

Influence of Effective Friction Angle (φ′)

Figures 8, 9 and 10 are SSC-simulated stress-strain responses for sample BH1-UD4 at the confining pressures of 30, 60 and 120 kPa, respectively, with different effective friction angles (φ′). Likewise, the results of sample BH2-UD5 are shown in Figures 11, 12 and 13.

We derive that for both samples and for all confining pressures, variation of φ′ causes a systematic, vertical shift of the deviatoric stress-strain curves that shows that φ′ is the primary stress-determinant parameter in SSC. Nevertheless, no distinct peak mobilisation and post-peak strain-softening behaviour is observed, even with increasing maximum stress. By contrast, the SSC model offers a smooth, ductile response that is nearly viscoplastic equilibrium stress-like.

This remark confirms that while φ′ has a decisive influence on the stress level in SSC simulations, it cannot be said to shape the basic shape of stress and strain which is under consideration in the formulation of viscoplasticity in the model. Therefore, the change of φ′ alone does not allow SSC to recover the prominent peak and post-peak degradations studied in laboratory CU triaxial studies.

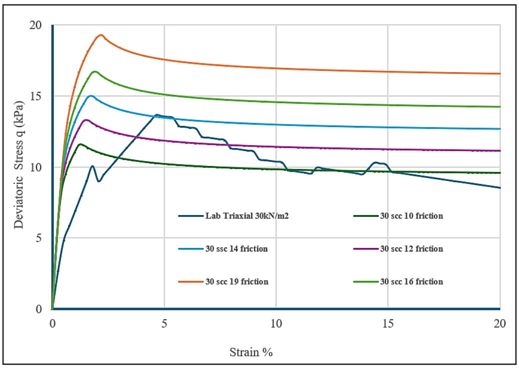

Figure 8. SSC-simulated CU triaxial deviatoric stress-strain response for sample BH1-UD4 with varying effective friction angle (φ′) under 30 kPa confining pressure (20% axial strain)

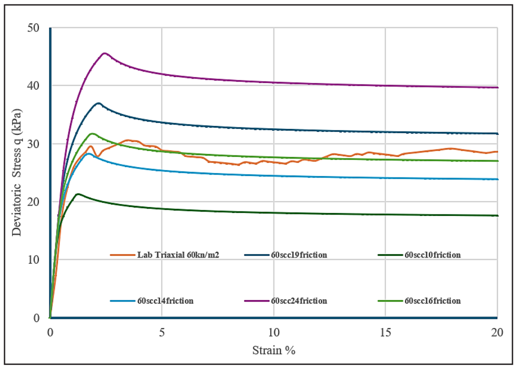

Figure 9. SSC-simulated CU triaxial deviatoric stress-strain response for sample BH1-UD4 with varying effective friction angle (φ′) under 60 kPa confining pressure (20% axial strain)

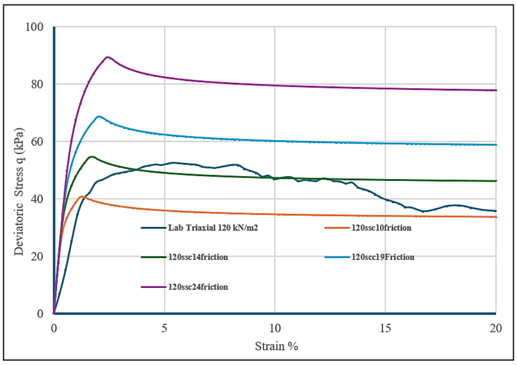

Figure 10. SSC-simulated CU triaxial deviatoric stress-strain response for sample BH1-UD4 with varying effective friction angle (φ′) under 120 kPa confining pressure (20% axial strain)

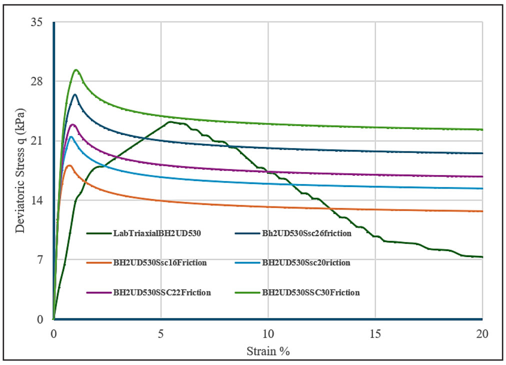

Figure 11. SSC-simulated CU triaxial deviatoric stress-strain response for sample BH2-UD5 with varying effective friction angle (φ′) under 30 kPa confining pressure (20% axial strain)

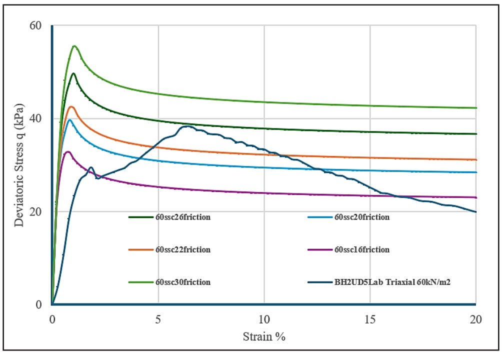

Figure 12. SSC-simulated CU triaxial deviatoric stress–strain response for sample BH2-UD5 with varying effective friction angle (φ′) under 60 kPa confining pressure (20% axial strain)

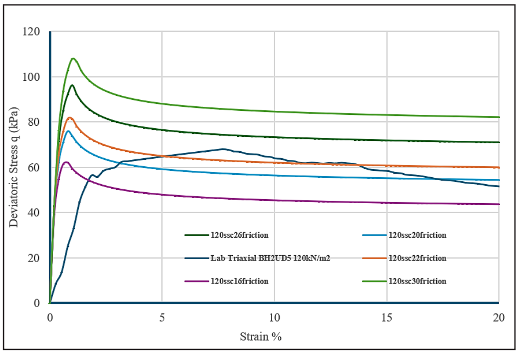

Figure 13. SSC-simulated CU triaxial deviatoric stress-strain response for sample BH2-UD5 with varying effective friction angle (φ′) under 120 kPa confining pressure (20% axial strain)

Influence of Reference Secant Stiffness (E_{50}ref)

Figure 14 and Figure 15 represent the influence of the reference secant stiffness modulus E_{50}ref (up to 20% and 5% axial strain in the HS model, respectively). E_{50}ref has a great impact on initial stiffness and strain mobilisation (most notably at small to medium axial strains).

Higher E_{50}ref values lead to steeper initial stress–strain slopes; lower E_{50}ref values induce more compliant responses. Nevertheless, the peak deviatoric stress magnitude remains constant. This further proves that E_{50}ref controls stiffness, rather than strength mobilisation (as expected under the HS model).

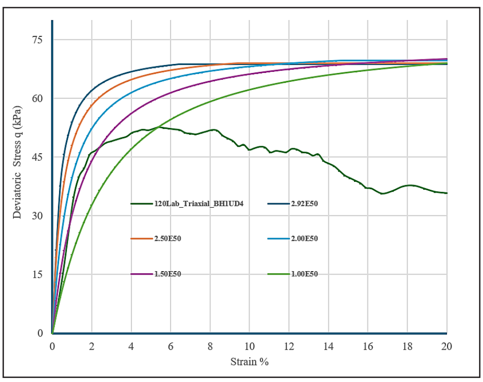

Figure 14. Effect of reference secant stiffness modulus (E_{50}, ref) on HS-simulated CU triaxial deviatoric stress-strain response for sample BH1-UD4 (20% axial strain)

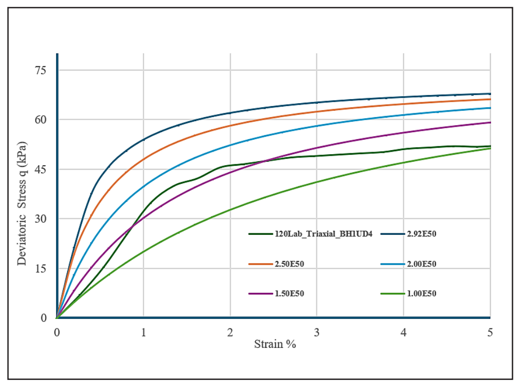

Figure 15. Effect of reference secant stiffness modulus (E_{50}, ref) on HS-simulated CU triaxial deviatoric stress-strain response for sample BH1-UD4 (5% axial strain)

Parameters with Limited Influence Under CU Triaxial Conditions

The effects of the stress dependency exponent (m) upon the HS-measured undrained shear under the applied consolidated undrained triaxial load are presented in Figure 16. Sensitivity analyses show that select parameters have a limited influence on the predicted undrained shear response in the HS model during consolidated undrained triaxial conditions. The effects of differences in the pre-overburden pressure POP mainly result in variability in volumetric yielding and stress history under one-dimensional

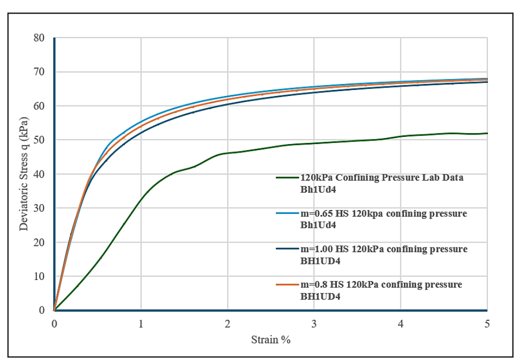

Figure 16. Effect of stress dependency exponent (*m*) on HS-simulated CU triaxial response for sample BH1-UD4 under 120 kPa confining pressure

compression, but do not directly have an impact on deviatoric stress mobilisation after isotropic consolidation. As a result, the variations in POP have a negligible effect on the deviatoric stress–strain response when CU triaxial loading occurs following isotropic consolidation.

Likewise, changes in the stress dependency exponent m in a realistic range as shown in Figure 16 also do not have a significant effect on the expected undrained shear response. The deviatoric stress-strain curves are approximately coincident, suggesting that, at varying confining pressures, m mainly controls stiffness evolution, rather than peak undrained shear strength at fixed confinement.

Implications for Model Calibration

The sensitivity analysis indicates that effective friction angle (φ′) is the most significant parameter controlling peak undrained shear resistance, while E_{50}ref controls stiffness and strain mobilisation. Parameters such as POP and m are indispensable in consolidation and stress-history-dependent problems yet have a limited influence on undrained triaxial shear response.

The results support targeting calibration effort towards φ′ and stiffness parameters in CU triaxial behaviour modelling, preventing unnecessary modification of parameters that do not strongly affect predicted stress-strain response. This enhances the efficiency of calibration and minimises the chances of compensating errors in numerical modelling. These results highlight that parameter sensitivity is highly influenced by stress path and loading mode, with conclusions resulting from CU triaxial calibration not being directly applicable to consolidation-dominated field problems.

Study Limitations and Sources of Uncertainty

Although the proposed laboratory-based calibration framework demonstrated good agreement between the measured and simulated responses, several sources of uncertainty should be recognised when interpreting the results. These uncertainties arise from the natural variability of tropical peat, laboratory testing procedures, constitutive parameter interpretation and simplifying assumptions adopted during numerical modelling. Acknowledging these limitations is important because constitutive model calibration does not produce a unique solution, and the predicted behaviour remains dependent on both the quality of the experimental data and the assumptions inherent in the constitutive formulations (Brinkgreve et al., 2023; Potts & Zdravković, 1999).

The first source of uncertainty is sampling disturbance. Tropical peat possesses a highly compressible and heterogeneous fibrous structure that is particularly susceptible to disturbance during drilling, sampling, transportation and specimen preparation.

Even when undisturbed sampling techniques are adopted, some alteration of the natural soil fabric is unavoidable. Such disturbance may reduce the apparent pre-overburden pressure (POP), modify stiffness characteristics and influence the measured undrained shear response obtained from laboratory testing. Consequently, the laboratory-derived constitutive parameters should be regarded as representative of the tested specimens rather than exact in-situ soil properties (Ladd & DeGroot, 2003). Recent studies continue to emphasise that sample disturbance remains one of the principal sources of uncertainty in the characterisation and design of soft soils.

A second source of uncertainty is laboratory variability. Tropical peat exhibits considerable spatial variability in fibre content, degree of decomposition, organic matter content, moisture content and density, even within relatively small areas. As a result, specimens obtained from adjacent boreholes or different sampling depths may exhibit significantly different compressibility, stiffness and shear-strength characteristics. Such variability contributes to the differences observed between the calibrated parameters of individual specimens and partly explains why certain specimens, such as BH1-UD2, required greater refinement during the calibration process. Therefore, the calibrated parameter values presented in this study should be interpreted as representative of the investigated Pontian peat rather than universally applicable values for all tropical peat deposits (Huat et al., 2014; Mesri & Ajlouni, 2007).

Another important source of uncertainty is parameter non-uniqueness. The Hardening Soil (HS) and Soft Soil Creep (SSC) constitutive models contain several interacting parameters that influence similar aspects of the predicted response. For example, the stiffness response predicted by the HS model is simultaneously affected by the reference secant stiffness (E_{50},ref), reference oedometer stiffness (Eoed, ref), stress dependency exponent (m) and pre-overburden pressure (POP). Likewise, long-term compression predicted by the SSC model depends on the combined influence of the compression index (Cc), swelling index (Cs), secondary compression index ($C\alpha$) and permeability coefficients. Consequently, different combinations of constitutive parameters may produce similarly acceptable numerical responses. To minimise this non-uniqueness, the present study adopted a laboratory-based calibration strategy in which most constitutive parameters were derived directly from laboratory testing, while only the most influential parameters identified through sensitivity analyses were refined during iterative calibration. This approach reduces subjective parameter adjustment and preserves the physical significance of the laboratory-derived parameters (Brinkgreve et al., 2023; Potts & Zdravković, 1999).

Finally, the numerical analyses incorporate several modelling assumptions that introduce additional uncertainty. The laboratory triaxial specimens were represented using an idealised axisymmetric finite element model with homogeneous material properties, isotropic permeability and ideal boundary conditions. Furthermore, the standard HS and SSC constitutive models implemented in PLAXIS do not explicitly incorporate anisotropy, destructuration, bond degradation, damage evolution or strain localisation, all of which may influence the mechanical behaviour of structured tropical peat. These simplifying assumptions are consistent with current engineering practice but inevitably limit the ability of the numerical models to reproduce every aspect of the observed laboratory behaviour. Consequently, the calibrated constitutive parameters should be interpreted within the scope of the adopted constitutive formulations and modelling assumptions rather than as unique material constants applicable to all loading conditions (Brinkgreve et al., 2023; Schanz et al., 1999; Wood, 1990).

Despite these limitations, the proposed calibration framework provides a systematic and transparent methodology for deriving constitutive parameters directly from laboratory testing while maintaining their physical significance. The integration of laboratory interpretation, sensitivity analysis, quantitative calibration using MAE and RMSE, and independent validation through numerical simulation improves confidence in the calibrated parameter sets and provides a robust basis for future finite element analyses involving tropical peat and other highly compressible soft soils. Nevertheless, future studies should investigate probabilistic calibration techniques, parameter uncertainty analysis and advanced constitutive models incorporating destructuration and anisotropy to further improve the predictive capability of numerical simulations.

Engineering Implications

The findings of this study demonstrate that constitutive model selection for tropical peat should be governed by the dominant engineering mechanism rather than by attempting to identify a single constitutive model capable of reproducing all aspects of soil behaviour. The laboratory results show that tropical peat exhibits highly nonlinear stress-strain behaviour characterised by distinct peak strength mobilisation, progressive strain softening and eventual residual-strength development. Since these deformation mechanisms arise from different constitutive processes, no single constitutive model available within the standard PLAXIS constitutive library can simultaneously reproduce the complete laboratory response.

For short-term geotechnical problems involving undrained loading, such as staged embankment construction, temporary excavations and bearing-capacity assessments, accurate prediction of peak undrained shear strength is essential because failure generally occurs before significant creep deformation develops. The Hardening Soil (HS) model reproduced the measured peak deviatoric stress and nonlinear stiffness response with satisfactory accuracy, demonstrating that its stress-dependent stiffness and isotropic hardening formulation is appropriate for analysing short-term stability. Nevertheless, engineers should recognise that the HS model cannot reproduce progressive post-peak strain softening or residual-strength mobilisation because its constitutive formulation does not include mechanisms describing destructuration, degradation of organic bonding, fibre breakage or damage evolution. Consequently, numerical analyses using the HS model may overestimate the available shear resistance after peak strength has been mobilised, particularly in problems involving progressive failure or large deformation.

Conversely, the Soft Soil Creep (SSC) model is more appropriate for engineering applications in which long-term deformation governs performance, including post-construction settlement, creep deformation and consolidation of embankments founded on tropical peat. The present study demonstrates that the SSC model reproduces the gradual evolution of stress associated with viscoplastic contraction and effective stress redistribution. However, the apparent reduction in deviatoric stress predicted during undrained loading should not be interpreted as true constitutive strain softening because it results primarily from excess pore-water pressure generation rather than progressive degradation of the soil skeleton. Accordingly, the SSC model should not be relied upon to evaluate short-term undrained stability or residual-strength mobilisation without independent verification against laboratory shear-strength data.

The sensitivity analyses further demonstrate that reliable numerical predictions depend on systematic laboratory-based calibration of constitutive parameters. For the HS model, the effective friction angle (φ′), reference secant stiffness modulus (E_{50}, ref) and pre-overburden pressure (POP) exert the greatest influence on peak strength mobilisation and stress–strain response. In contrast, the SSC model is governed primarily by the compression index (Cc), swelling index (Cs), secondary compression index (Cα) and stress-history parameters controlling long-term compressibility and creep deformation. These findings emphasise that constitutive parameters should be derived from high-quality laboratory testing and subsequently refined through controlled sensitivity analyses rather than adopted directly from empirical correlations or generic parameter databases.

The laboratory-based calibration framework developed in this study provides a transparent and reproducible methodology for constitutive parameter selection. By integrating laboratory testing, constitutive parameter interpretation, numerical back-analysis, sensitivity analysis and quantitative evaluation using MAE and RMSE, the proposed procedure enables engineers to distinguish between parameter-calibration error and limitations arising from the constitutive formulation itself. This distinction is important because improvements in parameter calibration cannot compensate for constitutive mechanisms that are absent from the mathematical model.

The present findings are consistent with recent studies of peat behaviour and creep-model selection. Muraro and Jommi (2021) demonstrated the importance of stress path and evolving structure in peat triaxial response, while Bhattarai et al. (2025) showed that SSC lacks the anisotropy and destructuration mechanisms included in more advanced creep formulations. These comparisons reinforce the need to align the selected constitutive model with the engineering objective rather than expecting one formulation to reproduce all aspects of tropical peat behaviour.

From an engineering perspective, the practical implication is that constitutive model selection should form part of the overall geotechnical design strategy. The HS model is recommended for evaluating short-term stability, peak undrained shear strength and construction-stage performance, whereas the SSC model is better suited for predicting long-term settlement, creep and consolidation. Where progressive failure, strain localisation or residual-strength mobilisation is expected to control engineering performance, the analysis should be supplemented by residual-strength evaluation and, where appropriate, more advanced constitutive formulations capable of representing anisotropy, destructuration or damage evolution. Such an approach provides a more realistic assessment of the behaviour of embankments, foundations and other infrastructure constructed on tropical peat and very soft clay deposits.

Constitutive model selection should therefore form part of the overall geotechnical design strategy rather than being treated solely as a numerical modelling decision. For short-term undrained stability, the HS model provides reliable prediction of stiffness and peak strength mobilisation. For long-term settlement and creep, the SSC model is more appropriate. Where progressive failure or residual-strength mobilisation governs performance, additional laboratory testing together with constitutive formulations capable of representing destructuration and damage evolution should be considered. This approach enables more reliable design of embankments, foundations and other infrastructure constructed on tropical peat and very soft clay.

Future Research

The present study established a laboratory-based constitutive calibration framework for evaluating the performance of the Hardening Soil (HS) and Soft Soil Creep (SSC) models in reproducing the undrained behaviour of Pontian tropical peat and associated soft soils. Nevertheless, several opportunities remain for extending this work.

First, future investigations should incorporate a larger number of undisturbed specimens collected from different depths and locations within tropical peat deposits. The current study is based on two representative specimens obtained from a single site in Pontian, Johor. Although these specimens adequately represent the investigated geological profile, a more extensive testing programme would enable statistical evaluation of spatial variability and improve the transferability of constitutive parameters to other tropical peat deposits.

Second, additional laboratory measurements should be undertaken to improve constitutive parameter determination. Direct measurement of fibre content, degree of decomposition, microstructural characteristics and controlled axial strain rates would provide a more comprehensive description of the mechanisms governing strain softening and compressibility. Such information could reduce uncertainty associated with constitutive parameter selection and improve the reproducibility of laboratory-based calibration.

Third, future research should investigate more advanced constitutive formulations capable of representing progressive degradation of structured organic soils. Although the HS model reproduced the nonlinear pre-peak stress-strain response with satisfactory accuracy, it could not simulate post-peak strain softening because its constitutive formulation does not include destructuration or damage evolution. Similarly, while the SSC model successfully represented creep-related behaviour, it was unable to reproduce the complete undrained stress–strain response. Recent reviews document continuing advances in time-dependent soil formulations (Liu et al., 2024). Constitutive models incorporating anisotropy, destructuration, bond degradation or damage evolution should therefore be evaluated to determine whether they provide a more realistic representation of tropical peat behaviour. Such models may include advanced research constitutive formulations that extend beyond the standard constitutive library available in PLAXIS.

Fourth, the laboratory-based calibration framework developed in this study should be validated using independent field case histories. Future studies should compare laboratory-derived constitutive parameters with monitored field performance from instrumented embankments and foundations without further parameter re-tuning. Such validation would provide a more rigorous assessment of the transferability of laboratory-calibrated parameters under realistic engineering conditions and strengthen confidence in their application to practical geotechnical design.

Finally, future numerical investigations should consider fully coupled hydro-mechanical analyses to evaluate the interaction between consolidation, excess pore-water pressure dissipation and long-term creep deformation during staged embankment construction. Recent studies show that coupled deformation-pore-pressure analysis and creep-aware consolidation formulations can improve the interpretation of soft-soil settlement and parameter uncertainty (Li et al., 2024; Huang et al., 2025). Integration of probabilistic calibration techniques with coupled numerical analyses would further enable quantification of parameter uncertainty and improve the reliability of constitutive model predictions for infrastructure founded on tropical peat.

Overall, these research directions would contribute to the development of more robust constitutive modelling strategies for tropical peat by integrating detailed laboratory characterisation, advanced constitutive formulations, field-scale validation and uncertainty quantification within a unified numerical modelling framework.

CONCLUSION

This study investigated the undrained shear behaviour of Pontian tropical peat through a combination of laboratory consolidated undrained (CU) triaxial testing and advanced finite element modelling using the Hardening Soil (HS) and Soft Soil Creep (SSC) constitutive models implemented in PLAXIS 2D. A laboratory-based constitutive calibration framework was developed to evaluate the capability of both models to reproduce the principal mechanisms governing the undrained response of tropical peat, including peak strength mobilisation, post-peak behaviour and parameter sensitivity.

The laboratory CU triaxial tests demonstrated that Pontian peat exhibits distinct peak deviatoric stress mobilisation at relatively small axial strains, followed by progressive post-peak strength degradation towards a residual-strength condition. This behaviour reflects the progressive degradation of the fibrous organic soil structure and provides the experimental benchmark for constitutive model calibration and evaluation.

The numerical simulations demonstrated that the Hardening Soil (HS) model reproduced the peak deviatoric stress and overall stress-strain response with good agreement over the range of confining pressures investigated. The HS model is therefore appropriate for evaluating short-term undrained stability and peak shear resistance. However, because its constitutive formulation is based on stress-dependent stiffness and isotropic hardening plasticity, it cannot reproduce the progressive strain-softening behaviour associated with destructuration and degradation of the soil microstructure.

In contrast, the Soft Soil Creep (SSC) model generated a smooth ductile stress–strain response without distinct peak strength mobilisation. The apparent reduction in deviatoric stress predicted by the SSC model under undrained loading was shown to result from creep-induced excess pore-water pressure generation and effective stress path evolution rather than true strain softening. Consequently, the SSC model is better suited to predicting long-term creep and settlement behaviour than peak undrained shear resistance or residual-strength mobilisation.

The sensitivity analyses identified the effective friction angle (φ'), reference secant stiffness (E_{50}, ref) and pre-overburden pressure (POP) as the most influential parameters governing the undrained response of the HS model, whereas the compression index (Cc), swelling index (Cs) and secondary compression index ($C\alpha$) exert the greatest influence on the long-term deformation behaviour predicted by the SSC model. These findings demonstrate that reliable constitutive modelling depends on careful laboratory-based parameter interpretation combined with systematic sensitivity analysis rather than extensive numerical parameter adjustment.

The principal contribution of this study is the development of a transparent laboratory-based constitutive calibration framework that integrates laboratory testing, sensitivity analysis and quantitative model evaluation using MAE and RMSE. This framework preserves the physical significance of laboratory-derived parameters while providing an objective methodology for calibrating advanced constitutive models for tropical peat.

Overall, the study demonstrates that no single constitutive model available within the standard PLAXIS constitutive library can simultaneously reproduce peak strength mobilisation, progressive post-peak strain softening and long-term creep behaviour of tropical peat. Consequently, constitutive model selection should always reflect the dominant engineering mechanism governing the problem under investigation. For short-term undrained stability analyses, the HS model is recommended, whereas the SSC model is more appropriate for long-term settlement and creep analyses. The proposed calibration framework provides practical guidance for finite element modelling of embankments, foundations and other infrastructure constructed on tropical peat and very soft clay deposits.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the financial support provided by the Ministry of Higher Education Malaysia under the Fundamental Research Grants Scheme (FRGS), Grant No. FRGS/1/2019/TK01/UNIMAS/02/2. The authors thank Universiti Malaysia Sarawak (UNIMAS) for providing the research premises and working space. Special thanks go to Sejati Teguh Engineering Sdn. Bhd. for providing the field and laboratory test data for this study. The authors also point out the invaluable involvement and commitment of all members of the research team, as well as the team members' contributions and dedication to research work during the preparation and development in the end.

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