AD FALCON API Manual

SANICLAY Model (Saturated)

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1 SANICLAY Model (Saturated)

SANICLAY is an anisotropic critical-state constitutive model for saturated clays with evolving anisotropy tensors, a pressure-dependent elastic law, and non-associated plastic flow.

1.1 Syntax

Configure SANICLAY in `% Materials` with `@UMAT:` and category `Mechanical`.

Example:

```
@UMAT: path/to/SANICLAYModelUMAT.cpp path/to/SANICLAYModelUMAT.hpp
Mechanical \
    Nu=0.20 Kappa=0.009 Lambda=0.63 Mc=1.18 Me=0.86 N=0.91 x=1.56 C=16.0 \
    P_min=1e-6 STOL=1e-3 FTOL=1e-8 LTOL=1e-6 \
    CustomVariable=P0,Pa,OCR,initialvoidratio,AlphaXX,AlphaYY,AlphaZZ,
AlphaZY,AlphaZX,AlphaXY,BetaXX,BetaYY,BetaZZ,BetaZY,BetaZX,BetaXY
```

Write the full `@UMAT:` command on one line in the actual input file. For readability it is wrapped here.

Example inputs used on this page:

Case family	Input
Ko-consolidated undrained triaxial compression/extension	CKoUC.txt, CKoUE.txt
Isotropically consolidated undrained triaxial compression/extension	CIUC.txt, CIUE.txt
Drained triaxial compression	CKoDC.txt, CIDC.txt
Baseline single-element verification input	input.txt

1.2 Material parameters

1.2.1 Core model parameters

Symbol	Keyword in input	Required	Role
`nu`	`Nu`	Yes	Poisson ratio.
`kappa`	`Kappa`	Yes	Swelling or reloading index.

Symbol	Keyword in input	Required	Role
`lambda`	`Lambda`	Yes	Virgin compression index.
`M_c`	`Mc`	Yes	Critical-state stress ratio in triaxial compression.
`M_e`	`Me`	Yes	Critical-state stress ratio in triaxial extension.
`N`	`N`	Yes	Yield-surface shape parameter.
`x`	`x`	Yes	Anisotropy saturation parameter linking the two anisotropy tensors.
`C`	`C`	Yes	Rotational hardening rate parameter.

1.2.2 Numerical controls

Keyword in input	Required	Role
`P_min`	Yes	Positive floor for pressure-dependent terms.
`STOL`	Yes	Local stress-integration tolerance.
`FTOL`	Yes	Yield-surface tolerance.
`LTOL`	Yes	Load-unload detection tolerance.

1.3 Custom state variables

Declare SANICLAY history variables with `CustomVariable=`.

Name	Required	Role
`Po`	Yes	Isotropic yield-surface size or preconsolidation variable.

Name	Required	Role
`Pa`	Recommended	Plastic-potential size used by the non-associated formulation.
`OCR`	Yes	Initialization multiplier used to keep the current stress state on or inside yield after conditioning.
`initialvoidratio`	Yes	Initial void ratio used in the elastic and hardening laws.
`AlphaXX`, `AlphaYY`, `AlphaZZ`, `AlphaZY`, `AlphaZX`, `AlphaXY`	Recommended	Components of the anisotropy tensor `alpha`.
`BetaXX`, `BetaYY`, `BetaZZ`, `BetaZY`, `BetaZX`, `BetaXY`	Recommended	Components of the anisotropy tensor `beta`.

Recommended practice:

- Initialize `initialvoidratio` to the same value as the starting void ratio.
- Always provide the full `alpha` and `beta` tensors for staged or restarted analyses.
- Keep `OCR >= 1`.

1.4 Model summary

1.4.1 Elastic law

SANICLAY uses a pressure-dependent elastic bulk modulus with the initial void ratio held as a stored history variable:

$$K = \frac{(1 + e_{\text{in}})\, p}{\kappa}, \qquad G = \frac{3(1 - 2\nu)}{2(1 + \nu)}\, K$$

where `initialvoidratio` supplies `e_in`.

1.4.2 Yield surface

With the shifted deviatoric stress

$$\mathbf{t} = \mathbf{s} - p\, \mathrm{dev}(\boldsymbol{\beta}),$$

the yield function is written as

$$f = \bar{q}^2 - (N^2 - \beta^2)\, p\, (P_0 - p), \qquad \bar{q}^2 = \tfrac{3}{2}\, \mathbf{t} : \mathbf{t}.$$

1.4.3 Plastic potential

With

$$\mathbf{u} = \mathbf{s} - p\,\mathrm{dev}(\boldsymbol{\alpha}),$$

the non-associated plastic potential is

$$g = u^2 - (M^2 - \alpha^2)\,p\,(P_a - p), \qquad u^2 = \tfrac{3}{2}\,\mathbf{u} : \mathbf{u}.$$

1.4.4 Hardening variables

SANICLAY evolves:

- `Po` for isotropic hardening,
- `alpha` for the plastic-potential anisotropy,
- `beta` for the yield-surface anisotropy.

The model therefore needs both scalar and tensor history to be initialized consistently.

1.5 Initialization and conditioning

Before stress integration, SANICLAY conditions the history so the current state is admissible and consistent with the stored anisotropy.

Key points:

- `Po` is enlarged if required so the current stress point lies on or inside the yield surface.
- `Pa` is recomputed so the plastic potential passes through the current stress point.
- `OCR` provides an interior offset so the conditioned state is not placed exactly on the yield boundary unless intended.
- `alpha` and `beta` are kept within their admissible bounds so denominator terms remain positive.
- `initialvoidratio` should remain consistent with the elastic compression law when `Po` is reset during conditioning.

For staged analyses, define the initial stress field and custom variables consistently before the first constitutive update.

1.6 Validation inputs

The supplied single-point validation set covers:

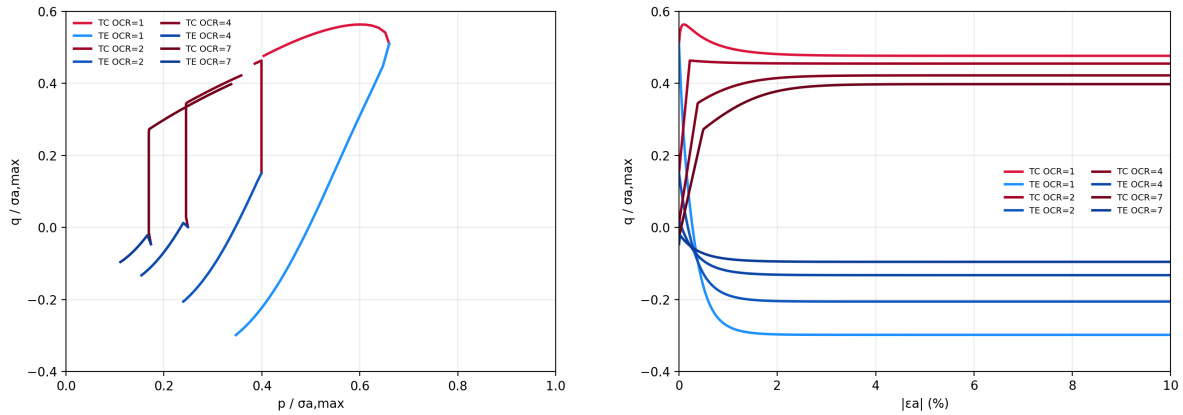
Family	Consolidation	Drainage	Sweep
CKo undrained triaxial compression and extension	Ko	Undrained	OCR
CI undrained triaxial compression and extension	Isotropic	Undrained	OCR
Anisotropic consolidation response	Anisotropic	Undrained	Kc
Plane-strain compression	Ko	Undrained	OCR
Drained triaxial compression	Ko and isotropic	Drained	OCR
Drained anisotropic triaxial compression	Anisotropic	Drained	Kc
Probe tests	Ko	Drained	Loading path

The validation plots below use paired layouts so the stress-path and stress-strain views for each benchmark family are read together.

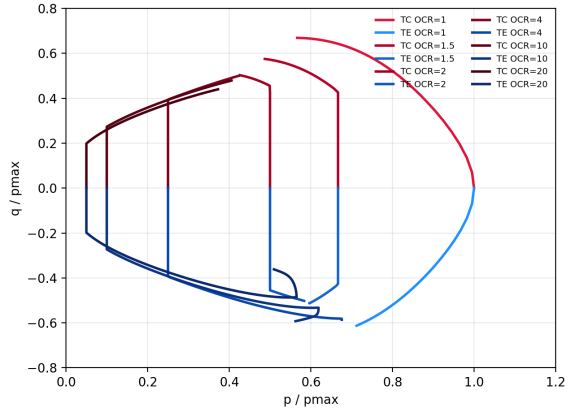
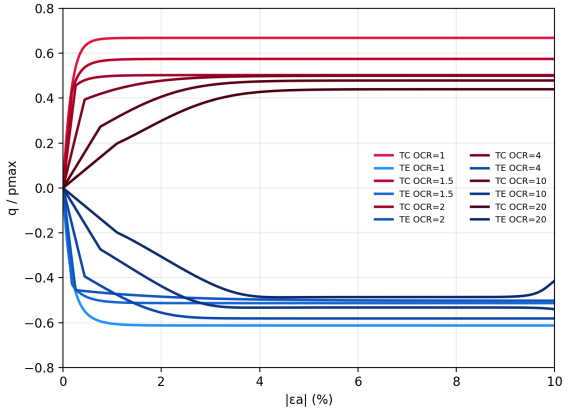
1.7 Single-Point Validation

1.7.1 CKo-consolidated undrained triaxial compression and extension

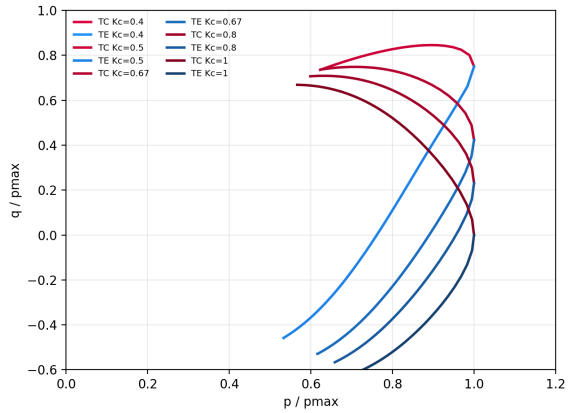
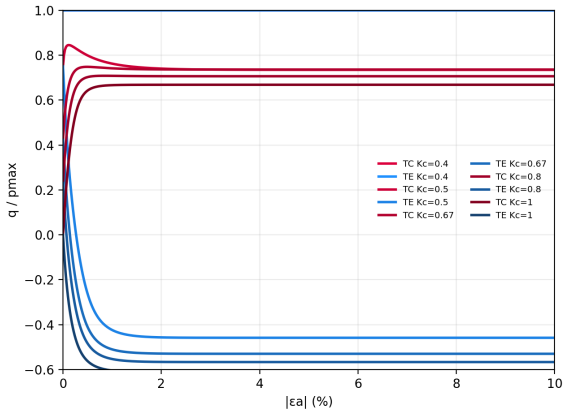
Stress path	Stress-strain



1.7.2 Isotropically consolidated undrained triaxial compression and extension

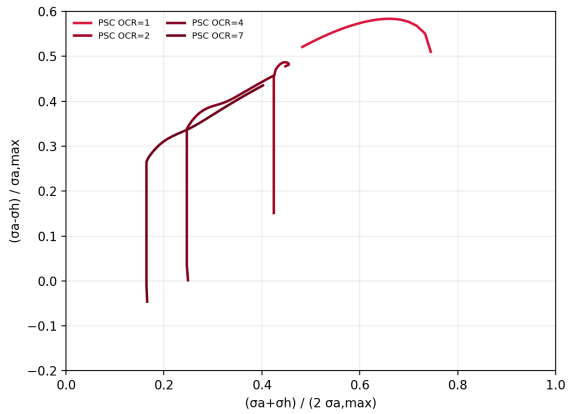
Stress path	Stress-strain
	

1.7.3 Anisotropic consolidation effect

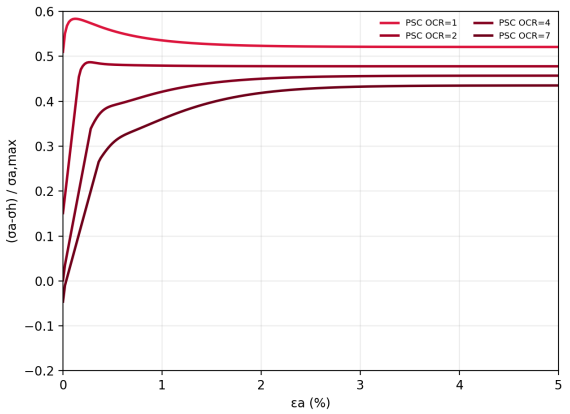
Stress path	Stress-strain
	

1.7.4 Plane-strain compression

Stress path

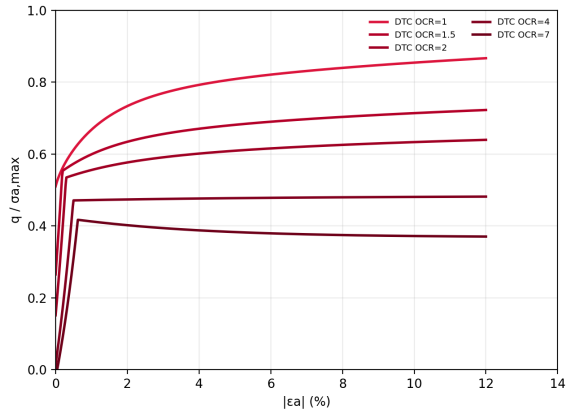


Stress-strain

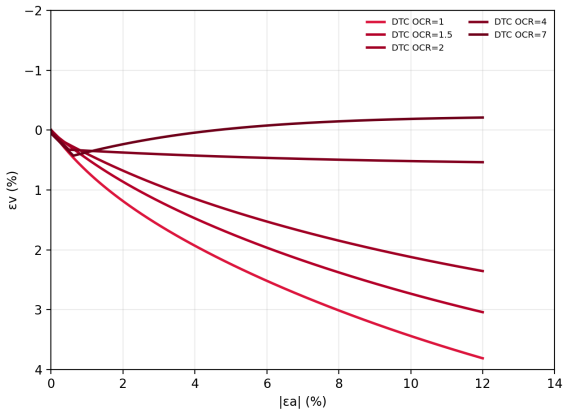


1.7.5 Ko-consolidated drained triaxial compression

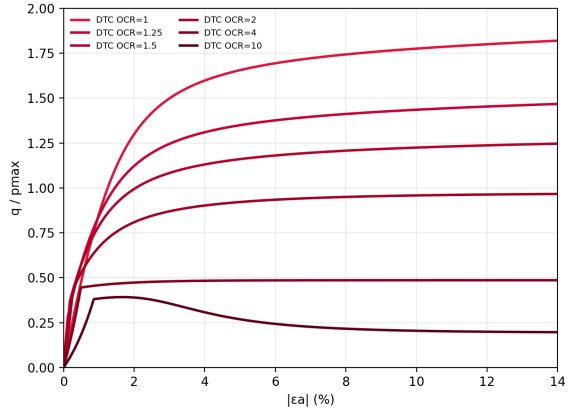
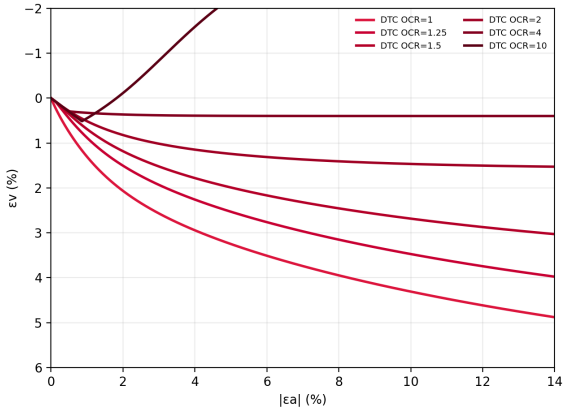
Stress-strain



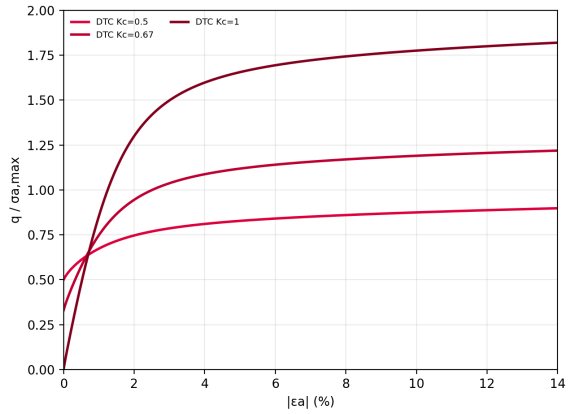
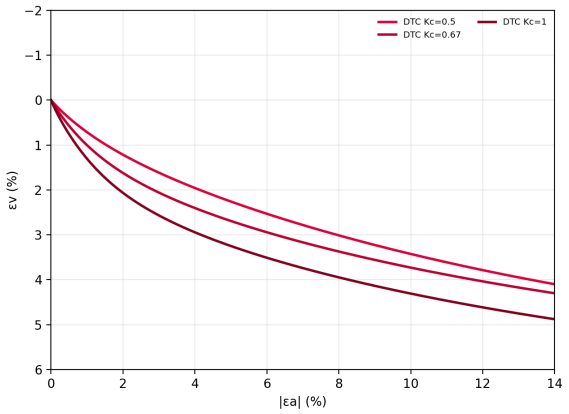
Volumetric strain



1.7.6 Isotropically consolidated drained triaxial compression

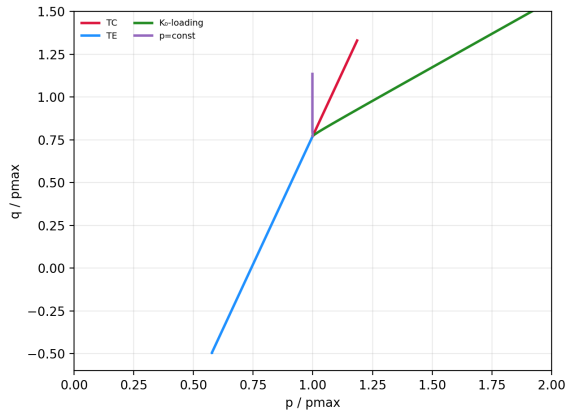
Stress-strain	Volumetric strain
	

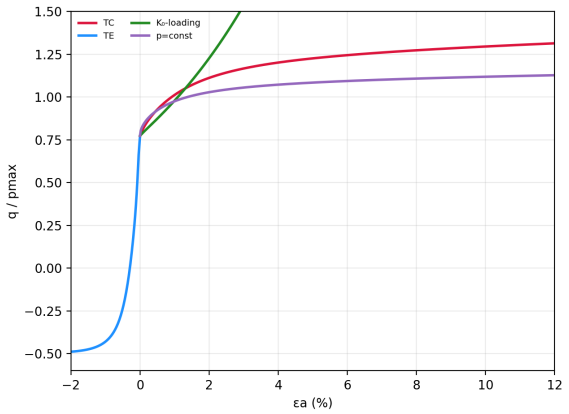
1.7.7 Anisotropic drained triaxial compression

Stress-strain	Volumetric strain
	

1.7.8 Probe tests

Stress path	Stress-strain





1.8 FALCON mini

The packaged mini tool id is `SANICLAY`. It lives under `mini_tools/SANICLAY`.

1.8.1 How to run

```
falcon --mini-root /path/to/UMATLIB_FALCON/falcon_minis --mini-tool SANICLAY
--mini-input
/path/to/UMATLIB_FALCON/falcon_minis/SANICLAY/cases/reduced_drained_tc
```

Packaged simulation families:

Packaged case	Path	Purpose
CI	`cases/ci/input.txt`	Isotropic consolidation reference state.
CIDC	`cases/cidc/input.txt`	Isotropic consolidated drained compression.
CK0	`cases/ck0/input.txt`	K0-consolidated reference state.
CK0UC	`cases/ck0uc/input.txt`	K0-consolidated undrained compression.
Reduced drained TC	`cases/reduced_drained_tc/input.txt`	Reduced drained triaxial compression.
Reduced undrained TC	`cases/reduced_undrained_tc/input.txt`	Reduced undrained triaxial compression.

Packaged case	Path	Purpose
Reduced undrained TE	cases/reduced_undrained_te/input.txt	Reduced undrained triaxial extension.
K0 verification undrained	cases/k0_verification_undrained/input.txt	Additional undrained K0 verification path.

1.8.2 Input syntax

input.txt uses whitespace-delimited Key Value pairs, for example:

```
Mode Drained
DrainedRule 1
Mc 1.18
Lambda 0.63
nSteps 400
```

The main selector is Mode.

Mode value	Meaning in the standalone mini
CI	Isotropic consolidation reference path.
CIDC	Isotropically consolidated drained compression.
CK0	K0 consolidation reference path.
CK0UC	K0-consolidated undrained compression.
Drained	General drained triaxial branch, further controlled by DrainedRule.
Undrained	General undrained triaxial branch.

Mini inputs used by the packaged cases:
Constitutive parameters:

Input key	Used by	Required / choices / defaults	Meaning
Nu, Kappa, Lambda	all cases	Required in packaged cases	Elastic and compression parameters.
Mc, Me, N, x, C	all cases	Required in packaged cases	Core SANICLAY critical-state and anisotropy parameters.

Input key	Used by	Required / choices / defaults	Meaning
P_min, STOL, FTOL, LTOL	all cases	Optional safeguards/tolerances; packaged cases set them explicitly	Numerical safeguards and tolerances.
IntegrationScheme	optional	Optional; choices depend on the standalone build; packaged cases use the driver default unless stated	Selects the local stress-update scheme.

Initialization and state inputs:

Input key	Used by	Required / choices / defaults	Meaning
InitFromK0, K0, UseGensK0, PhiEff	K0-related cases	Required only for K0-initialized cases; switches are typically 0/1	Controls K0-based state initialization.
OCR, P0, Pa or Pa_saniclay	many cases	Required when the chosen initialization path uses OCR / cap-size reconstruction	Overconsolidation and hardening-size inputs.
SigmaAmax, SigmaAmaxFromP0	selected cases	Optional; used only by cases that prescribe anisotropy-size initialization explicitly	Additional anisotropy-size initialization controls.
InitAlphaBetaFromK0, SetP0FromOCR	selected cases	Optional switches; choices 0/1	Auto-initialization switches for anisotropy and hardening.
VoidRatio, initialvoidratio	all cases	Required in packaged cases; either spelling may appear depending on source case style	Initial void ratio.

Input key	Used by	Required / choices / defaults	Meaning
`AlphaXX` to `AlphaXY`, `BetaXX` to `BetaXY`	selected cases	Optional; required only when anisotropy is prescribed directly	Explicit anisotropy tensor components.
`StressXX`, `StressYY`, `StressZZ`	all cases	Required in packaged cases	Initial total stress components.

Loading controls:

Input key	Used by	Required / choices / defaults	Meaning
`DrainedRule`	drained cases	Required for drained modes; packaged drained cases use `1`	Chooses the drained stress-path rule; the packaged drained examples use `1` for constant radial stress.
`PlaneStrain`	selected cases	Optional; choices `0`/`1`	Switches between axisymmetric and plane-strain undrained response.
`dEpsAxial`, `nSteps`	most triaxial cases	Required for most packaged triaxial cases	Axial strain increment and step count.
`OutFile` or `OutputCSV`	all cases	Optional; defaults to `stress_results.csv` if omitted in packaged usage	Output CSV file name.

1.8.3 Hydromechanical assumptions

The packaged SANICLAY mini is saturated only:

- there is no suction or retention update
- anisotropy evolution comes from the SANICLAY constitutive law itself
- the packaged examples emphasize consolidation path, anisotropy initialization, and drained/undrained triaxial response

1.8.4 Sample input

Reduced drained triaxial example Path: `mini_tools/SANICLAY/cases/reduced_drained_tc/input.txt`

```
Mode Drained
Nu 0.20
Kappa 0.009
Lambda 0.63
Mc 1.18
Me 0.86
N 1.18
x 1.0
C 0.0
VoidRatio 0.44
StressXX -200
StressYY -200
StressZZ -200
P0 200
Pa 200
dEpsAxial -1e-4
nSteps 400
```

This packaged case is the cleanest drained triaxial example in the mini. It is the main reference path for reading the drained anisotropic clay response without the extra complexity of the full figure-regeneration suite.

K0-consolidated undrained example Path: `mini_tools/SANICLAY/cases/ck0uc/input.txt`

This packaged case is the main undrained clay example after K0 consolidation. It is useful for checking how the anisotropy initialization affects the subsequent undrained stress path.

Consolidation reference examples Paths:

- `mini_tools/SANICLAY/cases/ci/input.txt`
- `mini_tools/SANICLAY/cases/cidc/input.txt`
- `mini_tools/SANICLAY/cases/ck0/input.txt`

These packaged cases are mainly used to build the paper-style consolidation and triaxial figure set shown below.

1.8.5 Output files and columns

Each packaged run writes `stress_results.csv`.

Output file	Produced by	Main use
`stress_results.csv`	all cases	Main SANICLAY history file used by the packaged figures.

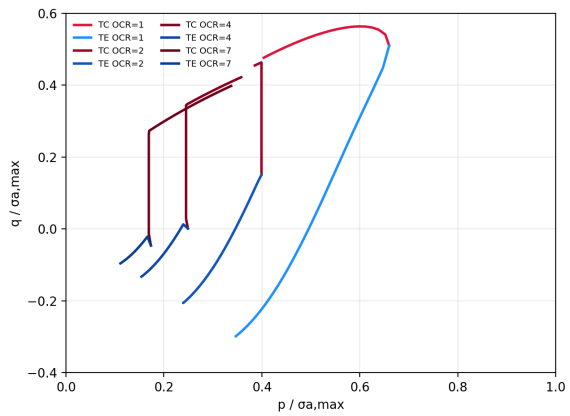
Primary columns:

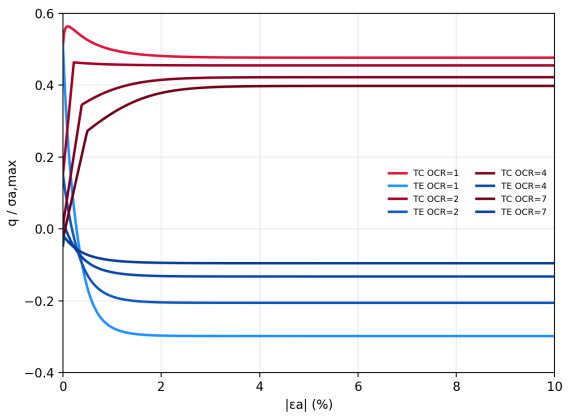
Output column	Meaning
`exx` to `exy`, `sxx` to `sxy`	Strain and stress components.
`q_raw`, `p_raw`, `q_eff`, `p_eff`, `q_norm`, `p_norm`	Raw and effective stress invariants plus normalized forms used in the paper-style plots.
`OCR`, `K0Used`, `SigmaAmax`, `P0`, `Pa`, `eta`, `e`	State and initialization measures.
`alpha_norm`, `beta_norm`, `alpha_scalar`, `beta_scalar`	Anisotropy measures written by the standalone driver.
`PlasticStrainIncXX` to `PlasticStrainIncXY`	Cumulative plastic-strain history when written by the case.
`Debug_*`	Driver and integration diagnostics.

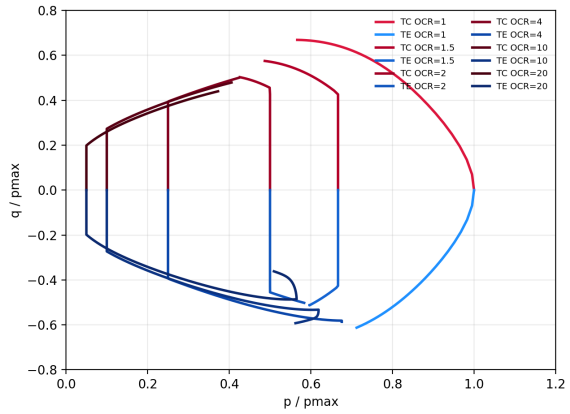
The plots in the next section are generated from these packaged case CSVs.

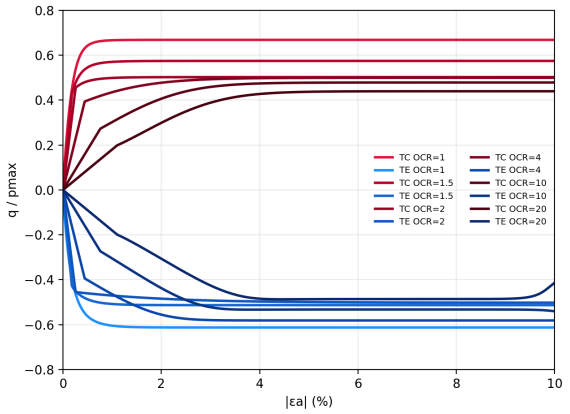
1.9 Results

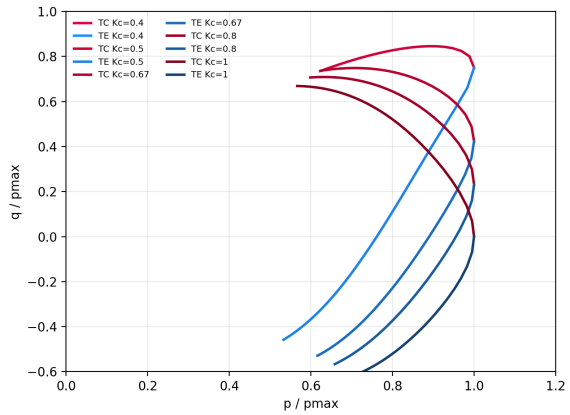
The figures below are produced directly from the bundled FALCON mini case inputs under `mini_tools/SANICLAY/cases`. The packaged set is organized to reproduce the main paper-style consolidation and triaxial responses.

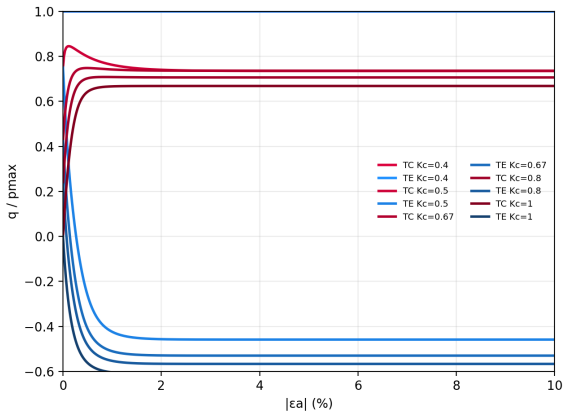


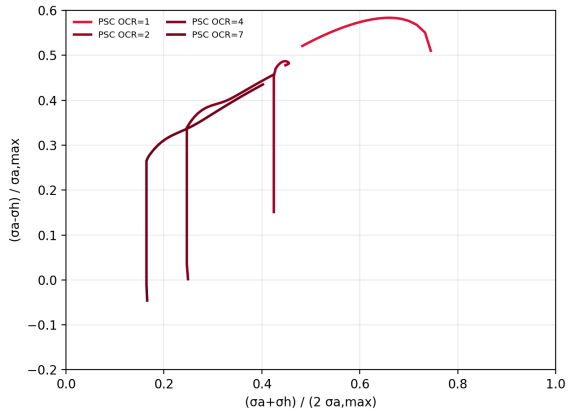


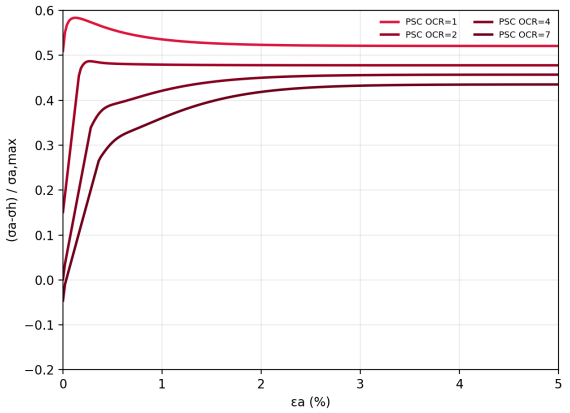

TC OCR=1
TE OCR=1
TC OCR=1.5
TE OCR=1.5
TC OCR=2
TE OCR=2
TC OCR=4
TE OCR=4
TC OCR=10
TE OCR=10
TC OCR=20
TE OCR=20
q / pmax
p / pmax

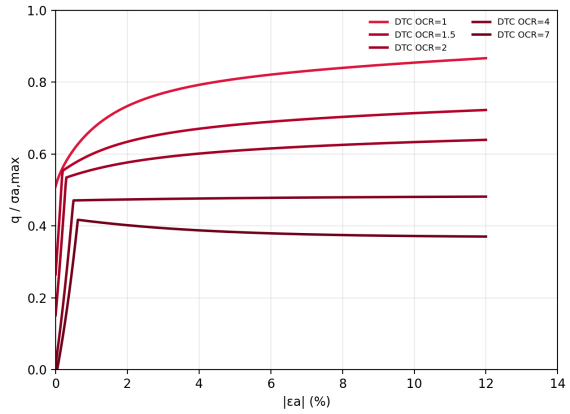

TC OCR=1
TE OCR=1
TC OCR=1.5
TE OCR=1.5
TC OCR=2
TE OCR=2
TC OCR=4
TE OCR=4
TC OCR=10
TE OCR=10
TC OCR=20
TE OCR=20
q / pmax
|εa| (%)

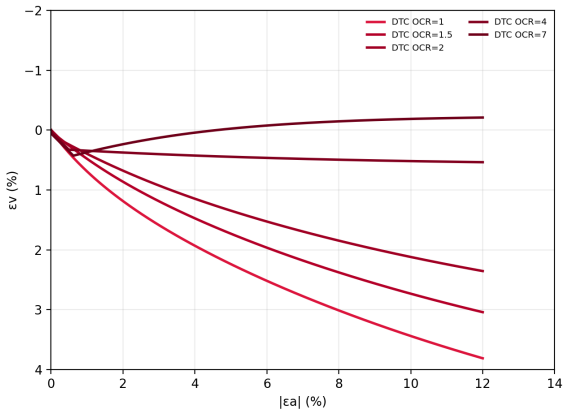

TC Kc=0.4
TE Kc=0.4
TC Kc=0.5
TE Kc=0.5
TC Kc=0.67
TE Kc=0.67
TC Kc=0.8
TE Kc=0.8
TC Kc=1
TE Kc=1
q / pmax
p / pmax

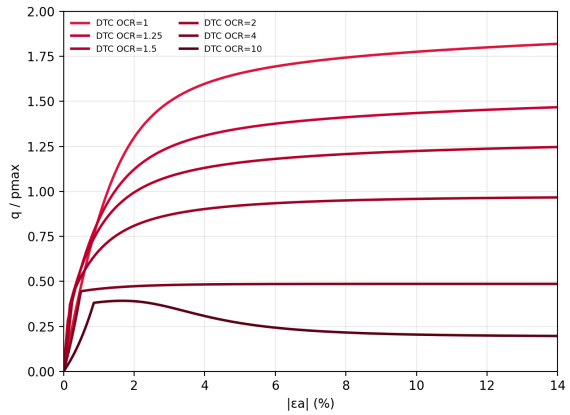

TC Kc=0.4
TE Kc=0.4
TC Kc=0.5
TE Kc=0.5
TC Kc=0.67
TE Kc=0.67
TC Kc=0.8
TE Kc=0.8
TC Kc=1
TE Kc=1
q / pmax
|εa| (%)

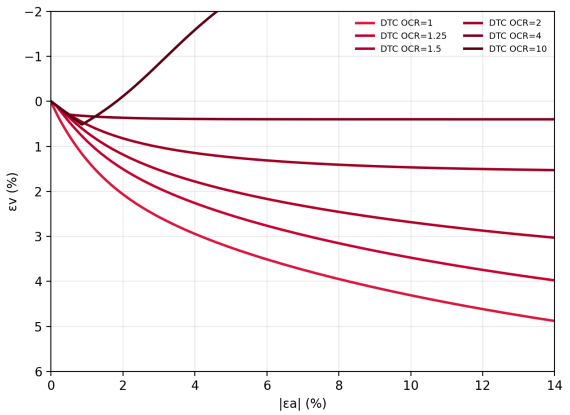

PSC OCR=1
PSC OCR=2
PSC OCR=4
PSC OCR=7
(σa-σh) / σa,max
(σa+σh) / (2 σa,max)

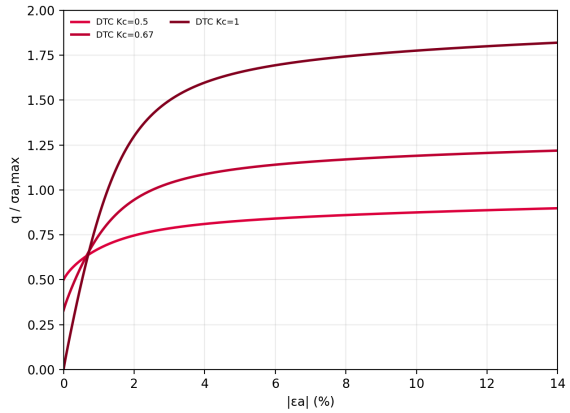

PSC OCR=1
PSC OCR=2
PSC OCR=4
PSC OCR=7
(σa-σh) / σa,max
εa (%)

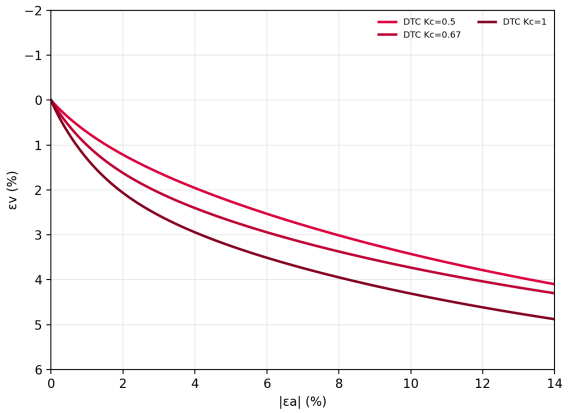

DTC OCR=1
DTC OCR=1.5
DTC OCR=2
DTC OCR=4
DTC OCR=7
q / σa,max
|εa| (%)

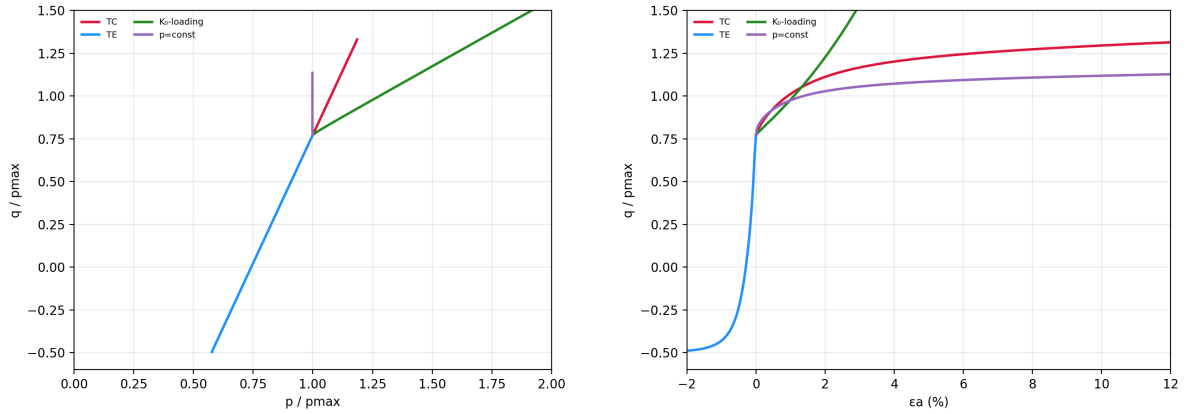

DTC OCR=1
DTC OCR=1.5
DTC OCR=2
DTC OCR=4
DTC OCR=7
εv (%)
|εa| (%)


DTC OCR=1
DTC OCR=1.25
DTC OCR=1.5
DTC OCR=2
DTC OCR=4
DTC OCR=10
q / pmax
|εa| (%)


DTC OCR=1
DTC OCR=1.25
DTC OCR=1.5
DTC OCR=2
DTC OCR=4
DTC OCR=10
εv (%)
|εa| (%)


DTC Kc=0.5
DTC Kc=0.67
DTC Kc=1
q / σa,max
|εa| (%)


DTC Kc=0.5
DTC Kc=0.67
DTC Kc=1
εv (%)
|εa| (%)



These figure panels are generated from the bundled consolidation and triaxial cases such as `cases/ci/input.txt`, `cases/cidc/input.txt`, `cases/ck0/input.txt`, `cases/ck0uc/input.txt`, and the reduced drained/undrained triaxial cases.

1.10 Applications and limitations

- Best suited to clay behavior with anisotropy, K0 conditioning, and drained or undrained effective-stress loading paths.
- Appropriate for uncoupled and effective-stress-based coupled analyses, but it is not an intrinsic unsaturated constitutive law.
- It is not intended as a sand liquefaction model or a general rock-strength model.

1.11 References

- Dafalias, Y. F., Manzari, M. T., and Papadimitriou, A. G. (2006). Simple anisotropic clay plasticity model. *International Journal for Numerical and Analytical Methods in Geomechanics*, 30, 1231-1257.