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Influence of Strain-Softening Behaviour of Fissured Clays on Deep Shaft Excavations

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ABSTRACT: Deep shaft excavations present significant challenges in fissured clays, which are typically highly plastic and characterised by slickensides and fissures formed through weathering and consolidation. These soils exhibit strain-softening behaviour, where shear strength progressively decreases beyond a critical strain level, increasing the risk of instability. This paper outlines limitations of conventional constitutive models—such as Mohr-Coulomb and plastic hardening soil models—which cannot capture the post-peak strength degradation typical of fissured clays. To address this, an advanced strain-softening model developed by the lead author is introduced, improving accuracy in simulating the complex stress–strain response. Practical implementation is illustrated through a deep shaft project in Queensland, identifying cases where traditional models remain applicable in early design stages and where the advanced model becomes essential under significant softening. The study offers guidance for geotechnical engineers and presents a robust framework for managing strain-softening in deep shaft design and numerical modelling.

1 INTRODUCTION

Castellanos (2014) highlighted the importance of recognising the transitional zone between peak and residual strength in fissured clays, proposing a framework for incorporating strain-softening into practical design. This work serves as a foundation for current efforts in numerical implementation and calibration against field data.

Soft fissured clays present a unique challenge to deep excavation projects due to their complex stress-strain behaviour, particularly the pronounced strain-softening response post-peak strength. Conventional design approaches based on peak or residual strength often fail to capture the transitional degradation of strength mobilised during deformation. This oversight may lead to underestimations of ground movement and structural demands during deep shaft excavations.

Recent advances in numerical modelling have enabled the implementation of strain-softening constitutive laws into finite difference and finite element codes, offering a more realistic simulation of progressive failure mechanisms. This paper builds upon previous research on tunnelling-induced ground movement, including the findings of Purwodihardjo (2003) on the effect of strain-softening on settlement due to tunnelling, and applies a strain-softening soil model to evaluate its influence on deep shaft stability in fissured clays.

This paper first reviews traditional constitutive modelling approaches, including the linear elastic perfectly plastic Mohr-Coulomb model and the plastic hardening soil model. These methods are widely used due to their computational efficiency and simplicity; however, they fall short in capturing the progressive strength degradation and stress–strain complexity typical of fissured clays. To overcome these shortcomings, the paper introduces an advanced strain-softening model, developed by the lead author, specifically tailored to simulate the transitional stress–strain behaviour observed in such soils. The model incorporates laboratory-derived strength parameters and is implemented in FLAC to simulate the evolving behaviour of deep excavations. This enhanced modelling framework enables more accurate prediction of deformation profiles and support requirements by realistically capturing the transition from peak to residual strength conditions.

The paper also bridges theory with practice by exploring scenarios where traditional constitutive models can still be effectively applied and where the advanced strain-softening model becomes indispensable. A real-world case study of a deep shaft excavation in Queensland is presented, illustrating the practical implementation of these approaches. The case study highlights how traditional models can be utilised in preliminary assessments or for less critical excavation phases, while the advanced model is applied in critical zones to ensure safety and optimise design performance. Construction methodologies, including excavation sequencing and stabilisation techniques, are also detailed to demonstrate the integration of these models in practice.

By evaluating the strengths and limitations of both traditional and advanced modelling approaches, this paper provides valuable insights and guidance for geotechnical engineers in conducting numerical simulations and assessments, offering a balanced framework for managing strain-softening effects in deep shaft excavations.

2 CASE STUDY - FISSURED CLAYS ON DEEP SHAFT EXCAVATIONS

2.1 *Detail of the shaft*

The case study involves the construction of a 350-metre-deep ventilation shaft at an underground coal mine in the Bowen Basin, Central Queensland. The finished internal diameter was 5.0 metres, and excavation was conducted using staged blind boring with a 12 mm thick steel liner installed progressively.

Excavation proceeded in three stages: 7.3 m diameter to 37 m depth (Stage 1), 6.5 m diameter to 58 m depth (Stage 2), and 6.0 m diameter to 350 m depth (Stage 3). Corresponding liner inner diameters were 6.6 m, 6.1 m, and 5.0 m, respectively. The annular gap was backfilled with flowable grout or concrete. Before boring commenced, a 10-metre-deep presink was excavated using open trenching with a 45° batter from 0–2 m depth and 60° batter to the base. A 7.4 m diameter steel pre-collar liner was installed and concreted in place.

Throughout the boring process, drilling fluid (mud) was used to support shaft walls and lift cuttings. Its use was guided by preliminary numerical analysis that indicated instability risks without support. Drilling fluid properties were carefully designed and maintained to match the site-specific ground conditions and ensure excavation stability during boring and liner placement.

2.2 *Geological setting*

The site lies within the Bowen Basin in Central Queensland, a major coal-bearing basin extending approximately 600 km. The geology comprises Quaternary alluvium overlying Tertiary Suttor Formation sediments, which in turn overlie the Permian Fort Cooper and Moranbah Coal Measures.

The Suttor Formation—generally less than 60 m thick however locally up to 150 m—consists of quartz-rich sandstone, conglomerate, sandy and silicified claystone, weathered in places to clay, silt, sand, and gravel. In its eastern extent, it is interbedded with or overlies basalt flows. Prolonged deep weathering of this unit led to a lateritic profile, likely contributing to the development of fissuring in clay-rich layers.

Hyperspectral and XRD analysis (Yu et al.) identified kaolinite as the dominant mineral, although SEM–EDS revealed honeycomb microstructures resembling smectite.

2.3 *Fissured clays*

Fissured clays were primarily encountered within the Tertiary strata, however also in residual soils weathered from Permian rocks. These clays often contain slickensides and fissures formed from differential consolidation and weathering. Residual clays may retain bedding features from the parent rock.

High plasticity fissured clays near the surface or at buried paleo-surfaces display seasonal shrink–swell characteristics. Fissuring tends to increase with higher clay content, liquid limit, and over consolidation ratio.

Triaxial tests from the case study indicate pronounced strain-softening behaviour, marked by significant strength loss beyond a threshold strain, further discussed in Section 3.

2.4 *Interpreted ground conditions*

The cored borehole at the shaft location revealed:

- 0 – 0.2 m: Topsoil
- 0.2 – 10.0 m: Quaternary Alluvium
- 10.0 – 53.0 m: Tertiary Alluvium
- 53.0 – 57.0 m: Extremely weathered Permian sandstone;
- 57.0 – 64.0 m: Highly to Moderately weathered Permian sandstone;
- 64.0 – >64.0 m: Fresh Permian

For the geotechnical analysis, the above stratigraphy was further sub-divided into refined geotechnical units and simplified. The adopted geotechnical units and simplified stratigraphy for geotechnical analysis are presented in Tables 1 and 2 respectively.

Table 1. Adopted geotechnical units

Units	Geological Origin	Sub-Unit	Description
Q	Quaternary Alluvium	Q1C	Stiff Clay/sandy Clay
		Q2A	Very loose to loose Sand/clayey Sand
		Q2B	Medium dense to dense Sand/clayey Sand
T	Tertiary Alluvium	T2	Hard sandy Clay (fissured Clay)
		T3	Hard Clay (fissured Clay)
P	Permian	P1	Highly weathered very low strength Sandstone
		P2	Slightly weathered low to medium strength Sandstone
		P3	Fresh medium to high strength Sandstone

Table 2. Adopted stratigraphy

Layer No.	Unit	Top Depth (m)	Bottom Depth (m)
1	Q2A	0.0	1.5
2	Q1C	1.5	4.0
3	Q2B	4.0	10.0
4	T2	10.0	12.0
5	T3	12.0	14.0
6	T2	14.0	18.0
7	T3	18.0	22.0
8	T2	22.0	24.0
9	T3	24.0	26.0
10	T2	26.0	30.0
11	T3	30.0	48.0
12	T2	48.0	53.0
13	P1	53.0	57.0
14	P2	57.0	64.0
15	P3	64.0	>64.0

Groundwater levels from standpipe readings at the shaft location varied from 46.19m to 46.26m bgl.

3 MODELLING STRAIN-SOFTENING BEHAVIOUR OF FISSURED CLAYS

3.1 *Conventional constitutive model*

Traditional constitutive models widely used in geotechnical analysis include the linear elastic perfectly plastic Mohr-Coulomb model and the plastic Hardening Soil model. These models are favoured for their simplicity and computational efficiency and are often adequate for early design phases or where deformation is limited. However, both exhibit limitations in capturing the progressive failure mechanisms and post-peak strength degradation characteristic of fissured clays.

The Mohr-Coulomb model assumes constant shear strength parameters (cohesion c, friction angle, j) and a linear yield surface. While it can simulate ultimate limit states, it does not account for the reduction of strength with increasing strain. As a result, it cannot replicate strain-softening behaviour or the transition from peak to residual strength that occurs in slickensides, over consolidated clays.

The Hardening Soil model improves on this by introducing stress-dependent stiffness and plastic strain hardening, as well as separate stiffness moduli for loading, unloading, and reloading. However, it still lacks a mechanism to reduce strength once the peak is exceeded and therefore cannot simulate strain-softening behaviour.

To compensate for these shortcomings, one approach is to undertake separate analyses using peak and residual strength parameters to bracket possible system responses. However, this technique does not model the progressive nature of strength degradation. More sophisticated modelling involves applying a strain-softening constitutive model, which progressively reduces strength parameters as a function of plastic shear strain. This approach, adopted in the present study, is detailed in the following section.

3.2 *Advanced strain-softening model*

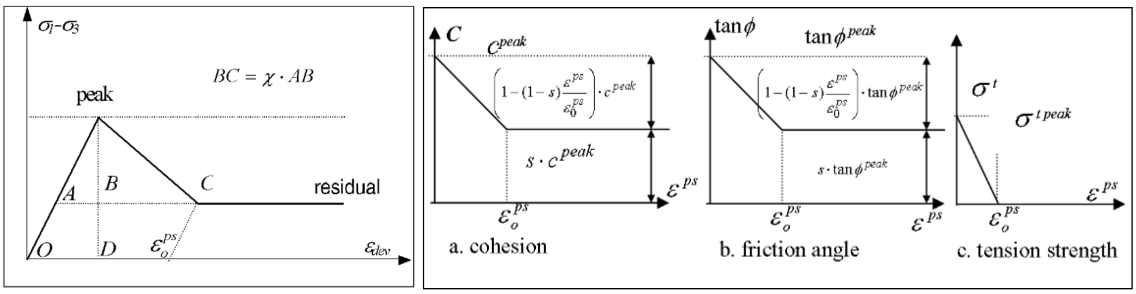
This model was developed by Purwodihardjo (1999, 2003) based on the main frame of the Mohr-Coulomb model with non-associated shear rule as described earlier. It is formulated within the Mohr-Coulomb framework and employs a non-associated flow rule. Unlike conventional models, it allows key yielding parameters, cohesion, friction angle, dilation angle, and tensile strength, to evolve as a function of accumulated plastic deviatoric strain (ε^p_dev) after yielding. These parameters may harden or soften, depending on material behaviour.

The yield and plastic potential functions are retained from the Mohr-Coulomb model. After the onset of plasticity, strength parameters are modified through a piecewise linear degradation model. This model comprises a softening branch, where parameters reduce from peak to residual, followed by a residual branch with constant values.

Two additional parameters are required: χ (the ratio of post-peak degradation to initial drop) and s (a scaling factor that governs the degradation slope). These are derived from triaxial tests and are key to replicating realistic strain-softening responses.

The model allows the evolution of shear strength and dilation angle to be described as follows:
- For ε^p_dev = 0 : c = c_peak, φ = φ_peak
- For 0 < ε^p_dev ≤ ε_0^{ps} : c and φ reduce linearly to residual values
- For ε^p_dev > ε_0^{ps} : c = c_res, φ = φ_res

Figures 1(a) and 1(b) illustrate the degradation path and yielding parameter relationships used in the simulations.



(a) (b)

Figure 1. Strain softening model (a) and yielding parameters defined (b)

Parameter identification and validation of this model have been extensively discussed in Purwodihardjo (1999, 2003), including application to axisymmetric triaxial test conditions. The model has been implemented via FISH scripting in FLAC to dynamically update strength parameters at the element level during plastic loading.

This advanced strain-softening model has been updated on the elastic part by adding a stress-dependent stiffness formulation for the elastic response, as illustrated below:

$$E_{ini} = E_{ini}^{ref}\left(\frac{c \cdot \cot\emptyset - \sigma_3}{c \cdot \cot\phi + p^{ref}}\right)^m \quad (1)$$

Where σ_3 refers to the minor principal stress, often representing the confining pressure in triaxial testing. The reference pressure, p^{ref} , denotes a reference stress, used to normalise the modulus. It is usually taken as 100 kPa.

3.3 *Triaxial Simulation of the Strain-Softening Behaviour of Fissured Clays*

Triaxial laboratory tests on fissured clays from units T2 and T3 were undertaken as part of the shaft geotechnical investigation. While Consolidated Drained (CD) tests are ideal for stiffness determination, Consolidated Isotropically Undrained (CIU) tests with pore pressure correction were used to expedite the programme. Five undisturbed samples were tested to failure under single stage loading as summarised in Table 3.

Table 3. summary of fissured clay samples for CIU triaxial test

Unit	Sample ID	Depth (m bgl)	Test Confining Pressure σ'_3(kPa)
T2	GT019b	10.30	199
	GT082	11.45	460
T3	GT083	19.50	780
	GT045	36.30	1000
	GT051	42.60	361

Test simulations were used to calibrate parameters for both the Plastic Hardening Soil (PHS) and Advanced Strain-Softening (ASS) models. PHS simulations used the PLAXIS 2D Soil Test feature, while the ASS model was implemented in FLAC 2D. The ASS model captured both peak and residual strengths in a single simulation, whereas the PHS model required separate runs for peak and residual envelopes. The assessed design parameters are summarised in Table 4 and Table 5 for PHS and ASS models respectively.

Table 4. Plastic Hardening Parameters (PHS) derived from triaxial test simulation

Unit	E_{50}^{ref} (MPa)	E_{oed}^{ref} (MPa)	E_{ur}^{ref} (MPa)	m	p_{ref} (kPa)	Peak Strength c'(kPa)	φ'(deg)	ψ(deg)	Residual Strength c'(kPa)	φ'(deg)	ψ(deg)	SR*
T2	120	120	360	0.8	100	1	36	0	0.5	32	0	0.85
T3	60	60	180	0.8	100	30	31	0	25	27	0	0.85

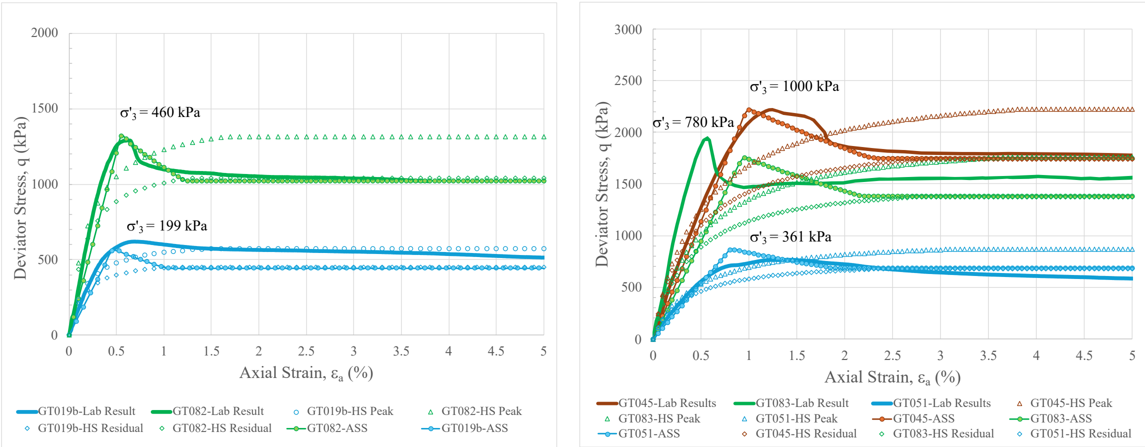
* SR = peak to residual strength reduction factor for both cohesion and internal friction angle (tan j')

Table 5. Advanced Strain Softening (ASS) parameters derived from triaxial test simulation

Unit	E_{ini}^{ref} (MPa)	m	p_{ref} (kPa)	Peak Strength c'(kPa)	φ'(deg)	ψ(deg)	Residual Strength c'(kPa)	φ'(deg)	ψ(deg)	χ	s*
T2	71.7	0.8	100	1	36	0	0.5	32	0	8.0	0.85
T3	48	0.8	100	30	31	0	25	27	0	8.0	0.85

* s = Peak to residual strength reduction factor for both cohesion and internal friction angle (tan j')

The results of the triaxial test simulations are presented in Figures 2 (a) and 2 (b) for fissured clay unit T2 and T3 respectively and the resulting parameters are summarised in Table 4 below.



(a) Unit T2 (b) Unit T3

Figure 2. Triaxial simulation results for Units T2 (a) and T3 (b)

The results confirm that the ASS model more accurately represents laboratory behaviour across the full strain range, particularly in capturing post-peak degradation. Unlike the PHS model—which requires separate analyses for peak and residual conditions—the ASS model simulates progressive strength loss in a single run, making it more suitable for fissured clays where residual strength drives deformation. Strength reduction was more pronounced under higher confining pressures, aligning with laboratory trends. Model parameters were conservatively selected to ensure simulated responses remained within or below observed test envelopes.

4 NUMERICAL ASSESSMENTS OF DEEP SHAFT EXCAVATIONS IN FISSURED CLAYS

Numerical assessments were performed using both PLAXIS 2D and FLAC 2D to leverage their complementary capabilities. The Plastic Hardening Soil (PHS) model, commonly used in practice, was implemented in PLAXIS for its intuitive interface and robust calibration tools. With the model now available in FLAC (since version 8.1), cross-platform consistency was also achieved.

The Advanced Strain-Softening (ASS) model, developed by the lead author, was implemented in FLAC via custom FISH scripting to simulate post-peak strength degradation. While PLAXIS enabled conventional PHS simulations, FLAC allowed advanced modelling tailored to strain-softening behaviour. This dual approach provided both industry-standard benchmarks and detailed insights into the progressive failure mechanisms of fissured clays.

4.1 *Shaft simulation using Plastic Hardening Soil Model - Plaxis*

Axisymmetric shaft excavation simulations through Units T2 and T3 were conducted in PLAXIS 2D to assess the Plastic Hardening Soil (PHS) model's capability in representing fissured clay behaviour. The analysis was limited to a depth of 58 m, capturing the critical zone of weak, strain-softening-prone clays between 10 m and 53 m. Although the full shaft extended to 350 m, the deeper Permian sandstone exhibited greater strength and stiffness, posing minimal deformation risk. The modelling therefore focused on the most vulnerable stratum where post-peak degradation governs performance.

The simulation followed the staged construction methodology applied on site:

- Phase 1: Open-cut excavation to 10 m depth with batter slope of 1V:1.5H.
- Phase 2: Installation of a 7.4 m internal diameter steel pre-collar liner.
- Phase 3: Blind bore excavation to 37 m depth using a 6.6 m diameter (assumed same as liner ID), executed in 4 m increments.

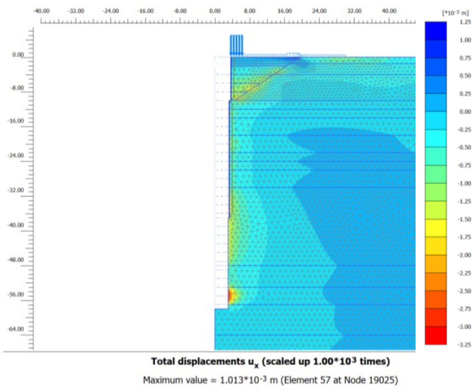
– Phase 4: Installation of 6.6 m ID steel liner.
– Phase 5: Blind bore excavation to 58 m depth using a 6.1 m diameter, also in 4 m increments.

Surcharge loads were applied in Phases 1–5 to replicate operational rig loads and ground surcharges. Uniform surcharge of 25 kPa was applied during the open excavation (Phases 1–2), while staged loadings ranging from 29 to 250 kPa were applied from Phases 3 to 5 to simulate the drilling rig's mass and operational influence near the shaft head.

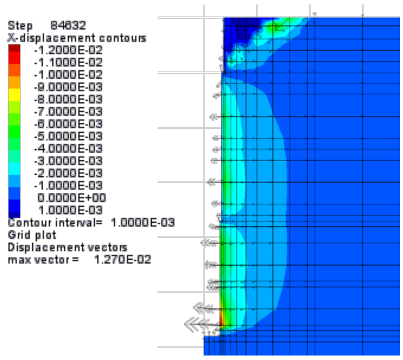
Initial simulations using peak strength parameters showed instability in unsupported conditions, particularly in Stage 1 where the excavation exceeded 6 m in diameter. Stability was restored by modelling a full-height water column to simulate drilling fluid support, enabling safe progression of the excavation and subsequent sensitivity analyses.

To explore the effect of strain-softening, sensitivity analyses were conducted by varying the strength reduction factor (SR). Values of 0.85, 0.5, 0.4, and 0.3 were applied to represent progressive degradation scenarios. The φ–c reduction method in PLAXIS 2D was then used to compute the Factor of Safety (FoS) for each case. Results show a clear trend: FoS drops from 4.78 (SR = 1.0) to 1.61 (SR = 0.3), indicating the impact of strength degradation on excavation stability.

Results clearly show that FoS decreases as SR lowers, with deformation increasing accordingly. As strain-softening progresses, reduced shear strength leads to ground movement. Figures 3a and 4a illustrates this trend. These outcomes highlight the importance of simulating post-peak behaviour realistically, especially in fissured and weathered clays where strength degradation controls performance.

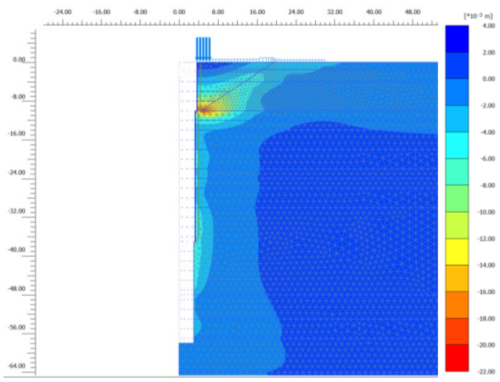


(a) Plaxis Simulation

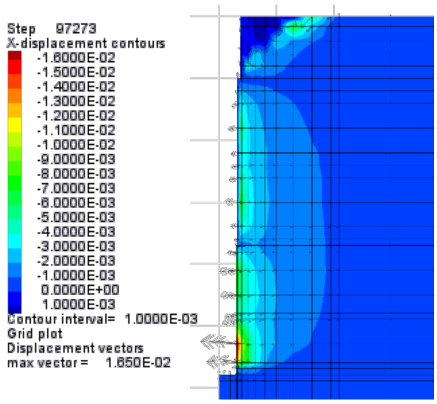


(b) Flac Simulation

Figure 3. Lateral deformation (in meters) at end of stage 2 blind bore – base case



(a) Plaxis simulation



(b) Flac simulation

Figure 4. Lateral deformation (in meters) at end of stage 2 blind bore – sensitivity case 4 (SR = 0.3)

4.2 *Shaft simulation using Advanced Strain-Softening Model - Flac*

FLAC 2D was used to simulate the shaft excavation using the Advanced Strain-Softening (ASS) model, developed by the lead author and implemented via FISH scripting. This custom model captures strength reduction as a function of accumulated plastic strain, allowing continuous transition from peak to residual strength in a single run.

The simulation adopted the same construction sequence and loading conditions outlined in Section 4.1, including staged excavation to 58 m and surcharge loads from 25 to 250 kPa. Model parameters—including peak and residual strengths and softening constants χ and s were derived from triaxial tests and are summarised in Table 5.

Results are shown in Figures 3b and 4b for SR values of 1.0 and 0.3, respectively. Under peak strength conditions, the ASS model yields greater deformation than the PHS model (Figures 3a vs 3b), due to its current limitation of not incorporating rebound stiffness—an important factor in excavation scenarios. However, at SR = 0.3, the ASS model produces less deformation than PHS (Figures 4a vs 4b), as it applies residual strength selectively, only where plasticity has developed, while the PHS model assumes residual strength throughout.

These results highlight the ASS model's ability to realistically simulate post-peak behaviour in fissured clays, offering a more accurate representation of spatially variable strength degradation compared to conventional approaches.

5 CONCLUSION

This study highlights the importance of selecting appropriate constitutive models for deep shaft excavation in fissured clays. The Plastic Hardening Soil (PHS) model, using separate simulations for peak and residual strengths, remains adequate when residual strength does not critically influence stability. However, in cases where strength degradation governs excavation response, this approach can significantly underestimate deformations.

The Advanced Strain-Softening (ASS) model addresses this limitation by capturing progressive strength loss within a single simulation. Results show that the ASS model offers a more realistic representation of post-peak behaviour and spatially variable degradation, making it more reliable in highly fissured and weathered clays.

Despite its strengths, the current ASS implementation lacks rebound stiffness modelling, which may overestimate deformation under peak strength conditions. Future refinement should focus on incorporating stress-dependent elastic recovery.

In practice, a combined modelling approach is recommended: using the PHS model for early-stage assessments and the ASS model for critical design zones. This strategy ensures more accurate prediction of deformation, stability, and support needs in soft ground conditions.

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