

ShoreKALC

User, Theory, and Numerical Formulation Manual

Staged excavation and soil structure interaction

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Table of Contents

Table of Contents	3
Summary	6
1. Background and scope	7
2. User Guide	8
2.1. Main user interface	8
2.2. Setting up a new problem	10
2.2.1. Project details	10
2.2.2. Geometry	11
2.2.3. Strata Profile	12
2.2.4. Soil Materials	13
Drained and undrained material selection	13
Selecting undrained shear strength	13
Indicative clay consistency ranges	14
Undrained Poisson's ratio	14
Preliminary retaining wall parameter examples	15
2.2.5. Wall definition and soil interface	16
2.2.5.1. Interface strength reduction Rinter	16
2.2.5.2. Initial earth pressure ratio and Jaky estimate	17
2.2.5.3. Initial stress in rock and over-consolidated ground	18
2.2.5.4. Choosing the initial stress method	19
2.2.5.5. Bonded and frictional contact modes	19
2.2.5.6. Contact stiffness factor	20
2.2.6. Struts and Anchors	21
2.2.7. Surcharges	23
2.2.8. Groundwater and Water-table	24
2.2.9. Construction Stages	25
2.2.10. Stage Water Levels	26
3. Results	27
3.1. Mesh preparation and analysis workflow	27
Independent wall element spacing	27
Mesh sensitivity comparison	28
3.2. User Interface Results	29
3.3. Calculation Report	31
3.3.1. What the report contains	31
3.3.2. Model definition and units	31
3.3.3. Construction sequence and wall contact	31
3.3.4. Reading the convergence table	32
3.3.5. Force envelopes and per-stage structural actions	33
3.3.6. Support force tables	34
3.3.7. Stage geometry and wall movement	35
3.3.8. Soil displacement and stress contours	36
3.3.9. Pore pressure, plastic strain and current yielding	37
3.3.10. Engineering assessment and limits	38
3.3.11. Scope of engineering assessments	38
3.3.12. Reviewing the report as a glass box	39
4. Theory	40
4.1. Relationship to established methods	40
4.2. Assumptions and applicability	40
4.3. Coordinates units and signs	41

4.4.	Governing equilibrium and finite element discretisation	42
4.5.	Elastic soil skeleton	43
4.6.	Drained Mohr-Coulomb strength and flow	44
4.7.	Constitutive return mapping and tangent	44
4.8.	Undrained B response	45
4.9.	Groundwater gravity and boundary water loads	46
4.10.	Initial stress and geostatic equilibrium	46
4.11.	Elastic wall formulation and rigidity changes	47
4.12.	Compression only struts	48
4.13.	Prestressed ground anchors	48
4.14.	Frictional wall soil contact	49
4.15.	Construction staging and loading	50
4.16.	Nonlinear solution and convergence	50
4.17.	Result recovery and engineering interpretation	51
4.18.	Calculation review and limitations	52
4.18.1.	Mesh and boundary sensitivity	52
4.18.2.	Independent engineering checks	52
4.18.3.	Current numerical bounds	53
5.	Worked analytical examples	53
5.1.	Initial stress and unit conversion	53
5.2.	Undrained storage increment	53
5.3.	Strut stiffness and installation reference	53
5.4.	Inclined anchor and tensile yielding	54
5.5.	Interface sticking and sliding	54
5.6.	Elastic cantilever response	54
	References	55
	Appendix A Computational sequence	57
	Appendix B Notation and glossary	58
	B1 Symbols and notation	58
	B2 Engineering terms	59
	Appendix C Detailed constitutive linearisation	61
	C1 Principal transformation	61
	C2 Tolerances and active set selection	61
	C3 Plastic strain commitment	62
	Appendix D Contact assembly and installation transfer	63
	D1 Relative displacement matrix	63
	D2 Transfer at wall installation	63
	D3 Independent wall interpolation	64
	Appendix E Mesh generation and numerical recovery	65
	E1 Uniform and graded mesh coordinates	65
	E2 Sparse assembly and band factorisation	65
	E3 Line search and branch recovery	66
	Appendix F Derivation of element and fluid equations	67
	F1 Virtual work and plane strain reduction	67
	Quadratic shape functions and quadrature	67
	F2 Wall beam interpolation and strain energy	67
	F3 No flow storage as a poro-elastic reduction	68
	Appendix G Ground behaviour (Informative)	69
	G1 From investigation to an analysis section	69
	G2 Wall movement and pressure mobilisation	70
	G3 Soil strength and wall interface strength	71

G4 Groundwater and surcharge interpretation	72
G5 Excavation and anchor sequence	73
G6 Failure mechanisms and model coverage	74
G7 Two simple hand checks	75
Dry soil with a uniform surcharge.....	75
Water table at midheight.....	75
G8 Applying independent checks to ShoreKALC	76
Appendix H Benchmark validation	77
H1 Scope and validation basis	77
H2 Benchmark3 tied back excavation	78
Benchmark3 problem and published reference mesh	79
Benchmark3 ShoreKALC verification meshes	81
H3 Benchmark4 dry cantilever excavation.....	82
Benchmark4 problem and published reference mesh	83
Benchmark4 ShoreKALC verification meshes	84
Benchmark4 final wall profiles	85
H4 Numerical results and interpretation	86
H5 Applicability and remaining validation.....	87
H6 Sources and reproducibility	87

Summary

ShoreKALC is RKALC's programme for analysing staged excavation and soil–structure interaction. This manual explains how to define a model, carry out an analysis and interpret its results, and then describes the engineering theory and numerical formulation behind the calculation. It is intended for engineers who select the ground and structural parameters and review the retaining system through its construction sequence.

The first part comprises the User Guide and Results chapters. The User Guide follows the input workflow: project details and units, geometry, strata and soil materials, wall properties and contact, struts and anchors, surcharges, groundwater and construction stages. The Results chapter explains mesh preparation, analysis controls, the result viewer and calculation report. It shows how to read displacement, wall actions, support forces, soil stresses, pore pressure, plastic response and engineering-assessment statuses in their stage context.

The second part, Theory, explains the assumptions, coordinates and signs, equilibrium and finite element discretisation. It develops the elastic and Mohr-Coulomb soil response, constitutive return mapping, Undrained B storage, groundwater loads and initial stresses, followed by wall beams, support springs, wall–soil contact, construction staging and nonlinear solution. The worked analytical examples connect these laws to input units, initial stresses, support forces and interface behaviour.

The appendices provide the calculation sequence, notation and glossary, detailed constitutive linearisation, contact assembly, mesh and solution procedures, and derivations of element and fluid equations. Appendix G is informative: it explains ground behaviour, pressure mobilisation, groundwater and surcharge interpretation, support sequence and simple hand calculations to assist engineering understanding and comparison with alternative methods. Appendix H records current benchmark comparisons, numerical verification and remaining validation scope.

RKALC's glass-box approach links these parts: inputs and assumptions can be followed through the governing calculation to the reported response. Engineers should use the stated assessment scope, numerical diagnostics and project criteria when making design decisions. Wall and support resistance, ground mechanisms, hydraulic behaviour and adjacent-asset movement require the additional checks identified throughout the manual.

1. Background and scope

ShoreKALC applies RKALC's glass-box engineering approach: the model assumptions, calculation methods and reported results are available for engineering review [10,11]. The User Guide explains the practical workflow; the Theory chapter and appendices provide the mathematical basis needed to understand the response.

A model represents a two-dimensional excavation section with horizontal contiguous strata, one vertical wall, excavation to its left, retained ground to its right, and specified groundwater and surcharge conditions. The engineer defines the construction sequence, including wall installation, excavation, support installation and stressing, load changes and water levels.

The calculation couples ground deformation, wall response and support forces. Each stage inherits the preceding stress and displacement history, so support timing and load changes affect subsequent results. Review the construction sequence as carefully as the final geometry.

The analysis uses small-strain plane-strain mechanics, an elastic wall and perfectly plastic soil. Prescribed hydrostatic heads represent the adopted water scenarios. The Theory chapter explains the model's applicability and limitations; the Results chapter identifies the scope of each engineering assessment and the checks requiring separate project design.

Use the manual alongside the geotechnical interpretation, structural design basis and construction requirements. Adopt parameters and acceptance criteria for the project, record their sources, and review both the calculated response and the mechanisms outside the model's scope.

A calculation review follows the model through the following steps:

- input
- stage history
- constitutive and structural response
- equilibrium diagnostics
- reported output
- independent engineering decision.

2. User Guide

2.1. Main user interface

The workspace combines the model canvas, Properties panel, Model control panel and analysis and reporting commands. Select Input data to open the model input dialog directly. The tabs provide Project details, Geometry, Strata profile, Soil materials, Wall / pile, Struts and anchors, Surcharges, Initial groundwater, Construction stages and Stage water levels.

Select a stage in the model-control panel to inspect that stage's geometry and active supports; the canvas can show the undeformed or deformed shape and selected result components.

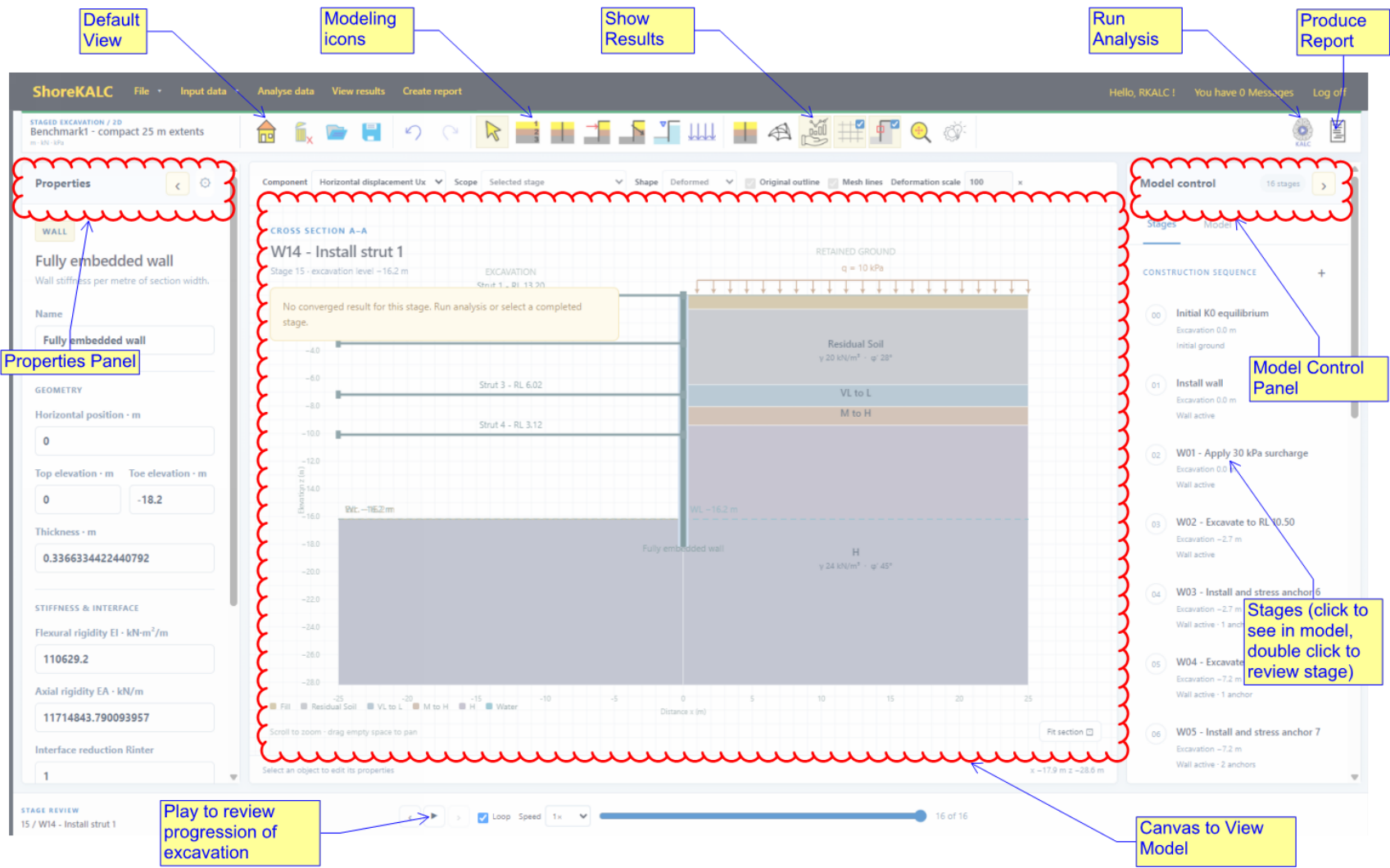
The displayed deformation is a visualised analysis result and may be scaled, so read the stated deformation scale before judging its magnitude.

Use the properties panel to edit the selected object, and run the staged analysis after the model inputs are complete; a stage without a converged result cannot be reviewed as a calculated response.

Hover over supported field labels or controls to read their explanations. Help is provided for drainage, drained cohesion and friction, dilation, S_u , undrained Poisson's ratio, interface ratios, K_0 , initial stress, contact mode, Rinter and contact stiffness. These explanations describe the implemented model and its defaults; they do not select project design parameters.

Use View results to select the calculated quantity, construction stage or envelope, deformed or undeformed shape, deformation scale, mesh lines and original outline. These controls change the display of the calculated results; a new mechanical analysis is required when model inputs change.

Figure 1 User Interface



2.2. Setting up a new problem

Use File > New problem, or the New toolbar button. Define the project name, domain extents, wall position and toe, wall rigidities, first material and first excavation level. The starter sequence contains initial conditions, wall installation and excavation. Add layers, surcharges and supports, then refine the construction sequence. New problems start with Bonded contact and Rinter = 1.

2.2.1. Project details

Project details identify the calculation and supply the descriptive information used in the model and its reports, including the project title, subtitle, job number, preparer and source of the soil information.

These fields do not change the mechanical solution, but they provide traceability: record the source report, investigation or interpreted profile so a reviewer can relate the adopted parameters to the ground model.

Use metres for geometry and elevations, kN and kPa for forces and stresses, and degrees for input angles. Soil modulus E' is entered in kPa: multiply an MPa value by 1000. Thus 25 MPa is entered as 25,000 kPa. Support EA is per member; wall EA and EI are per metre of wall width.

Apply the dialog to commit the edited project data; changing the input model clears previous analysis results, so rerun the calculation before issuing an updated report.



INPUT DATA [X]

Project details

Edit the inputs below. Apply updates the section and clears previous analysis results.

Project details | Geometry | Strata profile | Soil materials | Wall / pile | Struts and anchors | Surcharges | Construction stages | Stage water levels

Project title: Benchmark1 - compact 25 m extents

Subtitle: Ground datum RL 13.20 m; excavation on left

Job number: 210802

Prepared by: ShoreKALC benchmark

Soil information source: 220127-BH1 INTERPOLATED with BH2M.pdf / .out, revised 4 October

Units: metres, kN and kPa. Ground level is the 0 m datum.

Engineering assessment

Retained surface SLS settlement limit · mm

Wall horizontal SLS movement limit · mm

Soil strength-reduction target · greater than 1

Toe ground strength-reduction target · greater than 1

Assessment criteria / source

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[Apply to model] [Close]

Annotations:

- insert project titles, name of Engineer and the like This is important for informative filing and calc reports
- Insert user limits
- Safety factors (1.5 typically)

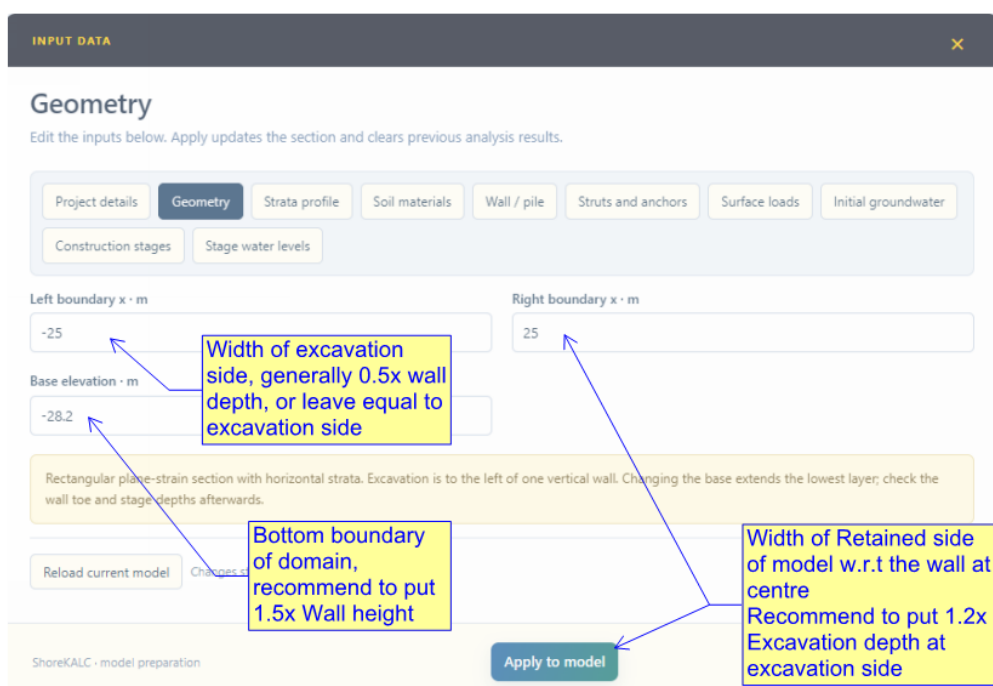
Figure 2 Project Details Dialog

2.2.2. Geometry

Geometry defines the left and right boundaries and base of the rectangular plane-strain domain. Set the wall position and toe under Wall / pile; excavation is on the left and retained ground is on the right. Elevations use the common ground datum $z = 0$.

The boundary distances and base depth are modelling limits rather than physical walls: if they are too close, restrained boundaries can influence computed movement and force. Extend the domain sufficiently beyond the excavation's likely deformation zone, then check sensitivity by enlarging the boundaries.

Choose domain extents from the expected deformation zone and assess boundary sensitivity. Changing the base extends the lowest layer; review the wall toe, layer boundaries and stage depths afterwards. A visually plausible domain does not establish boundary independence.



INPUT DATA ✕

Geometry

Edit the inputs below. Apply updates the section and clears previous analysis results.

Project details **Geometry** Strata profile Soil materials Wall / pile Struts and anchors Surface loads Initial groundwater

Construction stages Stage water levels

Left boundary x · m: -25

Right boundary x · m: 25

Base elevation · m: -28.2

Rectangular plane-strain section with horizontal strata. Excavation is to the left of one vertical wall. Changing the base extends the lowest layer; check the wall toe and stage depths afterwards.

Reload current model Changes saved

Apply to model

ShoreKALC · model preparation

Width of excavation side, generally 0.5x wall depth, or leave equal to excavation side

Bottom boundary of domain, recommend to put 1.5x Wall height

Width of Retained side of model w.r.t the wall at centre
Recommend to put 1.2x Excavation depth at excavation side

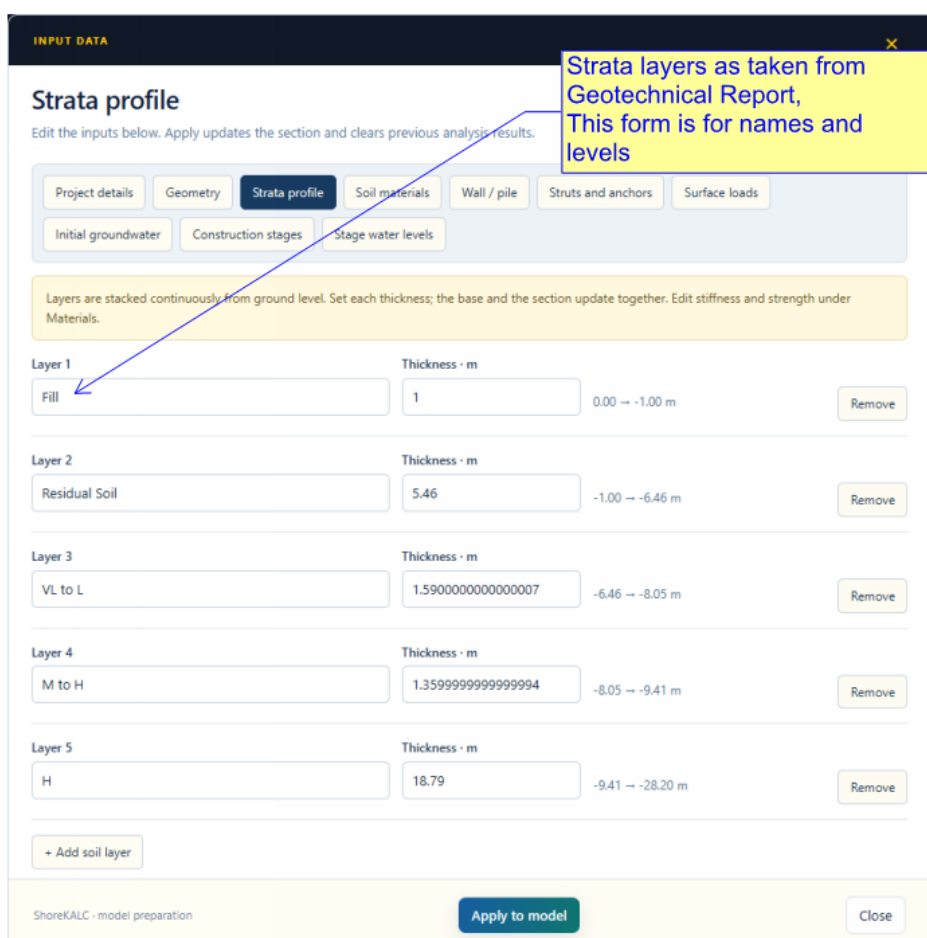
Figure 3 Geometry Dialog

2.2.3. Strata Profile

The strata profile defines the vertical sequence of horizontal soil layers from the ground datum. Enter layer names that match the geotechnical interpretation and thicknesses that place each interface at the elevations shown in the investigation; the displayed top and base levels update from the accumulated thicknesses.

Layer names and boundaries organise the model, while the constitutive properties are entered separately in Soil Materials.

Confirm that important layer boundaries, excavation levels, wall toe and water levels are represented at their intended elevations, because layer thickness determines which material is assigned to each continuum element and to wall-contact segments.



INPUT DATA

Strata profile

Edit the inputs below. Apply updates the section and clears previous analysis results.

Project details | Geometry | **Strata profile** | Soil materials | Wall / pile | Struts and anchors | Surface loads

Initial groundwater | Construction stages | Stage water levels

Layers are stacked continuously from ground level. Set each thickness; the base and the section update together. Edit stiffness and strength under Materials.

Layer	Thickness · m	Elevation Range	Action
Layer 1 Fill	1	0.00 → -1.00 m	Remove
Layer 2 Residual Soil	5.46	-1.00 → -6.46 m	Remove
Layer 3 VL to L	1.5900000000000007	-6.46 → -8.05 m	Remove
Layer 4 M to H	1.3599999999999994	-8.05 → -9.41 m	Remove
Layer 5 H	18.79	-9.41 → -28.20 m	Remove

+ Add soil layer

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Apply to model | Close

Figure 4 Strata Profiling

2.2.4. Soil Materials

Soil materials assigns the mechanical idealisation to each layer. Drained Mohr-Coulomb uses effective Young's modulus E' and Poisson's ratio ν' for stiffness, effective cohesion c' and friction angle ϕ' for strength, and dilation angle ψ for plastic volume change. Bulk and saturated unit weights govern self-weight. Blank saturated unit weight uses the bulk value; an entered saturated value must be at least the bulk value.

The interface friction ratio R_f and adhesion ratio R_c reduce the soil's frictional and cohesive resistance at the wall surface. They define $\tan \delta = R_f \tan \phi'$ and $c_i = R_c c'$. A blank layer ratio uses the wall's R_{int} value; an explicit zero removes that strength component.

For K_0 and In-situ rock stress initialization, blank K_0 uses Jaky's estimate. At $\phi' = 25^\circ$, this gives approximately 0.577; an entered value of 0.58 is used directly. Undrained B retains effective-stress stiffness and requires S_u separately; drained c' , ϕ' and ψ do not define S_u .

Choose parameters for the soil state and drainage condition being represented, because stiffness controls calculated movement and strength controls yielding and load redistribution.

Drained cohesion is the cohesive part of the effective stress shear-strength envelope. Friction angle controls its dependence on effective normal compression. Dilation controls plastic expansion during shearing; $\psi = 0$ gives no plastic dilation. Dilation and friction are separate inputs. The soil friction angle ϕ' is also distinct from the wall interface angle δ .

Drained and undrained material selection

Choose drainage behaviour for the material and construction timescale. Undrained B is mainly suitable for saturated clay when rapid loading or excavation prevents drainage. Clayey fill and some silts may behave similarly. Sand, gravel and freely draining granular fill generally use Drained. A name such as "Fill" or "Residual soil" does not establish drainage behaviour; use the geotechnical interpretation.

Undrained B requires an explicit S_u and effective stiffness E' and ν' . Its undrained shear-strength calculation uses zero friction and dilation. Drained c' and ϕ' do not determine S_u . Where K_0 is left blank, the entered effective friction angle is used in the Jaky initial-stress estimate, so assess K_0 independently where necessary. Appendix B defines the drainage and stress terminology.

Selecting undrained shear strength

S_u is an undrained shear strength in kPa, selected for the layer and relevant loading condition. Prefer the geotechnical report or interpreted undrained triaxial, field vane or calibrated CPT data. Sampling quality, stress history, loading direction and test interpretation affect the adopted value. Drained cohesion, friction angle and stiffness alone cannot reliably determine S_u [12].

For a suitable cohesive soil tested in unconfined compression, S_u is half the measured unconfined compressive strength q_u . For example, $q_u = 100$ kPa gives $S_u = 50$ kPa. This relationship is not a conversion from rock compressive strength or from drained c' [12].

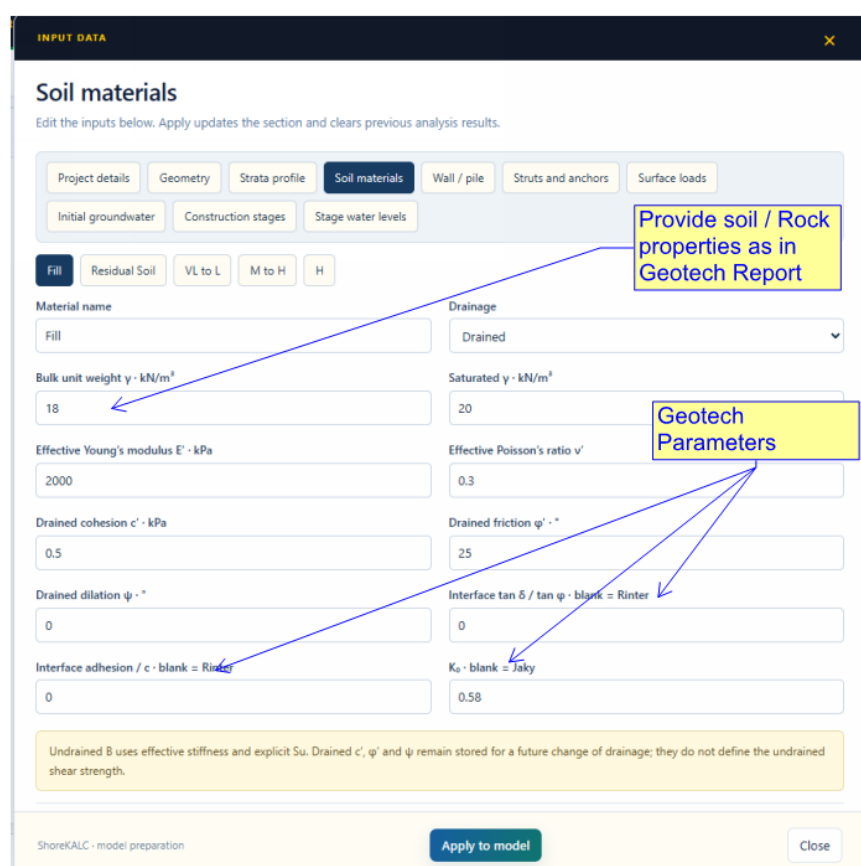
Indicative clay consistency ranges

The following ranges are classification guidance derived by halving the FHWA clay unconfined compressive strength ranges. They are not recommended design values for a particular layer or site [12,13]. There is no universal S_u for fill.

Clay consistency	Indicative S_u (kPa)
Very soft	<12.5
Soft	12.5–25
Firm or medium	25–50
Stiff	50–100
Very stiff	100–200
Hard	>200

Undrained Poisson's ratio

Undrained ν_u controls the volumetric stiffness response used to represent near-incompressible behaviour. Blank uses 0.49. The accepted range is 0.45 to 0.495 inclusive, and ν_u must exceed effective ν' . Values close to 0.5 can make displacement elements sensitive to volumetric locking; review mesh sensitivity. ν_u does not define undrained shear strength.



INPUT DATA

Soil materials
Edit the inputs below. Apply updates the section and clears previous analysis results.

Project details | Geometry | Strata profile | **Soil materials** | Wall / pile | Struts and anchors | Surface loads

Initial groundwater | Construction stages | Stage water levels

Fill | Residual Soil | VL to L | M to H | H

Material name: Fill

Drainage: Drained

Bulk unit weight γ · kN/m³: 18

Saturated γ · kN/m³: 20

Effective Young's modulus E' · kPa: 2000

Effective Poisson's ratio ν' : 0.3

Drained cohesion c' · kPa: 0.5

Drained friction ϕ' · °: 25

Drained dilation ψ · °: 0

Interface $\tan \delta$ / $\tan \phi$ · blank = R_{inter} : 0

Interface adhesion / c · blank = R_{inter} : 0

K_0 · blank = J_{aky} : 0.58

Undrained B uses effective stiffness and explicit S_u . Drained c' , ϕ' and ψ remain stored for a future change of drainage; they do not define the undrained shear strength.

ShoreKALC · model preparation

Apply to model

Close

Figure 5 Soil Materials

Preliminary retaining wall parameter examples

Material	Unit weight γ (kN/m ³)	Drained c' (kPa)	Soil ϕ' (°)	E (MPa)	Wall δ (°)
Fill	19	0	26	8	17
Alluvial soils	20	0	26	10	17
Residual soils	20	5	24	18	16
Class V siltstone	22	25	27	75	18
Class IV siltstone	22	50	28	250	19
Class III siltstone	24	100	30	500	20

These are illustrative values, not universal NSW material ranges. Rock classes and parameters must be interpreted against the project report; ShoreKALC represents rock as an isotropic Mohr-Coulomb continuum, without explicit joints or Hoek-Brown strength.

E in this reference table is in MPa; multiply by 1000 before entry into ShoreKALC. The source's wall friction angles illustrate its adopted interface assumption and are not applied automatically. Enter the friction ratio as $\tan \delta$ divided by $\tan \phi'$. The table does not prescribe S_u or Poisson's ratio.

2.2.5. Wall definition and soil interface

The wall is represented by an elastic Euler–Bernoulli beam positioned between the entered top and toe elevations.

Enter axial rigidity EA and flexural rigidity EI per metre of wall width; they govern axial extension and bending response. For a continuous rectangular wall of thickness b and modulus E_w , EA equals E_w times b , and EI equals E_w times b cubed divided by 12, per unit width. For a pile wall, derive equivalent rigidity per metre using the actual pile section and centre spacing; the single-pile three-dimensional response is outside this plane-strain model. Thickness alone does not calculate or update the entered rigidities.

Select the initial-stress method that matches the ground-state assumption.

Bonded contact enforces compatible wall–soil translations; frictional contact permits opening and Coulomb sliding, using the soil-layer interface ratios or Rinter defaults. Its penalty stiffness is approximately proportional to the contact factor and inversely proportional to adjacent cell width, so a finer soil mesh or higher factor stiffens the numerical interface and can affect conditioning.

Check both movement and mesh sensitivity. The wall remains elastic, so section capacity checks are separate.

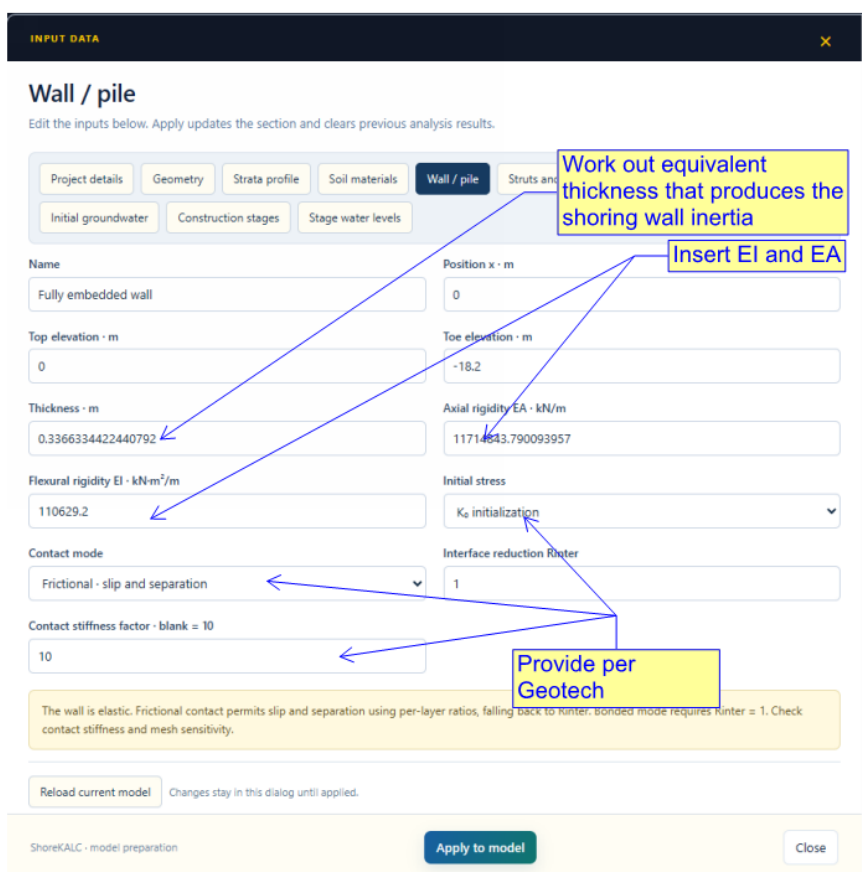


Figure 6 Wall Definition

2.2.5.1. Interface strength reduction Rinter

Rinter describes how much shear resistance the wall surface can mobilise compared with the surrounding soil (interface reduction factor). In ShoreKALC's frictional contact mode:

Rinter is the wall-wide default interface strength ratio and must be greater than zero and at most one. Rf is the friction ratio for a particular layer; Rc is that layer's adhesion ratio. Each layer ratio accepts zero to one independently. If both are blank, Rf = Rc = Rinter. Entered layer values override their respective defaults, so Rf and Rc may differ from each other and from Rinter.

$$\tan \delta = Rf \tan \phi', \quad c_i = Rc \, c'$$

$$|\tau| \leq c_i + \sigma_n' \tan \delta$$

Here δ is the interface friction angle, c_i is interface adhesion and σ_n, c is effective contact compression. Rf multiplies $\tan \phi'$ and Rc multiplies c' . Rinter supplies the default value for either ratio when its layer input is blank; it is not an additional multiplier applied to an explicitly entered Rf or Rc.

For Undrained B, interface friction is zero and adhesion is $R_c S_u$

For example, with $\phi' = 30^\circ$ $c' = 10 \text{ kPa}$ and both ratios equal to 0.67:

$$\delta = \tan^{-1}(0.67 \tan 30^\circ) \approx 21.1^\circ, \quad c_i = 6.7 \text{ kPa}$$

At $\sigma_n' = 100 \text{ kPa}$, the interface shear capacity is approximately 45.4 kPa, compared with 67.7 kPa for ratios of 1.

Effect on results:

reducing the ratios allows sliding at a lower shear traction. It changes vertical load transfer, soil movement and the distribution of contact pressure. Wall displacement, bending moments and support forces can consequently change, but their direction of change is not universally predictable: force can redistribute between the wall, soil and supports.

Two details are particularly important:

- Rinter = 1 in frictional mode still permits sliding and separation. It does not mean bonded contact.
- ShoreKALC calculates contact stiffness separately from these strength ratios; reducing Rinter does not directly reduce its elastic contact stiffness.

The ratio multiplies $\tan \phi'$ rather than ϕ' itself. For $\phi' = 30^\circ$ and a friction ratio of 0.5, δ is approximately 16.1°, not 15°. A chosen δ of 20° would require a ratio of approximately 0.63. Interface friction is a shear-capacity limit; the applied traction direction depends on how much shear is actually mobilised. With adhesion, the traction angle need not equal δ even at the shear limit.

A smooth mechanical interface needs zero friction and zero adhesion in Frictional mode.

Setting $\delta = 0$ does not turn this staged continuum solver into a Rankine earth-pressure calculation. Changing interface friction can redistribute movement and forces, so it is not automatically conservative for every result.

2.2.5.2. Initial earth pressure ratio and Jaky estimate

K_0 is the ratio of initial horizontal effective stress to vertical effective stress:

$$K_0 = \frac{\sigma_h'}{\sigma_v'}, \quad \sigma_h' = K_0 \sigma_v'$$

When K_0 or In-situ rock stress initialization is selected and the layer K_0 input is blank, ShoreKALC uses Jaky's expression:

$$K_0 = 1 - \sin \phi'$$

For the $\phi' = 25^\circ$ angle:

$$K_0 = 1 - \sin 25^\circ \approx 0.577$$

The displayed value of 0.58 is therefore approximately the Jaky value. Because it is entered explicitly, ShoreKALC uses 0.58.

For illustration, if $\sigma_v' = 100 \text{ kPa}$ and groundwater pressure is $u = 30 \text{ kPa}$:

$$\sigma_h' = 58 \text{ kPa}, \quad \sigma_h = \sigma_h' + u = 88 \text{ kPa}$$

These equations use compression-positive magnitudes; the solver stores soil compression with a negative sign.

K_0 is the initial horizontal-to-vertical effective stress ratio; active and passive earth-pressure coefficients describe different limiting conditions. Excavation response develops through deformation and yielding. Jaky's estimate principally represents normally consolidated soil.

Gravity equilibrium does not impose the entered K_0 or the Jaky ratio. Horizontal stress develops from self-weight, material response and boundary restraints. Therefore, changing K_0 affects the prescribed initial field only in K_0 and In-situ rock stress modes.

Over-consolidated soils and rock may require a different initial stress prescription supported by the geotechnical assessment.

Effect on results:

a higher K_0 starts the excavation from higher horizontal effective stress. It can increase the stress released by excavation and the demand on the retaining system. It also increases confinement, which affects soil yielding and frictional interface resistance. Consequently, it is not a simple multiplier applied to the final bending moments.

2.2.5.3. Initial stress in rock and over-consolidated ground

Jaky's relationship $K_0 = 1 - \sin \phi'$ is primarily an estimate of at-rest stress for normally consolidated soil. It should not be interpreted as a general relationship between rock-mass friction angle and in-situ horizontal stress.

Rock masses may contain substantial residual or locked-in horizontal stresses arising from previous burial, unloading, erosion and tectonic history, and the horizontal effective stress may equal or exceed the vertical effective stress. The two horizontal principal stresses may also differ.

Where these effects are significant, the initial stress state should be based on the geotechnical assessment, available field measurements and geological setting rather than automatically inferred from ϕ'

A user-defined K_0 may be appropriate where horizontal stress is reasonably proportional to vertical effective stress; the In-situ method should be considered where an additional stress component or more general initial stress representation is required. The equilibrated initial stress field should be reviewed before interpreting excavation results.

Changing the soil friction angle can also change the prescribed initial stress when K_0 is automatic.

In K_0 and In-situ rock stress modes, a blank K_0 uses the Jaky estimate. Changing ϕ' then changes both drained shear strength and the prescribed horizontal stress ratio. Enter an independently assessed K_0 or in-situ stress prescription where rock stress or stress history should be independent of ϕ' . Gravity equilibrium does not impose this automatic ratio.

2.2.5.4. Choosing the initial stress method

Method	ShoreKALC behaviour	Consequence
Gravity	Starts from zero assigned stress and equilibrates self-weight and stage-zero loading.	Horizontal stresses emerge from the material response and boundary restraints; the specified K_0 is not imposed.
K_0	Assigns vertical effective overburden stress and horizontal stress $K_0\sigma_v$ then equilibrates stage zero.	Provides control over the intended initial horizontal stress ratio.
In situ	Adds a specified horizontal stress offset and permits a different out-of-plane horizontal stress.	Represents an initial stress field beyond the simple K_0 assumption.

Initial stress is a model-wide choice displayed under Wall / pile and in project Properties. The adjacent table summarises the three methods. Each method is followed by stage-zero equilibrium; review the equilibrated stresses before interpreting excavation results.

In-situ rock stress adds the layer Horizontal compression offset in kPa to K_0 times vertical effective stress. Blank offset is zero. The Out-of-plane / in-plane stress ratio sets the second horizontal stress relative to the first; blank is one, and the accepted input range is 0.001 to one. These fields appear only in In-situ mode. The axes remain aligned with the model; arbitrary rotated principal stress directions are not an input option.

2.2.5.5. Bonded and frictional contact modes

Bonded contact shares wall and soil translations, preventing relative slip and mechanical separation. It is a compatibility assumption rather than a finite friction angle. This mode requires $R_{inter} = 1$ and independent wall spacing = 0.

Frictional contact permits:

- Sticking while shear traction remains below the interface capacity.
- Sliding when that capacity is reached.

- Separation when mechanical contact would require tensile normal traction.

When frictional contact opens, its mechanical normal and shear tractions become zero. Prescribed water pressure is handled separately.

Effect on results:

Bonded contact can overstate restraint where the real wall can slip or detach.

Frictional contact allows those mechanisms and can alter settlement, wall axial force, bending and support demand. Neither mode automatically produces a conservative value for every output.

2.2.5.6. Contact stiffness factor

This factor, β , controls the elastic stiffness used to transfer contact traction:

$$k_n = \frac{\beta E' (1 - \nu')}{(1 + \nu') (1 - 2\nu') h}, \quad k_s = \frac{\beta E'}{2(1 + \nu') h}$$

Here, h is the local soil-cell width used by ShoreKALC. Contact stiffness has units of pressure per displacement.

For sticking contact, the incremental relationships are approximately:

$$\Delta \sigma_n' = k_n \Delta g, \quad \Delta \tau = k_s \Delta s$$

A finite stiffness requires a small relative displacement to transfer force.

Effect on results:

- **Too low:** contact introduces appreciable additional compliance. The wall can move relative to the soil before developing the required traction, affecting displacement and load distribution.
- **Higher:** reduces that elastic relative movement for the same traction.
- **Excessively high:** can worsen numerical conditioning and make convergence more difficult, with little useful improvement in the response.

Increasing β does not increase the Coulomb shear-strength limit at a given normal pressure. It changes the displacement required to mobilise traction.

Blank contact stiffness factor uses 10; the accepted range is one to 100. This factor controls normal and shear penalty stiffness in Frictional mode and is unused by the Bonded shared-node wall. It is dimensionless and does not reduce soil strength or interface capacity. Check sensitivity to this factor and to both soil and wall meshes.

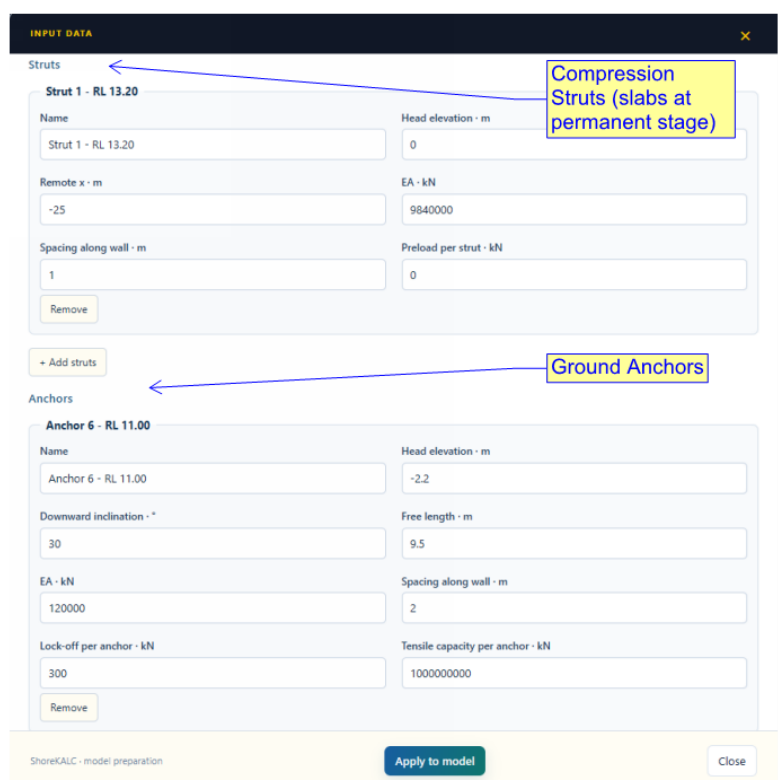
2.2.6. Struts and Anchors

Struts are compression-only springs connected from the wall to fixed remote points; their horizontal remote coordinate, EA, spacing and preload define axial resistance. Anchors act along the entered inclination and are tension-only springs with a free length, EA, spacing, lock-off force and tensile capacity.

For an active elastic support, the stiffness contributed per metre of wall is approximately $k' = EA/(Ls)$, where L is the strut span or anchor free length and s is spacing; the wall displacement projected along the support direction produces its force change. Thus shorter or stiffer supports attract more load, while spacing converts member force to force per metre.

A strut goes slack if it would carry tension. Anchor force is limited by tensile capacity and unloading follows its installation reference. Installation and stressing occur through construction stages, so an input support is not active until installed.

Check remote restraint, tributary spacing, lock-off and capacity against the actual support design.



The screenshot shows the 'INPUT DATA' dialog box in the ShoreKALC software. It is divided into two main sections: 'Struts' and 'Anchors'. The 'Struts' section is titled 'Strut 1 - RL 13.20' and contains fields for Name, Head elevation - m, Remote x - m, EA - kN, Spacing along wall - m, and Preload per strut - kN. The 'Anchors' section is titled 'Anchor 6 - RL 11.00' and contains fields for Name, Head elevation - m, Downward inclination - °, Free length - m, EA - kN, Spacing along wall - m, Lock-off per anchor - kN, and Tensile capacity per anchor - kN. Both sections have a 'Remove' button. There is also an '+ Add struts' button between the sections. At the bottom, there are 'Apply to model' and 'Close' buttons. Two yellow callout boxes with blue arrows point to the 'Struts' and 'Anchors' sections, labeled 'Compression Struts (slabs at permanent stage)' and 'Ground Anchors' respectively.

Figure 7 Anchor/Struts Definition

The below strand table is an illustrative section-property reference. Confirm strand area, modulus, strength and product certification against the current project specification before deriving tendon EA and tensile capacity.

Select lock-off, stressing and test loads through the anchor design and applicable requirements; neither a universal 100–500 kN load range nor a blanket 1.5 times lock-off rule establishes an adequate anchor design. Ground pullout, bonded-zone interaction and prestress losses are outside this solver.

TABLE 3.3.1
TENSILE STRENGTH OF COMMONLY USED WIRE STRAND AND BAR

Material type and Standard	Nominal diameter mm	Area mm ²	Characteristic minimum breaking load kN	Characteristic minimum breaking strength (f_{pb}) MPa
As-drawn wire, AS/NZS 4672.1	5.0	19.6	34.7	1700
	7.0	38.5	64.3	1670
Stress-relieved wire, AS/NZS 4672.1	5.0	19.9	33.8	1700
	7.0	38.5	64.3	1670
7 wire ordinary strand, AS/NZS 4672.1	9.5	55.0	102	1850
	12.7	98.6	184	1870
	15.2	143	250	1790
	15.2	143	261	1830
	15.7	150	279	1860
7 wire compacted strand, AS/NZS 4672.1	15.2	165	300	1820
	18.0	223	380	1700
Hot-rolled bars, AS/NZS 4672.1 (Super grade only)	26	562	579	1030
	29	693	714	1030
	32	840	865	1030
	36	995	1025	1030
	40	1232	1269	1030
	56	2428	2501	1030
	75	4371	4502	1030

Figure 8 Tendon Properties

2.2.7. Surcharges

A surcharge is uniform vertical pressure applied over a retained-ground interval. Specify its start and end x coordinates, elevation and pressure. The resultant per metre of wall is pressure times loaded width, before redistribution through the soil. Elevation zero represents ground surface; a negative elevation represents a buried load in the soil, without creating an excavation.

The resulting wall pressure is not assumed to equal q or a fixed lateral-pressure diagram; it develops from soil deformation, strength, water and support interaction.

Add uniform surcharges under Surcharges and activate each load separately under Construction stages. Surcharge and support changes can be carried into later stages. The analysis includes only the loads selected as active for that stage. The model supports uniform retained-ground intervals; general wall point loads and variable pressure profiles require a different modelling approach.

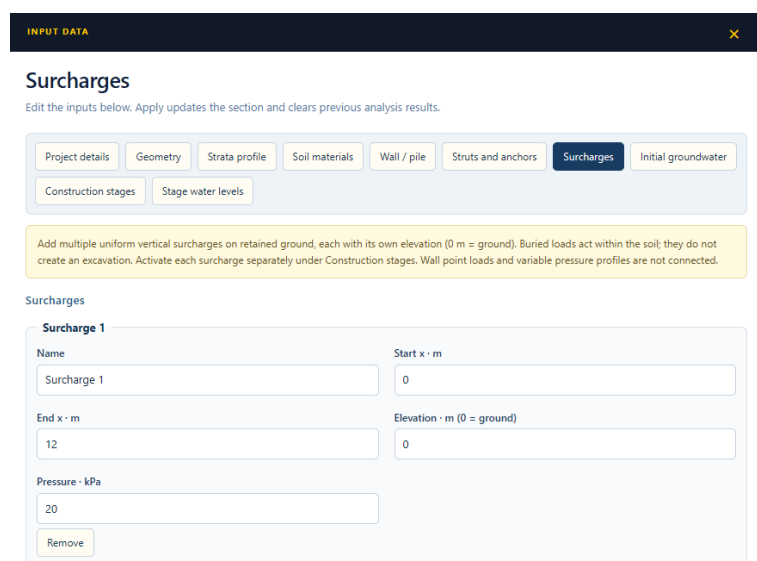


Figure 9 Surcharge Loads

Multiple surcharges can represent separate loaded footprints, such as the illustrated adjacent pad footings. Check their loaded widths, elevations and activation stages against the actual construction sequence.

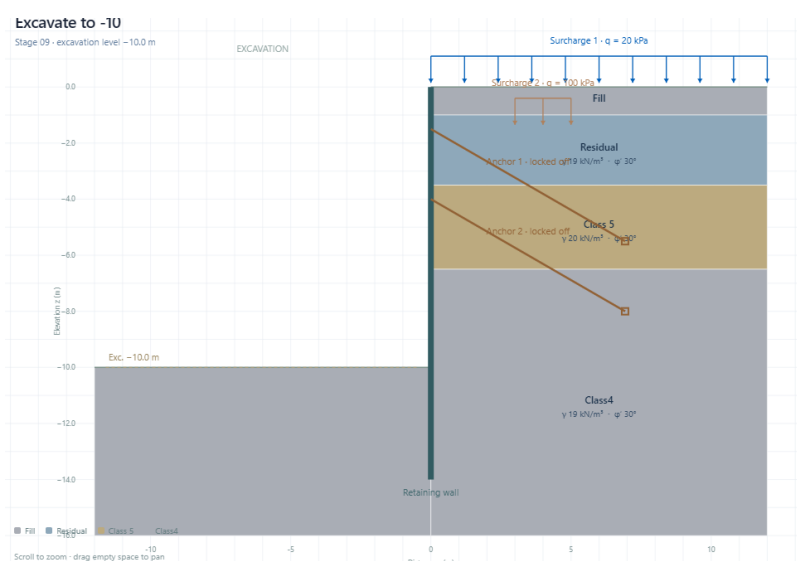


Figure 10 Pad Footing Surcharge

2.2.8. Groundwater and Water-table

The initial groundwater dialog sets whether hydrostatic water pressure is included, the water unit weight γ_w and the common initial head before construction stages introduce separate heads on each side of the wall.

At elevation z below head h_w , $u = \gamma_w(h_w - z)$; above the head, $u = 0$. For example, $\gamma_w = 10 \text{ kN/m}^3$ and 5 m of water head give $u = 50 \text{ kPa}$. In the solver's tension-positive stress convention, total normal stress is effective stress minus pore pressure, $\sigma = \sigma' - u$, so positive pore pressure makes total stress more compressive.

The prescribed water pressure also acts on the wall and excavation floor. ShoreKALC does not calculate seepage, drawdown flow, consolidation or suction.

Stage zero requires one common level; later dewatering or differential heads belong in Stage Water Levels. Check γ_w and saturated unit weights are consistent.

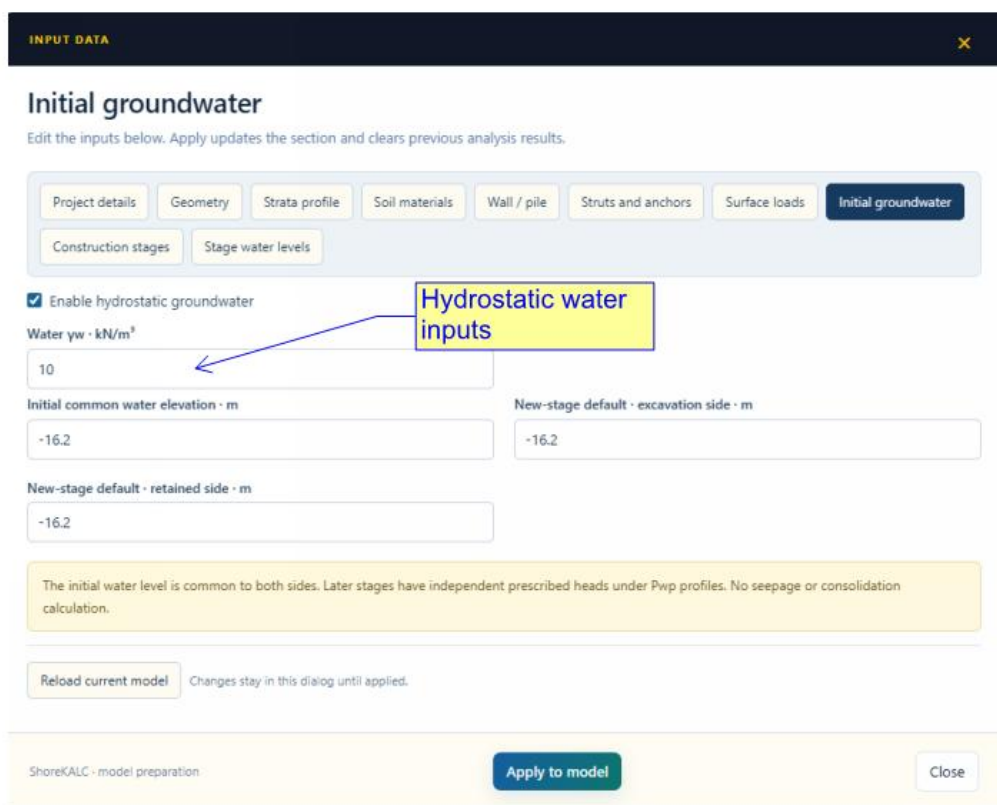


Figure 11 Initial Ground Water

2.2.9. Construction Stages

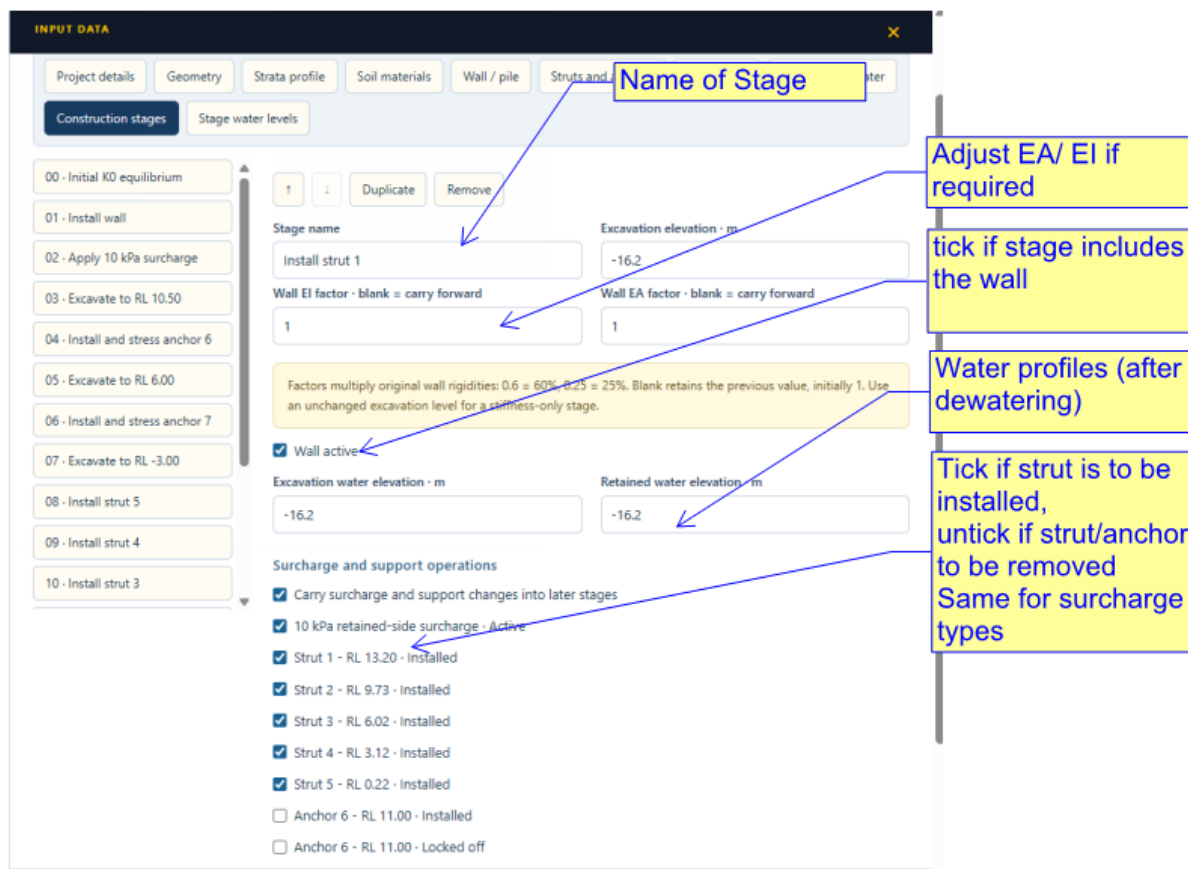
Construction Stages defines the order in which excavation, wall, surcharge, water and support conditions change. Each stage has an excavation elevation and can carry forward or change the wall stiffness factors, activate or deactivate loads, set water heads, and install or remove struts and anchors.

The stage name is a reporting label; its values and selections define the actual configuration. Wall activity is a stage control; each surcharge is activated separately. Mark supports installed when physically introduced, and mark anchors locked off in the stressing stage. The Carry surcharge and support changes option propagates those operations into later stages.

Results are calculated sequentially from the committed preceding stage; an error in installation order or an omitted load activation changes the subsequent stress path and support forces.

Install supports after excavation exposes their heads. Anchor installation and lock-off can be separate stages. Removing an anchor releases its force; removed anchors cannot be reinstalled, and unlocking an installed anchor is unsupported. Once installed, the wall remains active. Excavation levels cannot reverse upward to represent backfill.

Blank stage EA and EI factors carry forward the previous values, initially one. A specified factor multiplies the original wall rigidity rather than the preceding reduced value. Add a stage at the same excavation level to change stiffness without further excavation. Review the sequence after duplicating or reordering stages.



INPUT DATA

Project details | Geometry | Strata profile | Soil materials | Wall / pile | Struts and anchors | Water

Construction stages | Stage water levels

00 - Initial K0 equilibrium
01 - Install wall
02 - Apply 10 kPa surcharge
03 - Excavate to RL 10.50
04 - Install and stress anchor 6
05 - Excavate to RL 6.00
06 - Install and stress anchor 7
07 - Excavate to RL -3.00
08 - Install strut 5
09 - Install strut 4
10 - Install strut 3

Stage name: Install strut 1
Excavation elevation - m: -16.2
Wall EI factor - blank = carry forward: 1
Wall EA factor - blank = carry forward: 1

Factors multiply original wall rigidities: 0.6 = 60%, 0.25 = 25%. Blank retains the previous value, initially 1. Use an unchanged excavation level for a stiffness-only stage.

☒ Wall active

Excavation water elevation - m: -16.2
Retained water elevation - m: -16.2

Surcharge and support operations

☒ Carry surcharge and support changes into later stages

☒ 10 kPa retained-side surcharge - Active

☒ Strut 1 - RL 13.20 - Installed

☒ Strut 2 - RL 9.73 - Installed

☒ Strut 3 - RL 6.02 - Installed

☒ Strut 4 - RL 3.12 - Installed

☒ Strut 5 - RL 0.22 - Installed

☐ Anchor 6 - RL 11.00 - Installed

☐ Anchor 6 - RL 11.00 - Locked off

Annotations:

- Name of Stage
- Adjust EA/ EI if required
- tick if stage includes the wall
- Water profiles (after dewatering)
- Tick if strut is to be installed, untick if strut/anchor to be removed Same for surcharge types

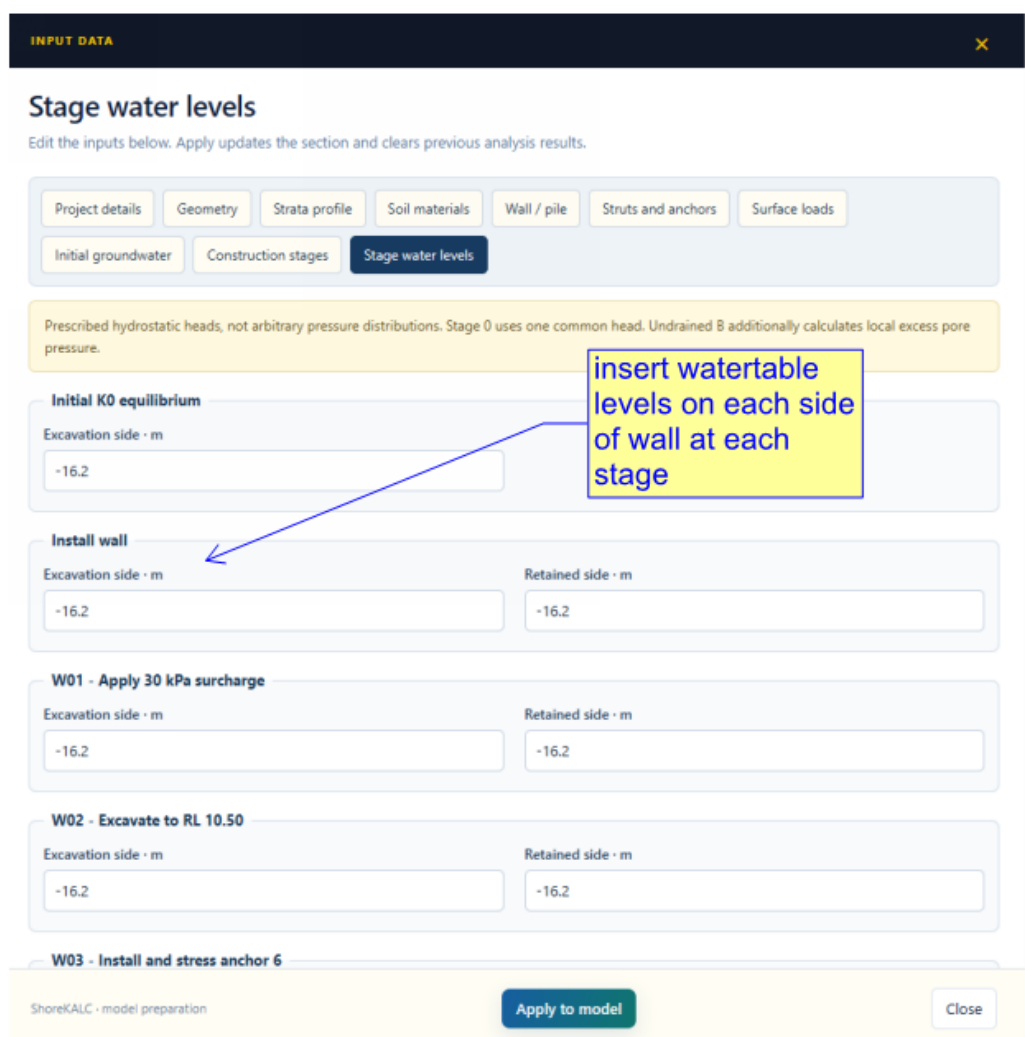
Figure 12 Construction Stages

2.2.10. Stage Water Levels

Stage Water Levels assigns the prescribed hydrostatic head on the excavation side $h_{w,L}$ and retained side $h_{w,R}$ for each construction stage. For either side, $u(z) = \gamma_w \max(0, h_w - z)$, giving a linear pressure increase below the head.

A head difference Δh creates a water-pressure difference $\Delta u = \gamma_w \Delta h$ below both water tables and can load the wall even where soil contact has opened. These entries are head elevations, not arbitrary pressures or seepage boundaries.

ShoreKALC does not solve groundwater flow or consolidation, so specify the heads from the adopted dewatering assumptions and review water loads at every stage. Undrained B excess pore pressure is an additional local response, not a replacement for external hydrostatic heads.



INPUT DATA

Stage water levels

Edit the inputs below. Apply updates the section and clears previous analysis results.

Project details | Geometry | Strata profile | Soil materials | Wall / pile | Struts and anchors | Surface loads

Initial groundwater | Construction stages | **Stage water levels**

Prescribed hydrostatic heads, not arbitrary pressure distributions. Stage 0 uses one common head. Undrained B additionally calculates local excess pore pressure.

Initial K0 equilibrium

Excavation side · m: -16.2

Install wall

Excavation side · m: -16.2 | Retained side · m: -16.2

W01 - Apply 30 kPa surcharge

Excavation side · m: -16.2 | Retained side · m: -16.2

W02 - Excavate to RL 10.50

Excavation side · m: -16.2 | Retained side · m: -16.2

W03 - Install and stress anchor 6

ShoreKALC · model preparation

Apply to model | Close

insert watertable levels on each side of wall at each stage

Figure 13 Staged Water Levels

3. Results

The analysis command builds the soil mesh, maps strata and loads to elements, and checks the model before solving.

3.1. Mesh preparation and analysis workflow

Open Analyse data and choose Solver 1 (quadrilateral) or Solver 2 (triangular mesh). Solver 1 uses Q8 and is the default; Solver 2 uses T6. Set mesh controls, then select Generate mesh & check. Resolve preparation findings before Run staged analysis. Input edits invalidate the previous mesh and results. Legacy CST files reopen with Solver 1; cached CST analyses are not restored.

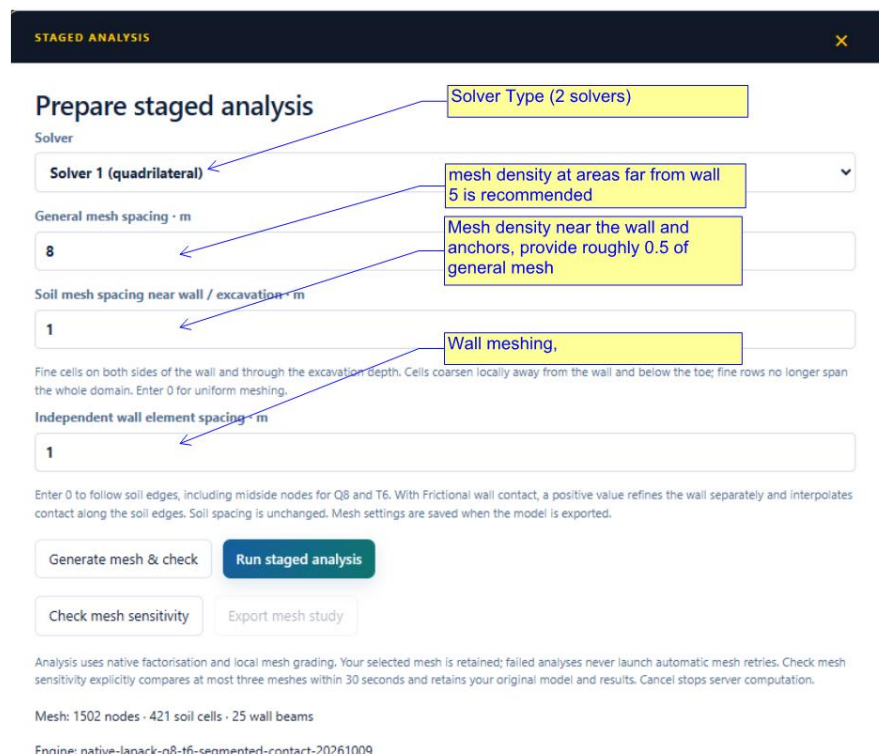
General mesh spacing sets the outer soil mesh target. Soil mesh spacing near wall / excavation refines both sides of the wall and extends below the wall toe and deepest excavation, with gradual coarsening toward the outer domain. Set local soil spacing to zero for uniform meshing. Mandatory geometry and stage elevations affect actual element lengths.

Independent wall element spacing

Independent wall spacing is the target beam length along the wall within the section view, normally vertically. It is unrelated to out-of-plane section width or strut and anchor spacing along the excavation. Set it to zero for the wall to follow soil mesh rows. A positive value requires Frictional contact, which interpolates soil movement along adjacent soil edges to separate wall nodes.

If Bonded contact and Rinter = 1 are selected but Run remains blocked with “Independent wall spacing requires Frictional wall-soil contact mode”, set independent wall spacing to zero and generate the mesh again. Rinter = 1 is valid for Bonded; the incompatible positive wall spacing causes this specific finding.

A finer wall mesh can improve beam-force resolution without refining the soil elements. It cannot remove error from a coarse soil mesh. Compare soil and wall refinement separately, alongside domain and contact-stiffness sensitivity.



STAGED ANALYSIS

Prepare staged analysis

Solver
 Solver 1 (quadrilateral)

General mesh spacing · m
 8

Soil mesh spacing near wall / excavation · m
 1

Independent wall element spacing · m
 1

Generate mesh & check Run staged analysis

Check mesh sensitivity Export mesh study

Mesh: 1502 nodes · 421 soil cells · 25 wall beams

Filename: native-lanark-n8-t6-segmented-contact-20261009

Figure 14 Illustrative analysis dialog; current solver choices are described in Section 3.1.

Mesh sensitivity comparison

A failed staged analysis retains the selected mesh and earlier completed stages; it does not automatically search alternative meshes. Check mesh sensitivity explicitly compares the reference mesh with local soil spacings of approximately 0.8 and 1.2 times the reference, within one shared 30-second deadline. General mesh spacing, solver choice and independent wall spacing remain fixed. The comparison retains the original model and results. Cancel stops server computation.

Use successful comparison cases to assess sensitivity before deliberately changing the model settings and rerunning. Equilibrium convergence is not evidence of mesh independence or a stability factor. Compare movement, moment, support forces, contact state and soil response; a comparison stopped at its deadline is incomplete.

The preparation output records the requested mesh spacing and the generated mesh. Requested spacing is a target: layer boundaries, excavation levels, support heads, water levels and load elevations also determine the final element lengths. Review the generated mesh and record the settings used for the calculation.

Each construction stage starts from the preceding converged state. The solver increments the stage change, assembles soil, wall, support and contact forces, and iterates until the normalized equilibrium residual meets the tolerance. In the report, Stage change is the achieved fraction of the phase force change, not the fraction of excavation depth.

Steps count accepted load increments; retries or cutbacks indicate increments that had to be reduced. Iterations count nonlinear equilibrium updates, so these quantities describe numerical effort rather than safety.

Review high iteration or cutback counts together with the stage change, contact response and mesh sensitivity. A completed equilibrium calculation still requires review of its inputs, boundaries and engineering assumptions.

3.2. User Interface Results

Select View results or View completed results to reopen the current analysis without running it again. Choose a completed construction stage to inspect its geometry, support activity and calculated response. Playback covers completed stages only; an incomplete final run does not show the requested final construction state.

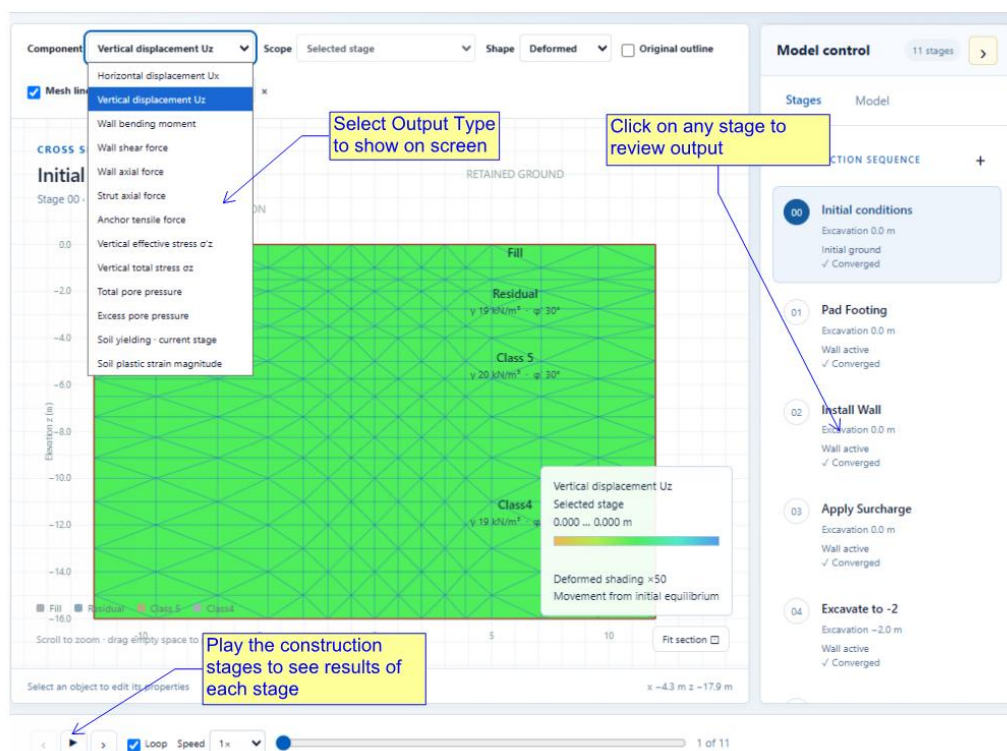


Figure 15 Results viewer and completed stage selection

Choose the result component and stage or envelope in the results controls. Scalar views show soil fields on the mesh; wall and support views show their corresponding structural actions. Use the legend and hover readings for values and units. Ux and Uz display in millimetres, while model coordinates and raw calculation data remain in metres.

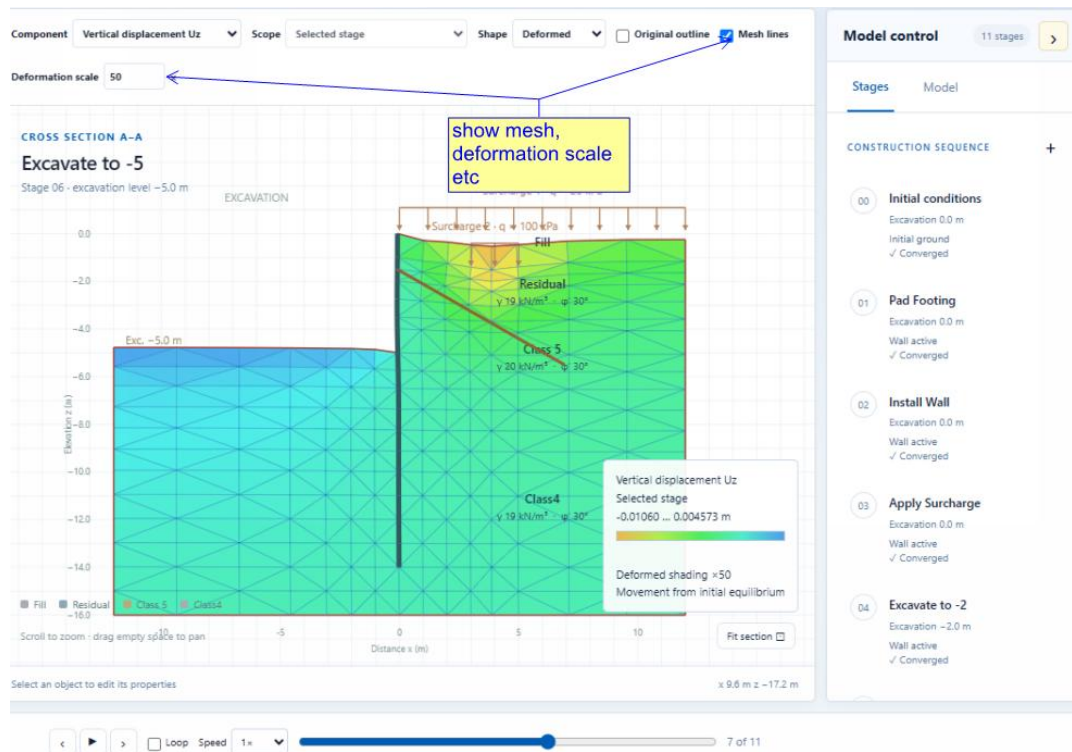


Figure 16 Deformed and undeformed result views with the stated scale

The deformed shape is a display view and may be amplified; read its scale before judging movement.

In View results, use Shape to switch between deformed and undeformed displays, and Original outline to compare the reference geometry. The Home button, labelled Reset to geometry view, returns to the model geometry. Envelope extrema can arise in different stages; inspect the controlling stage for compatible wall actions, support forces and soil response.

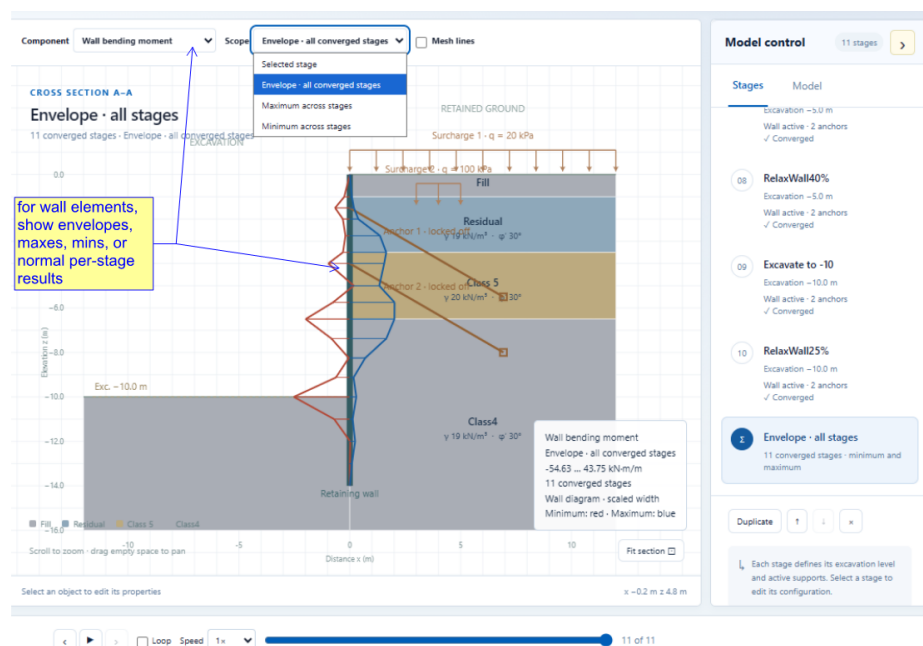


Figure 17 Wall-force envelopes over completed stages

3.3. Calculation Report

Use Create report to open the RKALC calculation report. Save the model file for a durable copy of inputs; the browser's local draft alone is not a project archive.

3.3.1. What the report contains

A ShoreKALC report records a model definition, a staged analysis and the results available for that run. Read it as a traceable chain: inputs and units define the problem; stage history defines what changes and when; numerical diagnostics describe solution progress; structural and soil outputs describe the computed response; engineering-assessment entries screen selected conditions.

The report is a snapshot, so confirm that it corresponds to the intended saved model and analysis run. Screenshots below illustrate typical report content only; values, labels and statuses vary with model and software version.

3.3.2. Model definition and units

The model-definition section lets the reviewer verify geometry, datum, groundwater conditions, strata, material properties, wall rigidity, support geometry, surcharge and contact assumptions before interpreting response.

Trace each reported quantity to the corresponding input and check that its unit and sign are understood. Common line quantities are force per metre of wall (kN/m), moment per metre (kN·m/m), stress and pressure (kPa), displacement (m or mm as labelled), and discrete member force (kN).

For member spacing s , the conversion is $F_{\text{member}} = F_{\text{line}} s$. Elevations use the report datum; do not infer a site RL unless its datum conversion is stated.

3.3.3. Construction sequence and wall contact

The construction table describes the state carried into each phase: excavation elevation, active wall and loads, water heads, installed supports and anchor lock-off events. Interpret each stage as a cumulative history, not as an independent final geometry.

A support installed in one phase may remain active later; an anchor's stress-free reference is set at its stressing event.

The contact summary reports the numerical contact state at wall-soil integration points, such as active, open or sliding points and peak traction.

Point counts depend on mesh and segmentation and are not lengths of wall. Use the contact law and its assumptions in the theory chapter to interpret these values.

		e	e		11.00, Anchor 7 - RL 6.50	Anchor 7 - RL 6.50
12 · W11 - Remove anchor 7	-16.2	Active	Active	-16.2 / -2	Strut 4 - RL 3.12, Strut 3 - RL 6.02, Anchor 6 - RL 11.00	Anchor 6 - RL 11.00
13 · W12 - Install strut 2	-16.2	Active	Active	-16.2 / -2	Strut 4 - RL 3.12, Strut 3 - RL 6.02, Strut 2 - RL 9.73, Anchor 6 - RL 11.00	Anchor 6 - RL 11.00
14 · W13 - Remove anchor 6	-16.2	Active	Active	-16.2 / -2	Strut 4 - RL 3.12, Strut 3 - RL 6.02, Strut 2 - RL 9.73	—
15 · W14 - Install strut 1	-16.2	Active	Active	-16.2 / -2	Strut 4 - RL 3.12, Strut 3 - RL 6.02, Strut 2 - RL 9.73, Strut 1 - RL 13.20	—

Support and lock-off columns describe cumulative state. The initial groundwater head is common to both sides. Subsequent heads are prescribed independently.

Wall contact results

Stage	Active contacts	Open	Sliding	Max compression kPa	Max shear kPa	Max slip m
Initial K0 equilibrium	0	0	0	0	0	0
Install wall	104	2	0	818.343	0.882	0
W01 - Apply 30 kPa surcharge	104	2	1	822.183	12.691	0.001
W02 - Excavate to RL 10.50	96	4	5	808.36	63.575	0.003
W03 - Install and stress anchor 6	96	3	2	830.158	95.541	0.003
W04 - Excavate to RL 6.00	80	9	2	798.037	191.896	0.001
W05 - Install and stress anchor 7	80	7	2	797.73	186.91	0.001
W06 - Excavate to RL -3.00	56	48	4	3,560.205	1,575.454	0.014
W07 - Install strut 5	56	48	4	3,560.205	1,575.454	0.014
W08 - Install strut 4	56	48	4	3,560.205	1,575.454	0.014
W09 - Remove strut 5	56	48	4	3,560.205	1,575.454	0.014
W10 - Install strut 3	56	48	4	3,560.205	1,575.454	0.014
W11 - Remove anchor 7	56	48	2	3,497.619	1,506.457	0.014
W12 - Install strut 2	56	48	2	3,497.619	1,506.457	0.014
W13 - Remove anchor 6	56	48	3	3,323.091	1,354.612	0.01

Figure 18 Example report excerpt: construction stages and wall-contact summary. The displayed stage names and values belong to the illustrative model.

3.3.4. Reading the convergence table

The convergence table is the numerical audit trail for staged equilibrium. It may report completion status, equilibrium residual, iteration count, accepted load steps, cutbacks or retries and elapsed time. A normalized residual has no force unit; it measures the remaining imbalance under the solver's scaling. Convergence means the algorithm met its stopping criteria for that stage.

It is evidence of numerical equilibrium for the adopted model, not proof of physical correctness or safety. If a run stops part-way, distinguish completed stages from the failed or unattempted stage.

Earlier complete results may remain useful, but they do not represent the requested final construction state; envelopes may therefore cover only completed active results.

3 · Analysis and convergence

MESH 414 nodes · 660 soil triangles · 26 wall beams	REQUESTED SPACING General 5 m; local 2 m; wall 1 m (0 = soil rows)
FORMULATION Small-strain effective-stress plane strain; CST triangles; drained Mohr-Coulomb or Undrained B (specified S_u , effective stiffness, no-flow fluid storage). Prescribed hydrostatic groundwater; no consolidation or seepage.	OUTCOME All continuum stages converged.

Stage	Status	Stage change %	Residual	Iterations	Steps	Retries	Time s
00 · Initial K0 equilibrium	Converged	100	1.07e-15	3	3	0	0.2
01 · Install wall	Converged	100	1.60e-15	4	3	0	0.3
02 · W01 - Apply 30 kPa surcharge	Converged	100	3.71e-13	6	3	0	0.4
03 · W02 - Excavate to RL 10.50	Converged	100	2.44e-8	10	3	0	0.5
04 · W03 - Install and stress anchor 6	Converged	100	4.36e-11	6	3	0	0.3
05 · W04 - Excavate to RL 6.00	Converged	100	2.12e-10	7	3	0	0.3
06 · W05 - Install and stress anchor 7	Converged	100	4.25e-11	5	3	0	0.2
07 · W06 - Excavate to RL -3.00	Converged	100	5.12e-10	115	6	3	10.4
08 · W07 - Install strut 5	Converged	100	8.23e-10	0	3	0	0
09 · W08 - Install strut 4	Converged	100	8.23e-10	0	3	0	0
10 · W09 - Remove strut 5	Converged	100	8.23e-10	0	3	0	0
11 · W10 - Install strut 3	Converged	100	8.23e-10	0	3	0	0.1
12 · W11 - Remove anchor 7	Converged	100	1.71e-7	14	3	0	0.4
13 · W12 - Install strut 2	Converged	100	1.72e-7	0	3	0	0
14 · W13 - Remove anchor 6	Converged	100	1.17e-8	20	3	0	0.5
15 · W14 - Install strut 1	Converged	100	1.18e-8	0	3	0	0

Stage change is the achieved fraction of the phase force change, not a fraction of excavation depth. Failed stages and subsequent stages have no completed result plots. Prior converged results remain valid as results of those earlier stages.

Figure 19 Illustrative legacy report excerpt. CST is not a current workspace option; use Solver 1 or Solver 2. Iterations and residuals are model-specific.

3.3.5. Force envelopes and per-stage structural actions

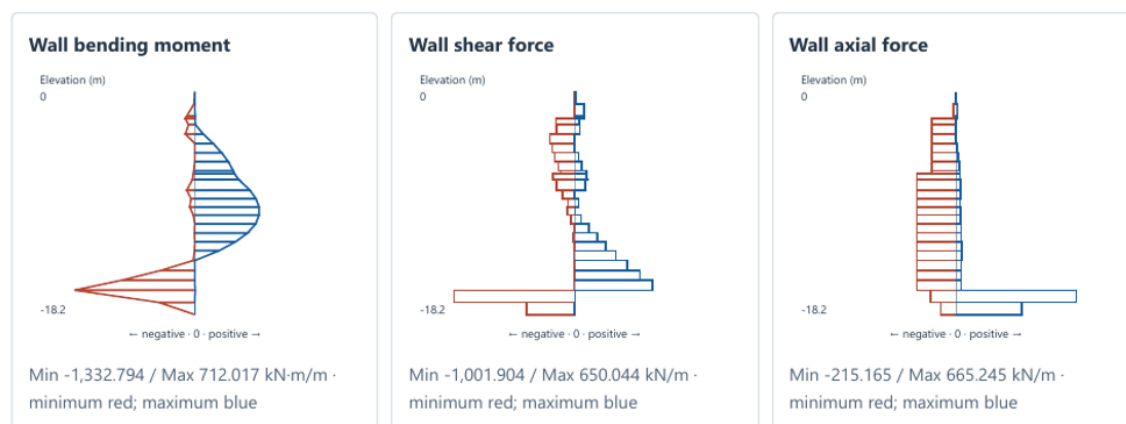
An envelope reports signed extrema at each wall location over the stages included in the analysis. A minimum and maximum can occur in different stages, so the two envelope curves are not a simultaneous force state.

Use envelopes to locate potentially critical demand, then open the controlling stage and review its compatible moment, shear, axial force, supports and soil state together.

Confirm the report's sign convention before interpreting positive and negative values. Inactive structural components do not carry stage demand. An envelope is a demand summary, not a structural capacity check.

4 · Wall and support force envelopes

Across all converged stages. Signed minimum and maximum at each station; inactive members are excluded.



Anchor	Min kN/m	Max kN/m	Min kN/member	Max kN/member	Entered capacity / resistance kN	Assessment
Anchor 6 - RL 11.00	150	271.766	300	543.532	1,000,000,000	Below tensile capacity
Anchor 7 - RL 6.50	87.5	175	175	350	350	At tensile capacity

Strut	Min kN/m	Max kN/m	Min kN/member	Max kN/member	Entered capacity / resistance kN	Assessment
Strut 5 - RL 0.22	0	0	0	0	—	Resistance not assessed
Strut 4 - RL 3.12	0	16.788	0	16.788	—	Resistance not assessed
Strut 3 - RL 6.02	0	148.168	0	148.168	—	Resistance not assessed
Strut 2 - RL 9.73	0	257.891	0	257.891	—	Resistance not assessed
Strut 1 - RL 13.20	0	0	0	0	—	Resistance not assessed

Figure 20 Example report excerpt: wall-force envelopes and support demands. Envelope extrema may come from different stages.

3.3.6. Support force tables

Support output should be read together with support type, spacing, orientation and activity stage. A line force represents the support contribution per unit wall length; a member force applies to one discrete strut or anchor and follows the stated spacing conversion. Inactive or not-yet-installed supports have no current stage demand.

Where capacity assessment is available, check exactly which limit is represented: an anchor tensile cap is not a bond or pull-out calculation, and a strut compression limit does not by itself establish buckling resistance. If a required resistance input is absent, an explicit “Not assessed” or equivalent status means no capacity conclusion was made.

3.3.7. Stage geometry and wall movement

A stage page identifies the construction state and shows the computed wall shape and structural actions for that stage. Displacement is generally measured from the initial equilibrated configuration, so it is the change from the analysis datum rather than an absolute survey position. Read axis labels and any plot magnification before judging the drawn shape; visual deformation is often amplified. The moment, shear and axial-force diagrams belong to the selected stage. Where a table gives values at element ends or stations, use the stated local/global sign convention and retain stage context.

Stage 15 · W14 - Install strut 1

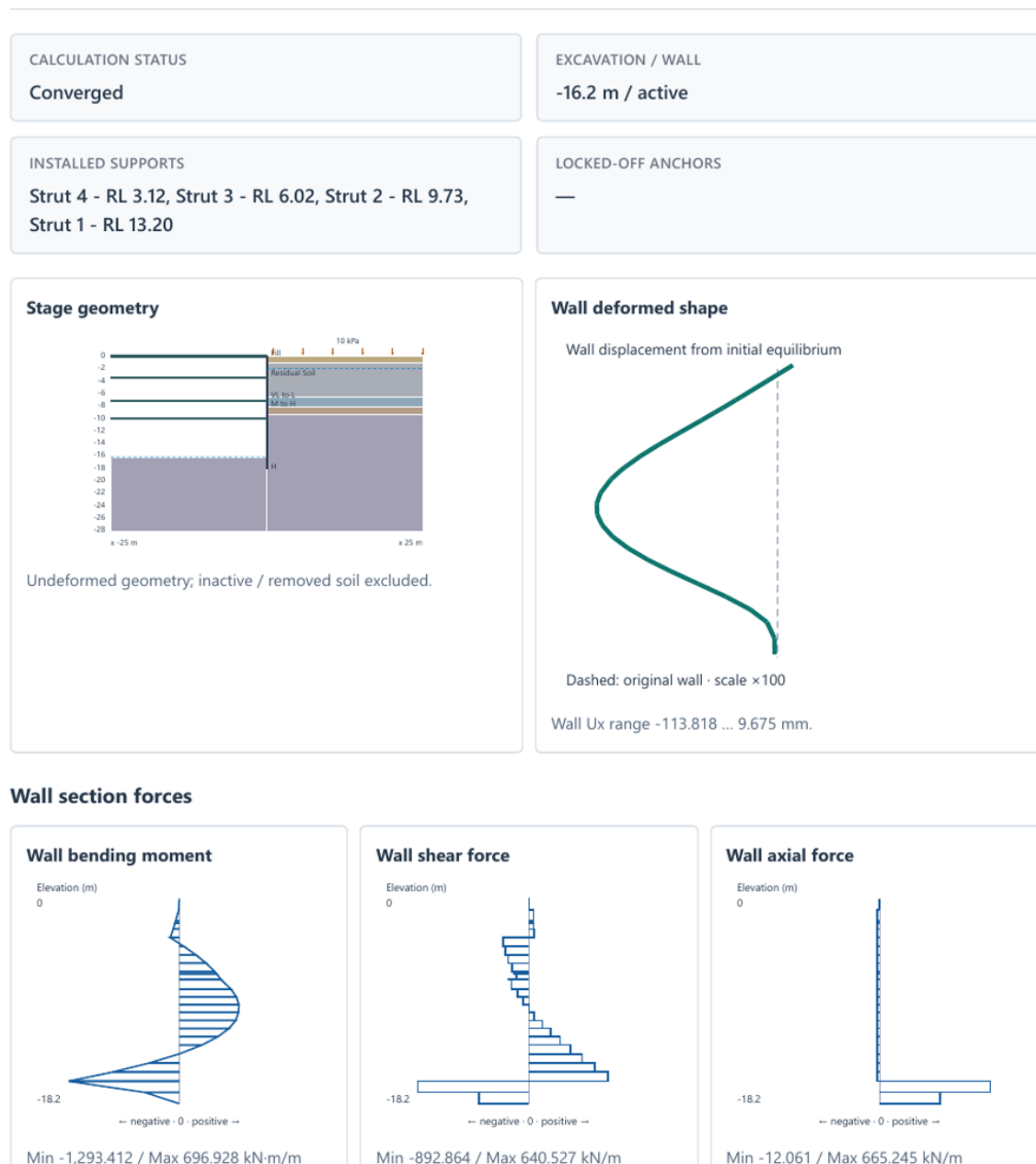


Figure 21 Example report excerpt: one stage's wall movement and structural actions. Plot scaling and numerical results are specific to that model.

3.3.8. Soil displacement and stress contours

Contour panels show selected computed fields over the model mesh for a reported stage. U_x and U_z are horizontal and vertical displacement components; with z positive upward, negative U_z indicates downward movement. Stress contours are field values at the displayed sampling locations and may be extrapolated or interpolated for plotting. Distinguish effective stress, total stress and pore pressure.

Under the tension-positive stress convention used here, effective stress and total stress are negative in compression; pore pressure is positive in compression. In the usual effective-stress relation, $\sigma = \sigma' - p$, or $\sigma' = \sigma + p$.

Read units, scale limits and stage labels; local extrema and contour colours need not describe a whole failure mechanism.

Check	Status	Detail
Base heave / bearing failure	Not assessed	Terzaghi-type base stability and foundation bearing checks require mechanism-specific geometry and strength assumptions.
Soil disintegration / strength loss	Not assessed	Plastic strain is not damage. Softening, erosion, piping, liquefaction and material breakup are not modelled.

Anchor and strut forces

Strut	Min kN/m	Max kN/m	Min kN/member	Max kN/member	Entered capacity / resistance kN	Assessment
Strut 1 - RL 13.20	0	0	0	0	—	Resistance not assessed
Strut 2 - RL 9.73	257.891	257.891	257.891	257.891	—	Resistance not assessed
Strut 3 - RL 6.02	74.405	74.405	74.405	74.405	—	Resistance not assessed
Strut 4 - RL 3.12	16.788	16.788	16.788	16.788	—	Resistance not assessed

Soil results · selected stage only

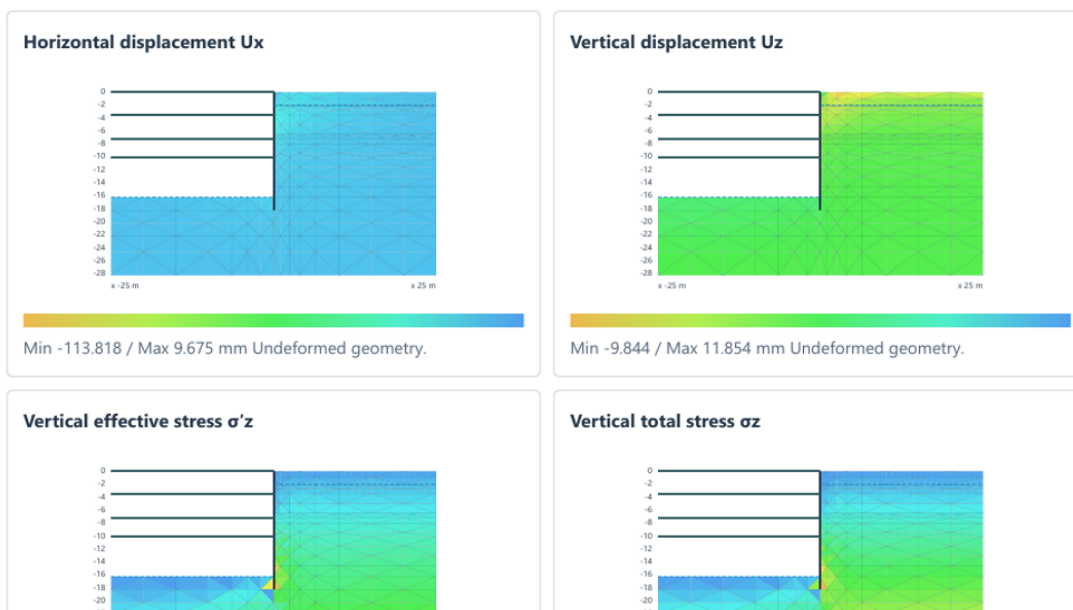


Figure 22 Example report excerpt: selected assessment entries, support results and contour output. The assessment scope must be read from its labels and rules.

3.3.9. Pore pressure, plastic strain and current yielding

Where shown, hydrostatic pressure is the prescribed water-pressure field and excess pressure is the calculated increment associated with the adopted undrained formulation. Their combination and sign must be read with the report's stated convention; these outputs do not constitute a seepage or consolidation analysis. Plastic-strain panels describe the reported constitutive history measure and should not automatically be read as accumulated damage or a factor of safety.

A current-yielding indicator describes whether the accepted state is on or near a yield condition under the implemented criterion; absence of current yielding does not erase prior plastic history. Interpret these fields with material parameters, stage changes, mesh and equilibrium diagnostics.

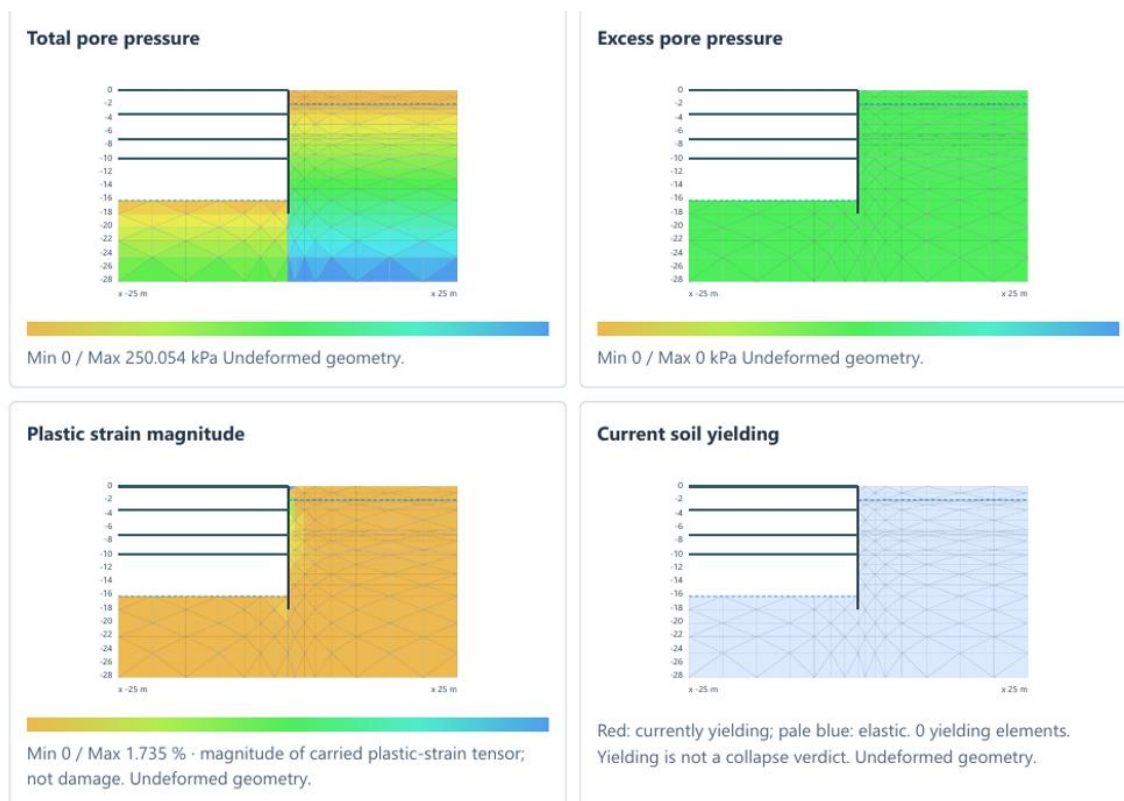


Figure 23 Example report excerpt: pore-pressure, plastic-strain and current-yielding panels. These fields show the illustrated stage only.

3.3.10. Engineering assessment and limits

Each stage report presents requirement checks and supporting observations.

- **PASS:** means the entered criterion is met by the implemented calculation;
- **FAIL:** means an entered movement limit or support design resistance is exceeded.
- **PASS- Target verified:** means equilibrium has been verified at the requested strength-reduction target; it does not establish a limiting factor of safety or a required embedment depth.
- **INCONCLUSIVE:** means the available numerical or input evidence does not resolve the requested check.
- **NOT ASSESSED:** identifies an unavailable criterion, resistance input or required calculation result; the supporting detail explains the omission.
- **NOT APPLICABLE:** identifies a check that does not apply to the stage.
- **CAPACITY REACHED:** means an ideal anchor model has reached its tensile cap, within the numerical tolerance used for this check; unconstrained excess demand and additional reserve are unknown. Yielding counts are observations and do not, by themselves, establish failure.

Read each status with its stated rule, basis and stage. The stage summary covers assessed checks only. Omitted optional limits do not fail automatically, and a passed subset is not certification of the whole design.

Surface settlement is the maximum immediate downward displacement at active retained-ground surface soil nodes, measured from initial equilibrium; it does not assess footing settlement, consolidation or differential asset movement.

Wall movement is the maximum absolute horizontal displacement at active wall nodes, also measured from initial equilibrium. Movement and entered resistance comparisons use unrounded values and accept equality.

An anchor that reaches its model tensile cap is reported as CAPACITY REACHED unless its entered design resistance is exceeded, in which case it fails.

3.3.11. Scope of engineering assessments

Optional soil stability and toe-ground strength-reserve targets branch from completed active-wall excavation stages. The soil branch reduces active soil strength and frictional interfaces; the toe branch reduces only excavation-side soil between formation and toe and its wall contacts. Loads, pore pressures, stiffness and installed support capacities stay fixed. The accepted trial verifies equilibrium at the requested reduction; it does not calculate a limiting factor of safety. The toe region is not a passive wedge and does not give required embedment depth.

Yielding counts are observations of active elements currently yielding in the accepted increment. “Yielding below formation” is a integration-point-based geometric count, not passive resistance or a collapse check. Anchor resistance comparisons use an engineer-entered governing design resistance on the action basis of the analysis; the ideal tensile cap is still a separate model limit. Strut resistance is engineer-entered and must include buckling and connection limits; the elastic spring does not model failure redistribution.

Wall section capacity, anchor bond and ground pullout, strut failure redistribution, limiting global stability factor, required embedment, basal heave, hydraulic uplift, piping, consolidation, differential asset movement and joint-controlled rock stability remain outside these verdicts. Do not infer them from convergence or from another green status.

3.3.12. Reviewing the report as a glass box

A useful review follows each conclusion back through the report: identify the stage and result; find the governing input and unit; identify the implemented equation or check; inspect the numerical diagnostic and any stated limitation.

For repeatability, retain the model version, input file, software/version information, mesh controls and analysis report together. Compare demands with capacities only when they refer to compatible stages, sign conventions, spacing basis and design basis.

A report can make a calculation transparent while still relying on assumptions that require independent engineering judgement.

4. Theory

This part explains the engineering idealisation and numerical calculation used by ShoreKALC. It starts with assumptions, units and signs, then develops the soil, wall, support and contact laws and their assembly through construction stages. The appendices expand the constitutive derivatives, contact transfer, mesh generation and element equations.

4.1. Relationship to established methods

The governing mechanics and finite element ingredients are established methods. The standard Mohr-Coulomb envelope and non-associated flow are described in Itasca documentation [1]; non-smooth principal stress return mapping is discussed by Sysala and Cermak [2]. ShoreKALC uses its own simultaneous active set algorithm and selected branch tangent. These references explain the theory rather than certify an identical implementation. The PLAXIS material manual [3] is a reference for drainage terminology; ShoreKALC has its own discretisation and storage treatment.

Soil stiffness is assembled from a two dimensional continuum, while struts and anchors are discrete springs. The constitutive return, installation reference, contact transfer and stage transition are linked parts of the same equilibrium calculation. The theory therefore specifies both local laws and their assembly and commitment.

4.2. Assumptions and applicability

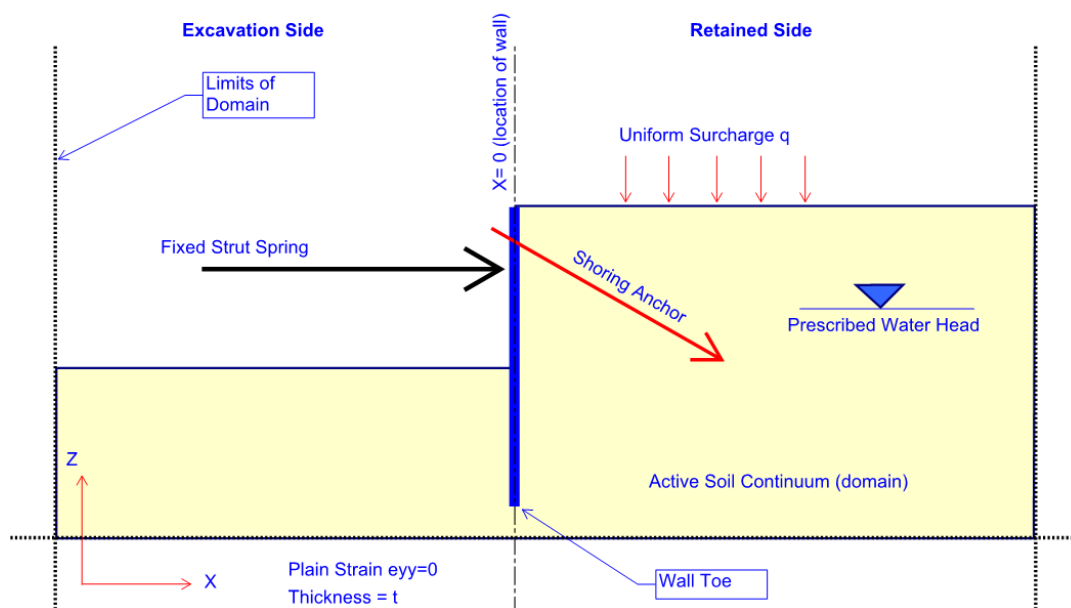


Figure 24 Section mechanics and sign convention. Schematic geometry with excavation to the left.

Assumption	Consequence for engineering interpretation
Small strain and fixed geometry	Strains and rotations must remain compatible with the linear kinematic approximation. No updated geometry or second order wall instability is calculated.

Assumption	Consequence for engineering interpretation
Plane strain and uniform section width	The section represents a long excavation. Three dimensional corners, ends and individual pile effects require separate assessment.
Isotropic constant elastic stiffness	One E' and v' per layer describe loading and unloading. Modulus variation with stress, strain and history is excluded.
Perfect plasticity	Strength has no hardening or softening law. Plastic localisation and displacement sensitivity require careful mesh review.
Prescribed hydrostatic heads	Water pressures change immediately with stage inputs. Duration and drainage paths do not determine their evolution.
Fixed remote support points	Remote frame, anchorage and ground movements are omitted. Tendon free length sets stiffness but not pullout resistance.
Elastic wall	EA and EI govern response; yielding, cracking and section resistance are not calculated. Stage multipliers change elastic rigidity only.
Finite computational boundaries	Side and base restraints can affect results. Boundaries must be varied to demonstrate adequate extent.

Input values must represent the adopted characteristic or design scenario consistently. The solver does not automatically apply geotechnical material factors or structural load factors. If factored strengths or actions are used, record the factors, combination and design basis outside the solver inputs and in the project calculation report. Analysis demands must be compared with capacities under the applicable project standard separately.

4.3. Coordinates units and signs

The in plane axes are x horizontally toward retained ground and z vertically upward; y is out of plane. Gravity acts in negative z. Excavation is to the left of the wall, so wall movement toward the excavation normally has negative U_x in the native result convention. Elevations are local coordinates in metres; an RL datum can be converted using $z = RL - RL_{ground}$. That datum conversion must also be applied to strata, wall toe, water heads and support levels.

$$z = RL - RL_{ground} \quad (1)$$

Soil stress and strain use tension positive signs. Compression is negative in stress output. Pore pressure p is positive in compression and subtracts from the normal total stresses. The interface law separately uses normal contact compression positive; mixing the two sign systems without conversion reverses contact and effective stress interpretation.

$$s' = [\sigma'_{xx}, \sigma'_{zz}, \sigma'_{yy}, \tau_{xz}]^T; \quad e = [\epsilon_{xx}, \epsilon_{zz}, \epsilon_{yy}, \gamma_{xz}]^T \quad (2)$$

$$\gamma_{xz} = \partial U_x / \partial z + \partial U_z / \partial x; \quad \epsilon_{yy} = 0 \quad (3)$$

$$s = s' - p m; \quad m = [1, 1, 1, 0]^T; \quad p = p_h + p_e \quad (4)$$

Here s' denotes effective stress, s total stress, p_h prescribed hydrostatic pressure and p_e excess pressure. Shear stress is identical in total and effective representations. The out of plane normal stress is retained although $\epsilon_{yy} = 0$; yielding is evaluated using all three principal stresses.

Quantity	Unit or convention
Coordinates and translations	m; displayed displacement commonly converted to mm
Soil E' c' S_u and stresses	kPa = kN/m ²
Unit weight γ and γ_w	kN/m ³
Wall EA	kN/m of wall width
Wall EI	kN m ² /m of wall width
Wall axial force and shear	kN/m of wall width
Wall moment	kN m/m of wall width
Strut and anchor EA	kN per physical support
Support force input	kN per support; divided by out of plane spacing for analysis
Support spring stiffness	kN/m displacement per metre of wall width
Angles and rotations	Input friction dilation and inclination in degrees; beam rotations in radians

Plane-strain quantities are expressed per metre of wall width. Soil stiffness, gravity and structural actions use the same section-width basis. For a support at spacing s , multiply its reported line force by s to obtain the force in one physical member. Use a consistent width basis when comparing forces, moments and resistances.

4.4. Governing equilibrium and finite element discretisation

With inertia neglected, the total stress field balances body force and boundary traction. The weak form is used to assemble nodal equilibrium, including wall, contact and support contributions. Prescribed displacements restrict the admissible virtual displacement field.

$$\nabla \cdot \sigma + b = 0; \quad \sigma n = \bar{t} \text{ on traction boundaries} \quad (5)$$

$$\int \Omega \delta \epsilon^T s \, dV = \int \Omega \delta u^T b \, dV + \int \Gamma t \delta u^T \bar{t} \, dS \quad (6)$$

The workspace offers two quadratic plane-strain soil formulations. Solver 1 uses eight-node serendipity quadrilaterals (Q8) with 2×2 Gauss integration. Solver 2 uses straight-sided six-node triangles (T6) with three area-integration points. Each soil node has U_x and U_z . Every integration point has its own effective stress, plastic strain and excess-pressure history. Both options reuse the same material model, wall beams, contacts, support laws and nonlinear solution procedures. These are continuum displacement elements, not shell elements [7].

$$u(x, z) = \sum_i N_i(x, z) u_i; \quad \Delta e_q = B_q \Delta u_e \quad (7)$$

$$N_i = L_i(2L_i - 1); \quad N_4 = 4L_1L_2; \quad N_5 = 4L_2L_3; \quad N_6 = 4L_3L_1 \quad (8)$$

For T6, L1, L2 and L3 are barycentric coordinates with sum one. The first three functions belong to vertices; N4, N5 and N6 belong to edge midpoints 1–2, 2–3 and 3–1. Q8 functions are defined on natural coordinates ξ and η in Appendix F. Physical gradients follow from the element geometry. The strain matrix block for each node is shown below; the third row is zero under plane strain.

$$B_i = \begin{bmatrix} \partial N_i / \partial x & 0 \\ 0 & \partial N_i / \partial z \\ 0 & 0 \\ \partial N_i / \partial z & \partial N_i / \partial x \end{bmatrix} \quad (9)$$

$$f_{int,e} = t \sum_q A_q B_q^T s_q; \quad K_e = t \sum_q A_q B_q^T D_{alg,q} B_q \quad (10)$$

The tangent changes as soil yields or contact changes branch. Total stress enters the internal-force sum; the effective skeleton tangent is supplemented by the no-flow contribution for Undrained B. A_q is the physical quadrature weight: $\det J_q$ for each Q8 point, and one third of the triangle area for each T6 point. Initial stress, pore pressure and unit weight are sampled at these points. Shape-function integration distributes body and boundary loads consistently.

$$F_{z,i} = -t \sum_q A_q \gamma_q N_i(q) \quad (11)$$

Quadratic nodal interpolation provides displacement continuity along connected edges. Q8 refinement transitions use exact quadratic displacement constraints; T6 transitions have shared matching corner and midside nodes. Material output is stored at integration points and may be discontinuous between elements. Contour shading does not establish stress accuracy. Distorted elements, nearly incompressible response and plastic localisation can affect conditioning and movement; compare mesh and domain sensitivity.

Solver 1 uses locally coarsened rectangular Q8 cells. A hanging edge node satisfies the neighbouring coarse quadratic edge interpolation exactly; its forces and stiffness are condensed consistently. Solver 2 triangulates graded cells and their transition polygons with matching shared nodes. T6 edges are straight with centred midside nodes. It is a conforming graded triangular mesh, not a general unstructured Delaunay mesher.

Solver 1 remains the default. Solver 2 provides an alternative discretisation for comparison; benchmark evidence does not establish generally greater accuracy or mesh independence. Appendix H records the numerical checks, published comparisons and remaining differences.

4.5. Elastic soil skeleton

Each layer has effective Young modulus E' and Poisson ratio ν' . The elastic skeleton is isotropic in three dimensions and is restricted to the plane strain kinematics only during element assembly. G is the shear modulus, λ_e the Lamé constant and K' the effective bulk modulus.

$$G = E' / [2(1 + \nu')]; \quad \lambda_e = E' \nu' / [(1 + \nu')(1 - 2\nu')] \quad (12)$$

$$K' = E' / [3(1 - 2\nu')]; \quad \Delta s' = D_e (\Delta e - \Delta e^p) \quad (13)$$

$$D_e = \begin{bmatrix} \lambda_e + 2G & \lambda_e & \lambda_e & 0 \\ \lambda_e & \lambda_e + 2G & \lambda_e & 0 \\ \lambda_e & \lambda_e & \lambda_e + 2G & 0 \\ 0 & 0 & 0 & G \end{bmatrix} \quad (14)$$

The shear entry is G because γ_{xz} is engineering shear. The stiffness must be calibrated to the deformation problem; an arbitrary strength based modulus correlation is not a substitute for site stiffness evidence. Since E' is constant, excavation unloading uses the same elastic modulus as loading. Choosing a larger E' to imitate unloading stiffness changes the complete response, including the initial equilibrium and subsequent loading.

Soil stiffness requires $0 < E' \leq 10^{12}$ kPa and $0 \leq \nu' < 0.495$. These are numerical input bounds. Select physically appropriate values from the ground interpretation. Q8 and T6 are displacement formulations; near-incompressible response can still produce volumetric locking and requires sensitivity assessment.

4.6. Drained Mohr-Coulomb strength and flow

Drained layers use effective cohesion c' , friction ϕ' , dilation ψ and the prescribed hydrostatic pressure field. Plasticity is rate independent and perfectly plastic. The classical shear strength equation can be written using positive effective compression σ'_n, c on a potential shear plane. It is useful for understanding the adopted parameters; the implementation actually evaluates principal stress planes.

$$\tau_f = c' + \sigma'_n \tan \phi' \quad (15)$$

Let p_i denote a tension positive principal effective stress. For each ordered pair of distinct principal directions i and j , the implementation checks one linear shear plane. All six permutations are checked; there is no need to sort the out of plane stress into a fixed major or minor slot. Feasible states satisfy every yield inequality.

$$f_{ij} = (1 + \sin \phi') p_i - (1 - \sin \phi') p_j - 2c' \cos \phi' \leq 0 \quad (16)$$

$$g_{ij} = (1 + \sin \psi) p_i - (1 - \sin \psi) p_j; \quad i \neq j \quad (17)$$

Plastic flow follows the gradient of g_{ij} . $\psi = \phi'$ gives associated shear flow; $\psi < \phi'$ gives nonassociated flow and generally an unsymmetric tangent. $\psi = 0$ suppresses volumetric plastic strain for the shear planes but does not suppress elastic volumetric strain. The accepted parameter range is $c' \geq 0$ and $0 \leq \psi \leq \phi' < 89$ degrees.

Drained materials also check three principal tension-cutoff planes. The workspace uses zero tensile strength, so drained soil cannot sustain positive principal tensile stress. The following equations give the general cutoff law in terms of tensile strength f_t ; its flow is associated.

$$f_{t,i} = p_i - f_t \leq 0; \quad g_{t,i} = p_i \quad (18)$$

$$0 \leq f_t \leq c' / \tan \phi', \quad \text{for } \phi' > 0 \quad (19)$$

The bound prevents the tension cutoff from lying beyond the Mohr Coulomb apex. The zero friction case has no such finite apex bound. Soil cohesion does not automatically represent a dependable tensile strength, and the workspace does not expose tensile strength as an independent layer parameter.

4.7. Constitutive return mapping and tangent

Every trial integration starts from a copy of the committed material state. The elastic predictor adds the skeleton elastic increment to the committed effective stress and calculates its principal values and directions. If all yield functions satisfy the scale dependent material tolerance, the step is elastic. Otherwise the algorithm enumerates independent active sets of one, two or three planes from the six shear and three tension planes. Return mapping and consistent linearisation background is given in [2,6].

$$s'_{\text{trial}} = s'_n + D_e \Delta e \quad (20)$$

In principal space, A collects the active yield normals as rows, G_p collects the corresponding flow gradients as rows, and l collects plane limits. D_p is the three by three normal block of D_e . Solving the following system returns the principal stresses simultaneously to an admissible face, edge or corner.

$$H = A D_p G_p^T; \quad H \Delta \lambda = A p_{\text{trial}} - l \quad (21)$$

$$p_{\text{return}} = p_{\text{trial}} - D_p G_p^T \Delta \lambda \quad (22)$$

$$\Delta \lambda \geq 0; \quad A_{\text{all}} p_{\text{return}} - l_{\text{all}} \leq \text{tolerance} \quad (23)$$

The candidate is accepted only if the multiplier and all surface tests pass. Singular dependent sets are skipped. Three independent planes are sufficient in three dimensional principal stress space. The approach does not smooth the envelope, substitute Drucker Prager or clip offending stress components independently. The return direction and yield normal differ when shear flow is non-associated.

Corrected principal stresses are recomposed with the trial principal directions. Stored plastic strain is recovered from the difference between total strain increment and the elastic strain associated with the returned stress increment. For engineering shear, elastic shear strain is $\Delta\tau/G$. Neither plastic history nor excess pressure is committed until global equilibrium accepts the increment.

$$\Delta e^p = \Delta e - D_e^{-1}(s'_{\text{return}} - s'_n) \quad (24)$$

The algorithmic tangent differentiates the selected constitutive return branch, including rotation of the in-plane principal directions. At yield corners the derivative is piecewise defined. The fixed-direction principal block below forms part of the full tangent; the Cartesian transformation also accounts for changing principal directions.

$$D_{p,\text{return}} = D_p - D_p G_p^T (A D_p G_p^T)^{-1} A D_p \quad (25)$$

The full Cartesian tangent also differentiates principal directions before assembly. Coincident principal stresses and changes of active set are non-smooth cases. Global residual reduction, branch recovery and cutbacks govern acceptance. The yield diagnostic is the maximum residual across all planes; it is a constitutive feasibility measure, not a factor of safety.

4.8. Undrained B response

Undrained B requires effective E' and ν' , explicit positive undrained strength S_u , and a numerical undrained Poisson ratio ν_u . The six shear planes use $c = S_u$ and $\phi = \psi = 0$. The stored material stress remains effective; pore pressure is stored separately and converts it to total stress for equilibrium. The original effective friction angle entered for the layer can still be used for automatic initial K_0 , but does not determine Undrained B shear strength.

$$f_{ij} = p_i - p_j - 2S_u \leq 0 \quad (26)$$

This is a pressure independent Tresca type envelope expressed through all principal pairs. Unlike drained layers, the tension cutoff is disabled in Undrained B by assigning its limits a very large value. It is therefore incorrect to apply the drained zero tension assumption to these layers. S_u is held fixed; no pressure dependent effective strength recovery or strain dependent degradation is calculated.

A local no flow bulk contribution, with Biot coefficient equal to one, models fluid storage. The numerical ν_u sets the target undrained bulk modulus K_u using the skeleton shear modulus. $M_f = K_u - K'$ is the additional fluid bulk stiffness. Effective stiffness conventions for Undrained B are documented in [3]; the equations here are the specific implemented storage law.

$$K_u = 2G(1 + \nu_u)/[3(1 - 2\nu_u)]; \quad M_f = K_u - K' \quad (27)$$

$$\Delta p_e = -M_f \Delta \epsilon_v; \quad \Delta \epsilon_v = \Delta \epsilon_{xx} + \Delta \epsilon_{zz} + \Delta \epsilon_{yy} \quad (28)$$

$$D_{\text{total}} = D_{\text{skeleton,alg}} + M_f m m^T \quad (29)$$

Compression gives negative volumetric strain and therefore positive excess pressure. The material response returns the skeleton tangent; the continuum adds M_f to all nine normal entries when no flow response is enabled. Stage zero disables excess pressure generation to establish initial equilibrium; subsequent workspace stages generate and retain excess pressure. Successful increments carry p_e forward with the other material history.

The default v_u is 0.49. Admissible values satisfy $0.45 \leq v_u \leq 0.495$ and $v' < v_u$. This is finite storage, not exact incompressibility and not a mixed displacement pressure element. No pressure diffusion equation is solved. The selected layer is treated as saturated throughout, including portions above a prescribed water head. Negative excess pressure has no cavitation cap, and no partial saturation law is provided. These features require assessment before treating calculated effective stress paths as representative of a field excavation.

4.9. Groundwater gravity and boundary water loads

Each stage prescribes left and right water elevations. Hydrostatic pressure is evaluated at every soil integration point using the head on that side of the wall. With groundwater disabled, the hydrostatic field is dry. Water unit weight γ_w defaults to 9.81 kN/m^3 . This nonnegative pressure field does not represent capillary suction.

$$p_h(x, z) = \gamma_w \max(0, h_{\text{side}} - z) \quad (30)$$

Gravity uses γ_{sat} below the prescribed head and γ above it, sampled at each integration point. Missing γ_{sat} falls back to γ . The continuum applies full total unit weight and subtracts pore pressure from effective stress during total-stress assembly; simultaneously substituting submerged weight would double count buoyancy. Effective overburden for initial stress subtracts hydrostatic pressure from layered total overburden.

$$V(z) = \int z^0 \gamma(\zeta, h) d\zeta; \quad V'(z) = \max(0, V(z) - p_h(z)) \quad (31)$$

Water traction acts separately on exposed excavation boundaries. Positive water pressure on the horizontal excavation floor produces downward force on the underlying soil. Pressure on the exposed left wall acts toward retained ground, in positive x . For a wall interval of length L with endpoint pressures p_1 and p_2 , linearly varying pressure is represented by consistent translational endpoint forces.

$$F_{x,1} = L(2p_1 + p_2)/6; \quad F_{x,2} = L(p_1 + 2p_2)/6 \quad (32)$$

These endpoint forces reproduce the resultant and its first moment for linear pressure. No consistent rotational nodal loads are added for the distributed wall water traction, so fine wall discretisation should be checked for local bending response. At a crossing of the water surface, endpoint interpolation can approximate the piecewise pressure distribution; the soil grid includes stage heads within the domain.

Changing a water head immediately replaces the hydrostatic base field and reequilibrates the model. Existing Undrained B excess pressure is carried forward through its local storage update; it does not dissipate over time. A stage sequence labelled dewatering therefore represents prescribed head scenarios, not a calculation of pumping rate, seepage gradient, drawdown duration or hydraulic heave.

4.10. Initial stress and geostatic equilibrium

Gravity mode begins with zero assigned effective element stress and establishes stage zero equilibrium under self-weight, pore pressure and initial loads. It does not automatically create a geological K_0 profile. The stress ratio after equilibrium depends on the material, finite boundaries and constraints. A zero assigned starting field is not equivalent to excavating initially stress free soil, because the gravity stage is solved first.

K_0 mode assigns effective vertical compression V' and equal in plane and out of plane horizontal compression $K_0 V'$. K_0 can be entered per layer or defaults to the Jaky expression based on the stored effective friction angle. That expression is an initialisation correlation, not a universal law for over-consolidated soil or stressed rock. See [4] for the geostatic context.

$$K_{0,\text{automatic}} = 1 - \sin \phi' \quad (33)$$

$$s'_0 = [-K_0 V', -V', -K_0 V', 0]^T \quad (34)$$

In situ rock stress mode adds a nonnegative horizontal offset H_0 and a minor horizontal ratio r . The major horizontal direction is x , the minor direction y , and the principal axes initially coincide with the model axes.

$$H = H_0 + K_0 V'; \quad h = r H; \quad s'_0 = [-H, -V', -h, 0]^T \quad (35)$$

H_0 is in kPa, defaults to zero and is limited to 10^7 kPa. r defaults to one and lies between 0.001 and 1. Gravity and ordinary K_0 modes ignore these two values. The coefficients act on effective overburden. A source correlation stated in total stress cannot be used unchanged without confirming the appropriate conversion.

For K_0 and InSitu initialisation, ShoreKALC checks the assigned stresses against the material yield surface before solving. Invalid assigned fields block preparation rather than being clipped. Stage zero then equilibrates the assigned field with the actual loads and restraints, so the final field can differ from the prescription. Initial stress should be checked using the equilibrated result, not only the input K_0 . InSitu directly prescribes stress; it does not reproduce an imposed tectonic strain phase.

Initial overburden integration uses the initial left water head and subtracts the hydrostatic pressure applicable to each element's side. Unequal initial heads can therefore produce a right-side stress prescription different from one integrated independently using that head. Use a common initial head for a conventional level-ground geostatic state, or review and justify the resulting stress field explicitly.

4.11. Elastic wall formulation and rigidity changes

The wall is divided into two node Euler Bernoulli beams with axial displacement, transverse displacement and rotation at each end. Translational degrees of freedom belong to the mesh; a rotation degree of freedom is added at every beam node. Beam rotations are ordered by node index after all continuum translations. The original wall EA and EI are specified per metre width. The elastic finite element beam follows the standard virtual work formulation [8].

$$q_{\text{local}} = [u_1, v_1, \theta_1, u_2, v_2, \theta_2]^T; \quad K_{\text{global}} = T^T K_{\text{local}} T \quad (36)$$

For beam length L , the nonzero coefficients in the standard local six by six matrix are $a = EA/L$, $b = 12EI/L^3$, $c = 6EI/L^2$, $d = 4EI/L$ and $e = 2EI/L$. The full matrix below fixes the local signs unambiguously.

$$K_{\text{local}} = \begin{bmatrix} a & 0 & 0 & -a & 0 & 0 \\ 0 & b & c & 0 & -b & c \\ 0 & c & d & 0 & -c & e \\ -a & 0 & 0 & a & 0 & 0 \\ 0 & -b & -c & 0 & b & -c \\ 0 & c & e & 0 & -c & d \end{bmatrix} \quad (37)$$

T resolves global translations onto the beam axis and its transverse direction, leaving rotations unchanged. A newly installed beam records the current nodal translations and rotations as its stress free reference. Installation therefore does not artificially impose all previous gravity settlement as wall strain. Subsequent beam force is based on displacement from that reference.

$$f_{\text{local}} = K_{\text{local}} T(u - u_{\text{install}}) \quad (38)$$

Bonded contact shares soil and wall translations. Frictional mode uses independent wall nodes coupled through contact. Entered wall weight, in kN/m height per metre wall width, acts downward while the wall is active; it is not derived from EA/EI . Section strength and cracked stiffness require separate design assessment.

Each construction stage can specify absolute multipliers α_{EA} and α_{EI} of the original rigidities. Blank carries the prior value forward, beginning at one. Values from 0.001 to 100 are accepted. A factor of 0.6 means 60 percent of the original rigidity, rather than a reduction by 40 percent of the previous stage rigidity.

$$EA_{\text{stage}} = \alpha_{EA} EA_0; \quad EI_{\text{stage}} = \alpha_{EI} EI_0 \quad (39)$$

Changing rigidity preserves the wall's installation reference. Forces at the existing deformation change with the specified rigidity, and stage equilibrium redistributes them. Each factor applies to every wall beam. This represents a changed elastic secant rigidity; it does not calculate cracking, damage evolution or a force-preserving change of tangent stiffness.

4.12. Compression only struts

A workspace strut is a horizontal axial spring connected between a wall node and a fixed point to the left. Its length is wall x minus start x , and its properties are EA per strut, out of plane spacing s and preload P_0 per strut. Converting to one metre of wall width gives the stiffness k and initial preload N_0 below.

$$k_s = EA_s / (L_s s_s); \quad N_{0,s} = P_{0,s} / s_s \quad (40)$$

$$N_s = \max[0, N_{0,s} - k_s(U_x - U_{x_{\text{install}}})] \quad (41)$$

Movement toward the excavation has negative ΔU_x and increases compression. Movement toward retained ground unloads the strut; once slack it supplies no tensile restraint. The active branch adds k_s to the horizontal stiffness. The strut is not a bending frame and does not move its remote point with adjacent soil or another wall. Buckling, section resistance, thermal effects and preload loss are outside the law.

Installation captures the current wall displacement. Unlike anchor stressing, a strut preload appears as the spring force at its installation reference and changes with subsequent equilibrium movement; it is not an exact force held at the final installation displacement. Removal releases the spring force through the staged equilibrium transition. A design check must convert the per metre demand back to the actual member spacing.

4.13. Prestressed ground anchors

An anchor has a head elevation, inclination α below horizontal into retained ground, free length L_f , EA per anchor, spacing s_a , lock off P_0 and tensile capacity $P_{\max}$. The unit vector d points from the head toward the fixed remote anchorage. The remote point is not connected to the soil mesh even when it is drawn inside that mesh.

$$d = [\cos \alpha, -\sin \alpha]^T; \quad k_a = EA_a / (L_f s_a) \quad (42)$$

$$N_{0,a} = P_0 / s_a; \quad N_{\max} = P_{\max} / s_a \quad (43)$$

Installation and stressing are distinct events. Installation records the present head position with zero prestress offset. During the first stressing stage, the lock off force is prescribed through equilibrium. Once that stage converges, the reference is locked at the final head position and the offset becomes $N_{0,a}$. Later stages follow an elastic tension only law with an ideal plastic tensile cap.

$$N_{\text{trial}} = N_{\text{offset}} - k_a d^T (u_{\text{head}} - u_{\text{ref}}) \quad (44)$$

$$N_a = \max[0, \min(N_{\max}, N_{\text{trial}})] \quad (45)$$

$$F_{\text{head}} = N_a d; \quad K_{\text{head}} = k_a d d^T, \quad \text{on the elastic engaged branch} \quad (46)$$

F_{head} is the physical force exerted on the wall; the assembled internal force contribution is its negative. The inclined anchor produces both horizontal and vertical wall actions. Its tangent has coupled horizontal and vertical terms. During imposed stressing the anchor force is fixed and its elastic tangent is omitted. Slack and yielded branches do not provide that elastic tangent.

If a converged increment exceeds capacity in the trial law, a permanent extension is committed by changing the projected reference. Subsequent unloading is elastic from the yielded state, rather than immediately recovering the original uncapped force path. Rejected equilibrium trials do not change this history.

$$w_{ref,new} = d^T u_{head} + (N_{max} - N_{offset})/k_a \quad (47)$$

Capacity is the entered ideal tensile force limit. Bond, grout, ground pullout and anchorage resistance must be established separately. The anchor law omits seating loss, relaxation, creep, bonded-length load transfer and remote anchorage movement. Removal is permanent within the construction sequence; model a replacement anchor as a separate support with its own installation and stressing stages.

4.14. Frictional wall soil contact

Frictional mode splits soil translations on opposite sides of the wall and introduces independent wall translations. Before wall installation, bonded ties connect the two soil faces to maintain approximate ground continuity. Installation replaces those ties with wall contacts, transfers their traction and stores relative displacement references. Retained contacts remain active; excavation removes left contacts over excavated intervals. Bonded shared node mode has no opening or sliding branch. Penalty contact and Coulomb friction background is given in [5].

Contact assembly interpolates quadratic soil-edge translations and linear wall-beam translations over each wall interval. Three Gauss samples integrate traction; adhesive opening and stick/slip transitions receive segmented integration as detailed in Appendix D. Initial ties and installed contacts use consistent interpolation and force distribution, preserving discrete virtual work. The formulation is a zero-thickness penalty contact with Coulomb friction.

$$u_{soil,c} = \sum_i w_i u_{soil,i}; \quad \sum_i w_i = 1 \quad (48)$$

Define closure δ_n positive in compression, relative vertical displacement δ_s and committed plastic slip s_p . Effective normal compression $\sigma_{n,c}$ and shear traction τ_c are positive or signed as specified below. Stored installation tractions $\sigma_{n,0}$ and τ_0 are included in the trial law.

$$\sigma_{n,trial} = \sigma_{n,0} + K_n \delta_n; \quad \tau_{trial} = \tau_0 + K_s(\delta_s - s_p) \quad (49)$$

If $\sigma_{n,trial} < 0$, contact opens: effective normal and shear traction become zero. Slip is reset so reclosure does not restore fictitious shear traction accumulated across an open gap. Otherwise effective compression is $\sigma_{n,trial}$, and the shear traction is constrained by adhesion plus friction.

$$\tau_{lim} = c_i + \sigma_{n,c} \tan \delta; \quad |\tau_c| \leq \tau_{lim} \quad (50)$$

$$\tau_c = \text{sign}(\tau_{trial}) \tau_{lim}, \quad \text{during sliding} \quad (51)$$

$$s_{p,new} = \delta_s + (\tau_0 - \tau_c)/K_s \quad (52)$$

The sticking tangent has K_n and K_s on its diagonal. On the sliding branch the shear derivative with respect to closure is $\text{sign}(\tau_{trial}) \tan \delta K_n$ and the shear derivative with respect to δ_s is zero. This unsymmetric coupling contributes to the need for an unsymmetric global solve. No interface dilation or normal tensile strength is present.

Layer friction ratio r_f multiplies $\tan \phi'$, while adhesion ratio r_c multiplies c' . Blank ratios use wall Rinter. In Undrained B friction is zero and adhesion multiplies S_u . Both independent layer ratios are between zero and one; wall Rinter is greater than zero and at most one. Frictional mode with Rinter = 1 can still open and slide. Explicit Bonded mode requires Rinter = 1 and gives shared translational compatibility.

$$\tan \delta = r_f \tan \phi'; \quad c_i = r_c c' \quad \text{or} \quad r_c S_u \quad (53)$$

The normal and shear penalties scale with the adjacent skeleton stiffness and the smaller adjacent horizontal cell width h . The penalty factor β defaults to 10 and accepts 1 to 100.

$$K_n = \beta E'(1 - \nu')/[(1 + \nu')(1 - 2\nu')h] \quad (54)$$

$$K_s = \beta E'/[2(1 + \nu')h] \quad (55)$$

K_n and K_s have units kPa/m. Contact forces multiply traction by tributary length and section thickness. Smaller h or larger β reduces penalty deformation but can worsen conditioning. Assess both force transfer and contact displacement under changes in soil mesh, wall mesh and β .

Installation converts transferred tie normal traction to effective contact compression by subtracting the contact hydrostatic pressure. That pressure is added back separately in total traction assembly. The prescribed water pressure can act even when the effective mechanical contact is open; this reflects an assumed hydrostatic fluid action, not a solved fluid gap model. Contact fluid pressure excludes local Undrained B excess pressure. Coupled fluid pressure at an undrained contact is therefore a material limitation of the formulation.

4.15. Construction staging and loading

Stages describe complete active configurations, not only lists of changes. Each stage specifies excavation elevation, wall activation, load activation, installed struts and anchors, newly stressed anchors, heads and optional wall rigidity factors. The initial stage has full ground and establishes the stress state before construction. In the workspace the wall remains installed once activated, and excavation levels cannot reverse upward to imply backfill.

An element is retained when its integration points lie on the retained side of the wall or below the stage excavation elevation. Mandatory boundaries align complete Q8 cells and T6 triangles with excavation levels; all integration records of an element activate or excavate together. Removed soil cannot be reactivated with its old history. Orphan degrees of freedom are held at their last committed displacement.

To move from one topology to another, the solver evaluates internal force on the new active topology at the stage start. That vector becomes the starting equivalent load. It ramps to the stage target external force, including only active soil gravity and the prescribed stage actions. This releases removed soil and removed support force through equilibrium while retaining surviving stress and plastic history.

$$F(\eta) = F_{\text{start,new}} + \eta(F_{\text{target}} - F_{\text{start,new}}); \quad 0 \leq \eta \leq 1 \quad (56)$$

$F_{\text{start,new}}$ is a transition vector used to establish equilibrium after a topology change. Target stage loads represent the complete actions for that stage. Adding each earlier stage's total load again would double count persistent actions. The stage configuration identifies which soil, wall, loads and supports remain active.

A uniform surcharge acts downward over its specified interval and elevation. The mesh includes its endpoints and elevation. Quadratic edge integration distributes the total force using endpoint weights one sixth each and midpoint weight two thirds. Overlapping active surcharges add; load activation follows the construction sequence.

$$F_z = -ql [1/6, 1/6, 2/3]^T \quad (57)$$

The workspace represents uniform retained-ground surcharges and fixed-point supports. General wall point loads, adjacent building frames and embedded pile rows require separate modelling. Any replacement of those actions by a surcharge or spring must preserve the intended load path. Support installation before or after excavation changes its reference and subsequent force history.

4.16. Nonlinear solution and convergence

The solver assembles the tangent and residual for free degrees of freedom. Non-associated soil and sliding contact can produce an unsymmetric tangent. Assembly uses an immutable sparse connectivity pattern and cached matrix positions. Reverse Cuthill–McKee reorders soil translations and wall rotations. Larger corrections use scaled, pivoted LU in a compact band envelope, with native LAPACK factorisation when

available and a managed band fallback. Dense LU is retained for small systems. The method does not assume symmetry or positive definiteness.

$$\mathbf{r} = \mathbf{F}_{\text{ext}} - \mathbf{F}_{\text{int}}; \quad \mathbf{K}_{\text{ff}} \Delta \mathbf{u}_f = \mathbf{r}_f \quad (58)$$

$$\mathbf{u}_{\text{candidate}} = \mathbf{u}_{\text{trial}} + \alpha \Delta \mathbf{u}; \quad 0 < \alpha \leq 1 \quad (59)$$

The line search halves α until the free residual norm decreases by a small required fraction. The main acceptance criterion compares the norm with a scale fixed for the stage from target and stage starting free force vectors, with a numerical floor of one in the native force scale. Translational and rotational residual entries are included in the assembled vector, so this norm is a numerical measure with mixed force and moment components rather than a dimensionless physical energy norm.

$$\rho = \|\mathbf{r}_f\|_2 / \max(1, \|\mathbf{F}_{\text{target},f}\|_2, \|\mathbf{F}_{\text{start},f}\|_2) \leq \epsilon_{\text{rel}} \quad (60)$$

The default relative equilibrium tolerance is 10^{-6} and the default iteration limit is 35. A converged state satisfies the physical residual. Nearby branch tangents and, for at most 600 free degrees of freedom, damped least-squares directions can help recover a step. A bounded trial across an adhesive-contact opening transition may temporarily increase the residual, but it does not commit state or relax the final equilibrium tolerance. Damping affects the iterative direction rather than the physical material law.

For Q8 and T6, the initial and maximum load-fraction increment is 0.05. A stage with negligible force change can complete in one checked increment. Failed increments halve the step. Analysis stops if the step falls below $1/16384$, the step-plus-cutback count exceeds 2048, or the configured time budget expires. The ordinary construction and optional strength-reserve checks share a default 58-second budget, bounded at 60 seconds. Numerical stopping alone does not establish a physical failure mechanism.

Only accepted increments commit displacement, effective stress, plastic strain, excess pressure, interface slip and anchor plastic extension. Only fully completed stages are published as stage results. If a later stage fails, the result contains earlier completed stages and diagnostics of the failed stage. It must not be described as reaching the requested final excavation or as providing a complete envelope.

4.17. Result recovery and engineering interpretation

Displayed deformation and displacement subtract the first converged stage, giving movement relative to initial ground equilibrium. Wall actions use the wall's installation reference. When comparing with another analysis or measured data, use the same physical reference stage for both sets of results.

$$\mathbf{u}_{\text{display},s} = \mathbf{u}_s - \mathbf{u}_{\text{stage0}} \quad (61)$$

Soil stress output is stored at integration points. The vertical effective component is σ'_{zz} and total stress is $\sigma_{zz} = \sigma'_{zz} - p$. Compression is negative. Total pore pressure is $p_h + p_e$; excess pressure is p_e . The viewer shades each integration point over its part of a Q8 cell or T6 triangle rather than treating every record as a separate overlapping element. Stress, pressure and movement should be assessed together.

The result viewer also reports a plastic strain magnitude, calculated from the norm of the stored tensor using engineering shear conversion and multiplied by 100 for percent display. It is a state magnitude, not accumulated equivalent plastic strain and not a strength reduction factor. Plastic activation identifies yielded material points but does not, alone, define a continuous slip surface or a computed collapse load.

$$\epsilon^p_{\text{display}} = 100 \sqrt{(\epsilon^p_{xx})^2 + (\epsilon^p_{zz})^2 + (\epsilon^p_{yy})^2 + (\gamma^p_{xz})^2 / 2} \quad (62)$$

For a stored effective stress vector, the in plane principal values and orientation follow the standard two by two eigenproblem. The third principal value is σ'_{yy} . The most compressive principal value is the minimum of all three under the tension positive convention.

$$p_{+, -} = (\sigma'_{xx} + \sigma'_{zz}) / 2 \pm \sqrt{((\sigma'_{xx} - \sigma'_{zz}) / 2)^2 + \tau_{xz}^2} \quad (63)$$

$$\theta = \text{atan2}(2\tau_{xz}, \sigma'_{xx} - \sigma'_{zz})/2; \quad p_y = \sigma'_{yy} \quad (64)$$

Wall beams return local end actions [N1,V1,M1,N2,V2,M2] per metre width. Workspace axial, shear and moment diagram endpoints use [-N1,N2], [-V1,V2] and [-M1,M2]. Beam orientation and project reporting signs must be stated explicitly.

Support compression and anchor tension are nonnegative per metre forces. Inactive objects are excluded from envelopes. Maximum and minimum envelopes are signed values over completed stages at stored endpoints or nodes. An absolute envelope selects the signed candidate of larger magnitude. The viewer interpolates stored endpoint envelopes; it does not recompute a separate envelope at every position between them. Local force peaks near point supports and boundaries warrant mesh review.

Deformation amplification changes drawing geometry only. Hover values refer to the model coordinates and computed components. Constrained reactions are internal force minus external force. An independent equilibrium review should balance all physical actions, reactions and moments with consistent signs and width; a low free residual does not check whether the entered actions were the intended ones.

4.18. Calculation review and limitations

4.18.1. Mesh and boundary sensitivity

Run at least a baseline and a refined soil mesh, keeping physical inputs and stage order identical. Where contact is frictional, refine the wall separately from the soil and vary the penalty factor. Compare wall displacement, moment, shear, support forces and selected soil stresses at common physical elevations. Report both absolute differences and relative differences; relative percentages are unstable when a baseline result is close to zero. Acceptance tolerances must be chosen for the project rather than inferred from the solver residual.

$$\Delta R = R_{\text{refined}} - R_{\text{base}}; \quad \text{relative change} = |\Delta R|/|R_{\text{base}}| \quad (65)$$

Move side boundaries outward and the base downward in separate studies. The workspace fixes both translations at the base and horizontal movement at the side boundaries. Soil domain enlargement can change confinement and stored initial stress as well as excavation movement. Refining only a wall beam cannot recover a poorly resolved soil stress field. Near incompressibility and plastic localisation can make displacement predictions mesh sensitive even while equilibrium is well converged.

4.18.2. Independent engineering checks

Wall bending, shear, axial force and combined section resistance; strut buckling and connections; and tendon, anchorage and bond resistance require external design checks. The optional soil and toe-ground branches verify entered strength-reduction targets, but do not find a limiting factor of safety or required embedment. Basal heave, hydraulic uplift, piping, consolidation and movement effects on adjacent assets require separate assessment. A model anchor cap is not a pullout check, and ShoreKALC does not apply a structural resistance standard.

Undrained B additionally requires justification of S_u , saturation and the finite storage choice. Drained MC requires justification of c' , ϕ' and ψ , including whether apparent cohesion is reliable at the relevant stress level. Initial rock stress needs site support and a consistent total or effective definition. A large horizontal stress offset can imply yielding before excavation; preparation rejects an inadmissible assigned stress rather than validating the chosen geological correlation.

4.18.3. Current numerical bounds

The calculation accepts up to 1,600 mesh nodes, 3,200 soil integration records, 9,600 contact records, 50 materials and 20 construction stages, with up to 1,600 wall beams, 50 struts and 50 anchors. Each Q8 cell uses four soil records and each T6 triangle uses three. Node counts include separate wall/contact nodes and constrained refinement nodes. These bounds control calculation size and do not establish an adequate engineering mesh.

General mesh spacing accepts 0.1 to 100 m. Local spacing is zero or between 0.1 m and the general spacing. Independent wall spacing is zero or 0.1 to 100 m; positive wall spacing requires Frictional contact. Select spacing from the geometry and response being resolved, then review mesh and boundary sensitivity.

5. Worked analytical examples

These examples show how entered properties and units become stresses and forces in the calculation. They are separate component calculations with stated assumptions. Use them to understand the sign convention, line-force conversion, installation reference and strength cap before interpreting a full excavation model. The applicable input dialog and calculated quantity are identified below.

5.1. Initial stress and unit conversion

Input connection: enter unit weights and effective friction angle under Soil materials, water head under Initial groundwater, and K_0 initialisation under Wall / pile. The calculation below gives the assigned initial field at one depth; stage-zero equilibrium can redistribute it.

Consider a homogeneous layer with $\gamma = 18 \text{ kN/m}^3$ above a water table at $z = -2 \text{ m}$, $\gamma_{\text{sat}} = 20 \text{ kN/m}^3$ below it and $\phi' = 30$ degrees. At $z = -6 \text{ m}$, total overburden is $18 \times 2 + 20 \times 4 = 116 \text{ kPa}$. Hydrostatic pressure is $9.81 \times 4 = 39.24 \text{ kPa}$. Effective compression V' is therefore 76.76 kPa . Automatic $K_0 = 0.5$ gives horizontal effective compression 38.38 kPa .

$$s'_0 = [-38.38, -76.76, -38.38, 0]^T \text{ kPa} \quad (66)$$

With no excess pressure, total stress is $[-77.62, -116.00, -77.62, 0]^T \text{ kPa}$. This illustrates signs and the full saturated weight convention. It is an assigned K_0 field before stage zero equilibration; it is not a claim that these values will remain unchanged in a finite mesh with all construction loads.

5.2. Undrained storage increment

Input connection: enter E' , ν' , S_u and ν_u for an Undrained B material. The example isolates the fluid-storage increment associated with a stated volumetric strain; pore-pressure contours show the combined history of the full staged calculation.

For $E' = 10,000 \text{ kPa}$, $\nu' = 0.30$ and $\nu_u = 0.49$, $G = 3,846.154 \text{ kPa}$, $K' = 8,333.333 \text{ kPa}$ and $K_u = 191,025.641 \text{ kPa}$. Hence $M_f = 182,692.308 \text{ kPa}$. A volumetric compression increment of -0.001 generates $\Delta p_e = +182.692 \text{ kPa}$. This large pressure change demonstrates sensitivity to the chosen finite storage and volumetric strain; it is not a calibrated site prediction.

5.3. Strut stiffness and installation reference

Input connection: enter EA , remote point, spacing and preload under Struts and anchors, then define installation under Construction stages. The results convert the force per metre of wall to force per member using the entered spacing.

For $EA = 200,000$ kN per strut, length 10 m, spacing 4 m and preload 400 kN per strut, $k_s = 5,000$ kN/m displacement per metre wall and $N_0 = 100$ kN/m. After installation, a 5 mm movement toward excavation gives $\Delta U_x = -0.005$ m, $N_s = 125$ kN/m and 500 kN per strut. A 25 mm movement toward retained ground gives an uncapped force of -25 kN/m and therefore a slack force of zero.

5.4. Inclined anchor and tensile yielding

Input connection: enter free length, EA, spacing, inclination, lock-off and model tensile cap under Struts and anchors. Installation and lock-off are separate stage operations. This example follows the anchor from elastic loading to capped tension and unloading.

Take $EA = 150,000$ kN, free length 15 m, spacing 3 m, angle 20 degrees, lock off 300 kN and capacity 600 kN per anchor. $k_a = 3,333.333$ kN/m displacement per metre, $N_0 = 100$ kN/m and $N_{max} = 200$ kN/m. After completed lock off, a projected head movement $d^T \Delta u = -0.006$ m increases tension to 120 kN/m or 360 kN per anchor. The corresponding head force is approximately $+112.763$ kN/m in x and -41.042 kN/m in z.

If projected movement reaches -0.040 m from the original locked reference, $N_{trial} = 233.333$ kN/m but the returned force is 200 kN/m. Taking the original projected reference as zero, the committed projected reference becomes -0.010 m. Subsequent projected head movement to -0.035 m unloads elastically to 183.333 kN/m, or 550 kN per anchor. This shows the permanent extension mechanism and why a cap alone without history would give a different unloading response.

5.5. Interface sticking and sliding

Input connection: select Frictional contact under Wall / pile and enter the layer friction and adhesion ratios under Soil materials. The example separates the soil strength from the wall-interface limit.

For $c' = 10$ kPa, $\phi' = 30$ degrees, $R_f = 0.67$ and $R_c = 0.50$, $c_i = 5$ kPa and $\tan \delta = 0.386825$, giving δ approximately 21.15 degrees. At effective contact compression of 100 kPa, the shear limit is 43.682 kPa. A trial shear traction of 60 kPa therefore slides and returns to $+43.682$ kPa. If the normal trial becomes tensile, the mechanical contact opens and effective normal and shear tractions become zero.

5.6. Elastic cantilever response

For an elastic cantilever wall of length L and constant EI under transverse tip force P , the following relationships give tip movement, tip rotation and base moment. They illustrate how flexural rigidity controls movement. Use P and EI on the same total-member or per-metre basis; an embedded, supported excavation wall has different restraints and loading.

$$v_{tip} = PL^3/(3EI); \quad \theta_{tip} = PL^2/(2EI); \quad M_{base} = PL \quad (67)$$

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Appendix A Computational sequence

1. Validate geometry, contiguous strata, strength and stiffness, water heads, support identities and legal construction history. Reject missing S_u for Undrained B. Check mesh controls and include duplicate or independent nodes in the budget.
2. Generate a boundary-aligned quadratic mesh and wall segmentation. Assign materials, initial stresses, gravity weights and hydrostatic pressure at integration points. Construct Q8 refinement constraints or conforming T6 transitions, support conversions and quadratic contact interpolation.
3. Assign gravity, K0 or InSitu initial stresses. For prescribed fields, check material admissibility. Solve stage zero with excess pressure generation disabled. Retain its equilibrated state and the displacement datum.
4. Start the next stage. Update active elements and structures, installation references, contacts, newly stressed anchors and carried wall factors. Preserve surviving soil state. Freeze orphan degrees of freedom.
5. Evaluate the new topology starting internal vector and the target stage external vector. Advance the load fraction and trial prescribed displacements. Evaluate trial constitutive, beam, support, contact and pressure response from committed histories.
6. Assemble total internal force and the sparse tangent. Solve the free residual equation with scaled unsymmetric factorisation, line search and bounded branch recovery. If unsuccessful, cut back without committing the rejected state.
7. Commit accepted displacement and histories. Continue to complete the stage. Lock newly stressed anchors at the final head position. Recover reactions and active result components. Publish the stage only after completion.
8. Stop on failure with diagnostics and earlier complete stages. On success, calculate signed envelopes from active complete results. Prepare the engineering report with datum, inputs, construction sequence, convergence evidence and independent checks.

Appendix B Notation and glossary

B1 Symbols and notation

Symbol	Meaning
A and A _q	Physical triangle area and soil quadrature weight
t	Continuum section thickness
E' ν' G K'	Effective elastic Young modulus Poisson ratio shear modulus and bulk modulus
c' φ' ψ f _t	Drained cohesion friction dilation and tensile strength
S _u ν _u K _u M _f	Undrained strength numerical Poisson ratio undrained bulk modulus and fluid bulk addition
s' s e e ^p	Effective stress total stress total strain and plastic strain vectors
p _h p _e m	Hydrostatic pressure excess pressure and normal stress selector
p _i	Tension positive principal effective stress
B D _e D _{al} g	Strain displacement matrix elastic matrix and algorithmic tangent
A G _p l Δλ	Active yield normal matrix flow gradient matrix plane limits and plastic multipliers
V V' K ₀ H ₀ r	Total and effective overburden initial ratio horizontal offset and minor horizontal ratio
E A E _I α E A α E I	Axial and flexural rigidity and stage factors
L _s L _f s _s s _a	Strut length anchor free length and support spacings
d N _{offset} N _{max}	Anchor direction force offset and tensile capacity per metre
K _n K _s β h	Interface penalties factor and adjacent horizontal cell width
δ _n δ _s s _p c _i δ	Closure relative shear displacement plastic slip adhesion and interface friction angle
η α ρ ε _{rel}	Stage load fraction line search factor relative residual and convergence tolerance

B2 Engineering terms

Term	Definition in this manual
Plane strain	A two-dimensional idealisation with zero out-of-plane strain; out-of-plane stress remains in the soil material calculation.
Effective stress	Stress carried by the soil skeleton. With tension-positive normal stresses, total stress equals effective stress minus positive pore pressure.
Pore pressure	Pressure in the pore fluid. Hydrostatic pressure follows the entered water head; excess pressure is the additional response generated by the Undrained B storage law.
Drained analysis	An analysis using effective cohesion and frictional strength with the prescribed pore-pressure field. Select it for the drainage conditions of the construction stage.
Undrained B	A saturated-soil idealisation using effective stiffness and explicit undrained strength S_u . Its strength law uses zero friction and dilation, while a local no-flow storage law generates excess pore pressure.
Undrained strength S_u	Shear strength used for the selected undrained loading condition, in kPa. It must be interpreted from appropriate geotechnical evidence.
K_0	The initial horizontal-to-vertical effective stress ratio. It is imposed in K_0 or in-situ initialisation and reviewed after initial equilibrium.
Jaky estimate	The correlation $K_0 = 1 - \sin \phi'$, principally associated with normally consolidated soil. It is not a general rock-stress relationship.
Cohesion c' and friction ϕ'	The intercept and slope parameter of the drained effective-stress shear envelope, $\tau = c' + \sigma' n, c \tan \phi'$.
Dilation ψ	The plastic-flow angle controlling volume change during shear. It is a separate input from the strength friction angle.
Rinter	The default wall-interface strength ratio. It supplies R_f and R_c for a layer when their respective inputs are blank.
Friction ratio R_f	The layer ratio defining $\tan \delta = R_f \tan \phi'$. An entered value replaces the friction default from Rinter.
Adhesion ratio R_c	The layer ratio defining $c_i = R_c c'$; in Undrained B it scales S_u . An entered value replaces the adhesion default from Rinter.
Bonded contact	Wall and soil share translations, preventing relative mechanical slip and opening. It requires Rinter = 1 and wall spacing following soil rows.
Frictional contact	A wall-soil interaction law that permits sticking, Coulomb sliding and mechanical opening, with water traction treated separately.
Contact stiffness factor	A dimensionless control of the numerical penalty stiffness. It affects the relative displacement needed to transfer traction, independently of the interface strength ratios.
Soil yielding	Plastic response in the accepted increment when the constitutive strength limit is mobilised. Local yielding alone does not define a global failure mechanism.
Plastic strain	The carried irreversible strain component. The displayed tensor magnitude is not a damage measure or a stability factor.
Perfect plasticity	A material model whose strength does not harden or soften with plastic strain.

Term	Definition in this manual
Quadratic soil element	A soil displacement element using Q8 quadrilateral or T6 triangular quadratic interpolation, with separate material histories at its integration points.
Volumetric locking	An overly stiff numerical response that can occur when displacement elements represent nearly incompressible behaviour inadequately.
Equilibrium residual	The remaining imbalance between assembled internal and external actions. The solver compares its scaled norm with the convergence tolerance.
Convergence	Satisfaction of the numerical equilibrium criteria for a stage. Engineering adequacy also depends on model assumptions and the checks within its scope.
EA and EI	Axial and flexural rigidities. Wall values are per metre of wall width; support EA is per physical member.
Preload and lock-off	An initial strut compression or an anchor force applied during stressing. Their subsequent forces follow the support law and installation reference.
Force per metre and per member	Line force applies per metre of wall. Multiplication by out-of-plane support spacing gives the force in one strut or anchor.
Envelope	Signed extrema over the included completed stages. Different extrema can arise in different stages and need not form a simultaneous force state.
Serviceability limit state SLS	A project performance requirement such as an entered movement limit. Its value and measurement basis must be selected for the assets and construction conditions.
Strength-reserve target	An entered strength-reduction target tested on a separate branch with fixed stage loads and pore pressures. Accepted equilibrium at the target does not identify the limiting factor of safety.
Toe-ground strength reserve	A target check reducing excavation-side ground between formation and wall toe and its wall contacts. It does not calculate a passive wedge or required embedment depth.
Embedment	The wall length below the excavation formation. Its design adequacy requires a suitable resistance and equilibrium assessment.
Free-field surface settlement	Downward movement of retained-ground surface soil nodes from initial equilibrium. Footing settlement, differential asset movement and consolidation require additional assessment.

Appendix C Detailed constitutive linearisation

C1 Principal transformation

Return mapping in principal space and differentiation back to Cartesian components must be consistent. Let θ be the in-plane principal angle, $C = \cos \theta$ and $S = \sin \theta$. The trial principal vector is $[p_+, p_-, \sigma'_{yy}]$, without sorting the out-of-plane component. The six ordered-pair shear planes account for all principal pairs. Trial principal directions remain fixed during the stress return, while their dependence on trial strain contributes to the algorithmic tangent. Principal return mapping and consistent linearisation are described in [2,6].

$$\sigma'_{xx} = C^2 p_+ + S^2 p_-; \quad \sigma'_{zz} = S^2 p_+ + C^2 p_- \quad (68)$$

$$\tau_{xz} = CS(p_+ - p_-); \quad \sigma'_{yy} = p_y \quad (69)$$

For a column j of the four component strain increment, first differentiate the elastic trial principal values. Let D_{ij} be the skeleton elastic entries, including engineering shear. The trial projection uses the same C and S as the eigenvectors.

$$p_{+,j} = C^2 D_{0j} + S^2 D_{1j} + 2CS D_{3j} \quad (70)$$

$$p_{-,j} = S^2 D_{0j} + C^2 D_{1j} - 2CS D_{3j}; \quad p_{y,j} = D_{2j} \quad (71)$$

For a plastic state, form $H = A D_p G p^T$ from the accepted active set, as defined under Constitutive return mapping and tangent. Solve $H \lambda_{,j} = A p_{,j}$ and calculate $r_{,j} = p_{,j} - D_p G p^T \lambda_{,j}$. Project the returned Cartesian stress into the same trial principal directions to obtain r . This keeps the derivative consistent with the selected constitutive branch.

$$\theta_j = [d D_{3j} - \tau_{\text{trial}}(D_{0j} - D_{1j})]/[d^2 + 4\tau_{\text{trial}}^2] \quad (72)$$

Here $d = \sigma'_{xx,\text{trial}} - \sigma'_{zz,\text{trial}}$ and τ_{trial} is the trial shear stress. When the denominator is at most 10^{-24} , $\theta_{,j}$ is set to zero. This treats the repeated in-plane principal-stress case, for which no unique principal angle exists. On a nondegenerate branch, differentiation of the recombination equations gives the following Cartesian tangent entries.

$$D_{\text{alg},0j} = C^2 r_{+,j} + S^2 r_{-,j} + 2CS(r_- - r_+)\theta_j \quad (73)$$

$$D_{\text{alg},1j} = S^2 r_{+,j} + C^2 r_{-,j} + 2CS(r_+ - r_-)\theta_j \quad (74)$$

$$D_{\text{alg},2j} = r_{y,j} \quad (75)$$

$$D_{\text{alg},3j} = CS(r_{+,j} - r_{-,j}) + (C^2 - S^2)(r_+ - r_-)\theta_j \quad (76)$$

Indices 0, 1, 2 and 3 correspond to xx , zz , yy and xz . The equations include the eigenvector rotation term. An elastic return uses D_e directly; a plastic return differentiates the accepted active set. A branch change can prevent a Newton step from reducing the residual, in which case the global recovery and cutback procedure governs acceptance.

C2 Tolerances and active set selection

The local yield tolerance is 10^{-9} times the maximum of one, cohesion and the absolute trial principal stresses. Plastic multipliers below -10^{-12} reject a candidate. All nine surface residuals must be within the local tolerance; an active surface residual is not independently clipped. Candidates are enumerated first by active set size, then by a bitmask over surface indices 0 through 8. The first admissible independent set is returned. Surface ordering follows the ordered principal pairs and then the three tension planes.

$$\text{tolerance}_{\text{local}} = 10^{-9} \max(1, c, |p_{\text{trial},1}|, |p_{\text{trial},2}|, |p_{\text{trial},3}|) \quad (77)$$

The constitutive active-set equations use a scaled dense solve and reject singular or non-finite solutions. If no admissible set is found, the global increment is reduced and retried. No fallback stress-clipping law is used. Assigned initial stresses are checked separately against a tolerance of $10^{-6} \max(1, V')$, because initialisation and incremental integration serve different purposes.

C3 Plastic strain commitment

The material state carries effective stress, the four plastic strain components, a flag for plastic return in the current evaluation, active surface indices and excess pore pressure. The flag is reset for an elastic evaluation and is not a statement that the point has never yielded. Previously accumulated plastic strain remains even if the present increment is elastic. The plastic strain tensor is updated additively after a returned stress is accepted locally; global commitment still awaits equilibrium acceptance.

$$\Delta \varepsilon_i^p = \Delta \varepsilon_i - [\Delta \sigma'_i - \nu'(\Delta \sigma'_j + \Delta \sigma'_k)]/E' \quad (78)$$

$$\Delta \gamma_{xz}^p = \Delta \gamma_{xz} - \Delta \tau_{xz}/G \quad (79)$$

For an Undrained B point, local no flow pressure increments use total volumetric strain, not only elastic strain. The plastic shear planes have $\psi = 0$, so their plastic volumetric increment vanishes on an ideal exact return. No global conservation equation for fluid flux follows from this local update. The storage law and global tangent must be interpreted together.

Appendix D Contact assembly and installation transfer

D1 Relative displacement matrix

The interface supports weighted soil and target nodes, each side with weights summing to one. Quadratic workspace contacts interpolate three soil-edge nodes and two independent wall-beam nodes; preinstallation ties target the opposite soil edge. Signed weights are positive on the soil side and negative on the target side. The normal sign is +1 for the left face and -1 for the right. Relative movement subtracts the target interpolation from the soil interpolation.

$$v = \sum_i w_{\text{soil},i} u_{\text{soil},i} - \sum_j w_{\text{target},j} u_{\text{target},j} \quad (80)$$

$$\delta_n = n(v_x - v_{x,\text{install}}); \quad \delta_s = v_z - v_{z,\text{install}} \quad (81)$$

The contact B_c matrix maps all involved translations to closure and relative shear. For a node with signed weight w , its two by two block is diagonal $[nw, w]$. The mechanics traction vector contains effective compression plus prescribed hydrostatic pressure in its first component for an installed frictional contact, and signed shear in its second component. A bonded initial tie uses its stored total traction without separately adding pressure.

$$q_c = [\sigma_{n,c} + p_{h,c}, \tau_c]^T \quad (82)$$

$$f_c = t l_c B_c^T q_c; \quad K_c = t l_c B_c^T D_c B_c \quad (83)$$

l_c is tributary length. Consistent use of interpolation in both relative displacement and force distribution preserves virtual work. Equal and opposite soil and wall nodal actions follow from the signed weights. The physical normal contact law is evaluated without pressure; adding prescribed water traction during assembly does not increase frictional strength.

$$D_{c,\text{stick}} = \begin{bmatrix} K_n & 0 \\ 0 & K_s \end{bmatrix} \quad (84)$$

$$D_{c,\text{slide}} = \begin{bmatrix} K_n & 0 \\ \text{sign}(\tau_{\text{trial}}) \tan \delta K_n & 0 \end{bmatrix} \quad (85)$$

For open contact D_c is zero and effective mechanical tractions are zero. At exactly zero normal trial the closed branch is used; at exactly the shear limit the sticking branch is used. These one sided choices matter to the Newton tangent near a transition. A bonded tie uses the sticking matrix without compression or shear limits and can transmit either sign of normal traction.

D2 Transfer at wall installation

Before installation, initial soil ties transmit total normal and shear traction across the split soil. The new wall contact records the current relative displacement as its reference, resets its slip state and evaluates the designated source ties at the installation displacement. The initial effective normal compression is the weighted source normal traction minus the new contact hydrostatic pressure. Left shear retains the source sign; right shear reverses it so opposite wall faces receive consistent actions.

$$\sigma_{n,0} = \sum_j \omega_j \sigma_{\text{tie},j} - p_{h,c}; \quad \tau_0 = s_{\text{transfer}} \sum_j \omega_j \tau_{\text{tie},j} \quad (86)$$

Transfer weights sum to one, so the installed wall receives a consistent initial traction field. Contact installation references preserve the pre-existing soil stress; introducing zero-traction contacts would otherwise disturb equilibrium artificially. If transferred traction exceeds the new interface strength, friction and opening can require redistribution during wall-installation equilibrium.

D3 Independent wall interpolation

An independent wall mesh can split a quadratic soil edge into several beam intervals. Within each interval, three Gauss samples interpolate soil translations quadratically and wall translations linearly. With $\lambda = (z_{top} - z)/(z_{top} - z_{bottom})$, the soil weights are shown below; the two wall weights follow its own beam interval. The integration weights are interval length times 5/18, 4/9 and 5/18.

$$\lambda = (z_{top} - z)/(z_{top} - z_{bottom}); \quad w_s = [(1 - \lambda)(1 - 2\lambda), \lambda(2\lambda - 1), 4\lambda(1 - \lambda)] \quad (87)$$

Initial ties and installed wall contacts use the same interpolation and interval partition, preserving traction transfer and virtual work. For adhesive quadratic contacts, integration is further split at opening and stick/slip transitions; three-point Gauss integration is applied on the resulting smooth pieces, and slip history is committed only after equilibrium. This avoids a finite assembled adhesive-force jump when a fixed sample changes branch. Independent wall refinement still cannot replace soil refinement.

Appendix E Mesh generation and numerical recovery

E1 Uniform and graded mesh coordinates

Uniform subdivision retains all mandatory coordinate boundaries and divides each interval $[a,b]$ into $\text{ceil}((b-a)/h_{\text{general}})$ equal parts. Intervals less than 10^{-7} m are rejected as near coincident boundaries. Layer interfaces, excavation and water levels are included before subdivision, so refining does not silently move a construction boundary.

Local refinement extends around the wall with horizontal radius $R = \max(2 \text{ m}, 2h_{\text{local}})$. Its lower limit is the lower of the wall toe and final excavation level, minus R , clipped to the model base; its upper limit is ground datum. Spacing increases linearly outside this zone toward the general spacing. Density-coordinate sampling produces a graded mesh while retaining mandatory boundaries.

$$h(a) = \min[h_{\text{general}}, h_{\text{local}} + 0.4 d(a, \text{zone})] \quad (88)$$

$$\chi(a) = \int_{a_{\text{start}}}^a 1/h(\zeta) d\zeta \quad (89)$$

Candidate grid coordinates retain mandatory boundaries. Local spacing is generated by density sampling, then far-field rectangles coarsen locally using distance from the wall/excavation zone and an aspect-ratio check. This is geometry-controlled grading, not error-estimator-driven adaptation. Requested spacings are targets; actual edge lengths depend on mandatory coordinates and transitions.

For Q8, $u_h = \sum_j w_j u_j$ at each hanging node h , using the three coarse-edge nodes and the quadratic weights in equation (87). This relation applies to both translations. Local strain matrices and force vectors use the same transformation. Constraint chains are expanded to independent degrees of freedom; structural and contact nodes remain independent.

For T6, each graded cell perimeter includes neighbouring cell corners and required load-boundary vertices. Quality-ranked polygon triangulation connects these vertices; a shared edge dictionary creates one midpoint node per soil edge. Wall/contact rows remain explicit edges. Frictional soil faces meet at the wall tip and remain continuous below the toe. Neither geometry-controlled refinement procedure is an error-estimator-driven adaptive analysis.

E2 Sparse assembly and band factorisation

The stiffness graph is constructed once for the model. Element, beam and contact contributions update values at cached positions. Q8 hanging-node relations transform local strain matrices and distribute forces to independent nodes before solving. Reverse Cuthill–McKee reordering includes wall rotations to reduce the matrix band envelope. Column and row scaling then reduce disparities between soil and structural equations without changing the physical solution.

$$\tilde{K}_{ij} = K_{ij}/(a_i c_j); \quad \tilde{r}_i = r_i/a_i \quad (90)$$

$$\tilde{K} y = \tilde{r}; \quad \Delta u_j = y_j/c_j \quad (91)$$

Scaled, partially pivoted LU retains fill within compact row bands without numerical dropping. Native LAPACK band factorisation is used when available; the managed band factorisation is a fallback. Systems with fewer than 160 free degrees of freedom use dense LU. Storage and work depend on the reordered band width and fill rather than a full dense matrix for every ordinary solve. This is a sparse-assembly/band-direct method, not a general sparse multifrontal factorisation.

E3 Line search and branch recovery

The main line search tries $\alpha = 1$ and successive halves for up to 25 trials, accepting only when the residual norm is less than $(1-10^{-4}\alpha)$ times its previous value. If the chosen branch direction is not a descent direction, the iteration probes fractions 0.001, 0.01 and 0.1 of the correction to obtain alternative nearby tangents, solves those against the original right hand side and applies another residual reducing line search. Probe evaluation never commits material or contact history.

If branch probes fail and there are at most 600 free degrees of freedom, the solver builds the column-scaled least-squares system below. Set $s_i = \max(1, \max_{\text{row}} |K_{\text{row},i}|)$, $Q = K \text{ diag}(1/s_i)$, $g = Q^T r$ and $Hls = Q^T Q$. Damping values 10^{-6} , 10^{-4} , 10^{-2} and 1 are tried with line search. Larger systems avoid this dense normal-equation recovery and rely on branch trials and load cutbacks.

$$(Q^T Q + \mu I) y = Q^T r; \Delta u = \text{diag}(1/s_i) y \quad (92)$$

This recovery does not add stiffness to the excavation model. Trial stresses use the original laws and committed history. For a cohesive-contact opening change, at most eight bounded full-Newton trials per equilibrium attempt can cross a branch if the relative residual is below 0.25; these are intermediate trials, not accepted increments. Acceptance still requires the original tolerance. Failure leads to cutback and eventually a reported stop. Rotational residuals have moment units; translational residuals have force units.

Appendix F Derivation of element and fluid equations

F1 Virtual work and plane strain reduction

Multiplying total-stress equilibrium by an admissible virtual displacement and integrating by parts gives the weak form described under Governing equilibrium and finite element discretisation. Stress symmetry permits the displacement gradient to be replaced by the symmetric virtual strain. In the four-component representation, τ_{xz} multiplies engineering shear γ_{xz} , so virtual work requires no additional factor of two. Plane strain removes virtual ϵ_{yy} but retains σ_{yy} in the material update and yield surface [7,8].

$$s^T \delta e = \sigma_{xx} \delta \epsilon_{xx} + \sigma_{zz} \delta \epsilon_{zz} + \sigma_{yy} \delta \epsilon_{yy} + \tau_{xz} \delta \gamma_{xz} \quad (93)$$

For quadratic elements, the strain matrix varies over the element. Internal force and tangent are evaluated using the same quadrature points and committed point histories. T6 uses three equal area weights; Q8 uses four 2×2 Gauss points. The tangent differentiates the quadrature internal force, including the material algorithmic tangent and any Undrained B fluid stiffness. It is not formed from a separately averaged secant modulus.

$$\delta f_{int,e} = t \sum_q A_q B_q^T D_{total,q} B_q \delta u_e \quad (94)$$

A straight quadratic edge under constant traction has consistent force fractions 1/6 at each endpoint and 2/3 at its midpoint. Soil gravity uses the same shape functions as displacement interpolation. For a straight T6 with constant unit weight, integrated vertex body forces are zero and each midside node receives one third of the resultant; the total force and first moment are preserved. Applied nodal forces use the same physical section-width basis as assembled loads.

Quadratic shape functions and quadrature

For Q8, the corner natural coordinates are $(a,b) = (-1,-1), (1,-1), (1,1), (-1,1)$. The midside nodes follow edges 1–2, 2–3, 3–4 and 4–1. The serendipity functions are:

$$N_{corner} = (1 + a\xi)(1 + b\eta)(a\xi + b\eta - 1)/4$$

$$N_5 = (1 - \xi^2)(1 - \eta)/2; \quad N_6 = (1 + \xi)(1 - \eta^2)/2$$

$$N_7 = (1 - \xi^2)(1 + \eta)/2; \quad N_8 = (1 - \xi)(1 - \eta^2)/2$$

The mapping is $x = \sum N_i x_i$ and $z = \sum N_i z_i$. With $J = \partial(x,z)/\partial(\xi,\eta)$, physical gradients are J^{-T} times natural gradients. Q8 uses $\xi, \eta = \pm 1/\sqrt{3}$, with unit natural weights and positive $\det J$. The four independent histories are activated or excavated together.

T6 uses the three barycentric permutations of $(2/3, 1/6, 1/6)$, each with physical weight $A/3$. The mapping is affine for straight edges with centred midsides. The three-point rule exactly integrates elastic stiffness for this geometry and consistent constant body loads; nonlinear stress evolution still requires refinement checks. Curved T6 edges are rejected.

For either formulation, total stress enters quadrature equilibrium and effective stress enters the constitutive update. The no-flow fluid term adds to the tangent at each active integration point. Quadratic interpolation does not create a pressure degree of freedom or remove near-incompressible locking automatically.

F2 Wall beam interpolation and strain energy

For an initially straight prismatic beam, axial displacement is interpolated linearly and transverse displacement with cubic Hermite functions. Define $\xi = l/L$ along the member; local θ is the derivative of transverse displacement with respect to the beam-axis coordinate. The six nodal components comprise axial translation, transverse translation and rotation at each end, as described under Elastic wall

formulation and rigidity changes. Euler-Bernoulli theory introduces no independent transverse shear strain [8].

$$u(l) = (1 - \xi)u_1 + \xi u_2 \quad (95)$$

$$v(l) = H_1 v_1 + H_2 \theta_1 + H_3 v_2 + H_4 \theta_2 \quad (96)$$

$$H_1 = 1 - 3\xi^2 + 2\xi^3; \quad H_2 = L(\xi - 2\xi^2 + \xi^3) \quad (97)$$

$$H_3 = 3\xi^2 - 2\xi^3; \quad H_4 = L(-\xi^2 + \xi^3) \quad (98)$$

Axial strain is du/dl and curvature is d^2v/dl^2 . Integrating axial and bending strain energy over L gives the six-by-six local stiffness matrix under Elastic wall formulation and rigidity changes. Its EA/L , $12EI/L^3$, $6EI/L^2$, $4EI/L$ and $2EI/L$ coefficients follow from interpolation and virtual work. The stage rigidity factors scale axial and bending energy separately. Shear deformation, initial curvature, geometric stiffness and wall material yielding are excluded.

$$U_{\text{beam}} = \int_0^L [EA(du/dl)^2 + EI(d^2v/dl^2)^2] dl/2 \quad (99)$$

For $dx = x_2 - x_1$ and $dz = z_2 - z_1$, $C_b = dx/L$ and $S_b = dz/L$. Each endpoint translation block in T is $[[C_b, S_b], [-S_b, C_b]]$, and its rotation entry is one. This transforms translations to axial and transverse beam directions. Local positive force signs depend on the node ordering, which is why stored actions and display endpoints must be distinguished.

F3 No flow storage as a poro-elastic reduction

The effective stress split and local storage term can be related to the small strain poro-elastic framework of Biot [9]. With Biot coefficient one, a local increment of fluid content ζ can be expressed as volumetric strain plus pressure divided by a storage modulus. Setting fluid content change to zero gives the no flow pressure update. This reduction explains the sign and the rank one normal tangent term. ShoreKALC does not solve the broader coupled consolidation equations of the reference.

$$\Delta \zeta = \Delta \epsilon_v + \Delta p_e / M_f; \quad \Delta \zeta = 0 \Rightarrow \Delta p_e = -M_f \Delta \epsilon_v \quad (100)$$

$$\Delta s = \Delta s' - \Delta p_e m = \Delta s' + M_f m m^T \Delta e \quad (101)$$

Because normal total stress is effective stress minus pressure under tension positive signs, compression increases pore pressure and stiffens the normal total stress tangent. The implemented M_f is obtained from numerical K_u minus skeleton K' rather than an independently entered permeability or fluid compressibility law. Hydrostatic pressure has no displacement derivative within a stage. During stage zero the storage update is disabled, so that increment uses only the skeleton tangent even in an Undrained B material.

Appendix G Ground behaviour (Informative)

This informative appendix reviews soil and rock behaviour, earth-pressure mobilisation, groundwater loading and construction sequence. The figures and hand calculations explain fundamentals that help engineers select assumptions, interpret ShoreKALC results and compare them with alternative analytical methods. Each hand method applies only under its stated geometry, drainage and movement assumptions.

G1 From investigation to an analysis section

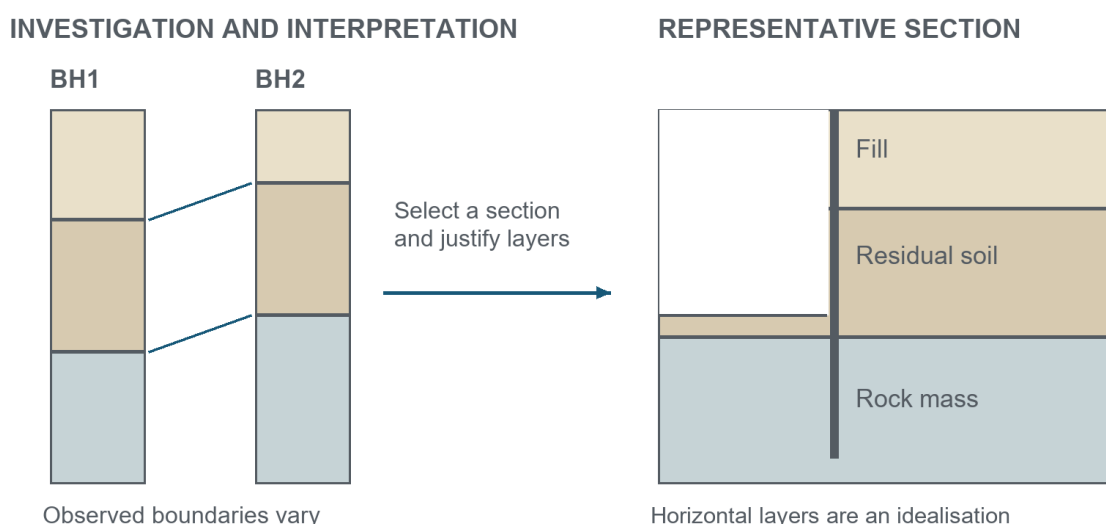


Figure G1 Interpreting boreholes as a representative section

Read the boreholes together with the geology, groundwater observations, excavation geometry and nearby foundations. Choose the wall section being analysed and translate site RLs to ShoreKALC's ground datum. For a common datum, model elevation equals site RL minus the adopted ground RL. Apply the same conversion to strata, excavation, support and water levels.

ShoreKALC's workspace has horizontal contiguous layers. Where the actual boundaries vary, assess representative and adverse sections rather than assuming one averaged profile captures every wall location. A weak seam or dipping joint may need a separate assessment. Rock class photographs illustrate weathering and discontinuities; they do not establish E' , c' , ϕ' or S_u by themselves.

G2 Wall movement and pressure mobilisation

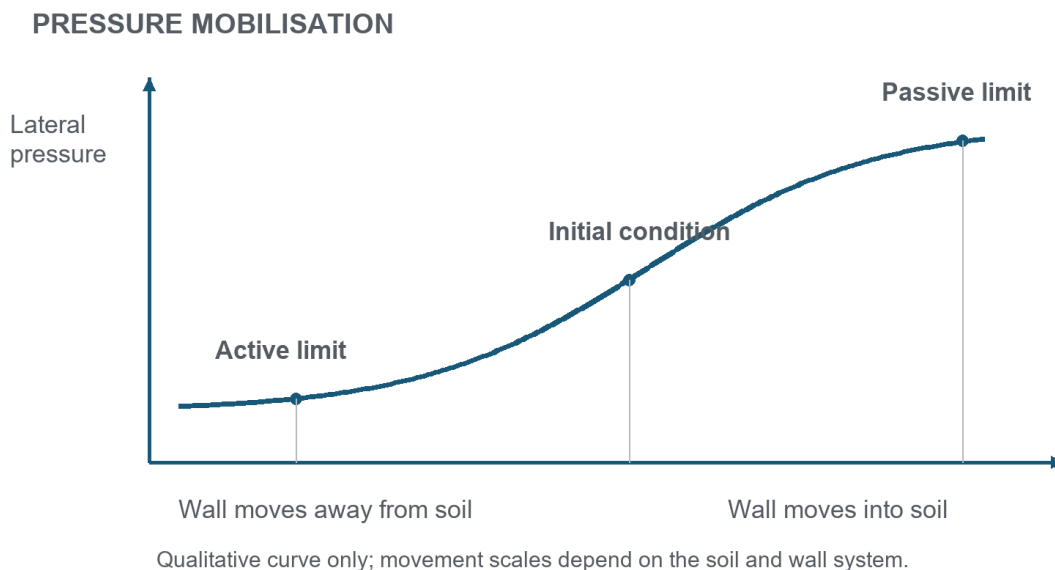


Figure G2 Movement changes the pressure mobilised against the wall

At-rest stress describes the initial ground condition. Movement away from retained soil can reduce horizontal compression toward an active limit; movement into soil can increase compression toward a passive limit. The movement required depends on soil state, wall deformation and the construction system. A stiff wall does not by itself establish the initial K_0 .

For a smooth vertical wall with level, homogeneous cohesionless ground, Rankine gives the following limiting coefficients. These are useful background references; ShoreKALC does not apply them as a prescribed pressure diagram.

$$K_a = (1 - \sin \phi') / (1 + \sin \phi'); \quad K_p = (1 + \sin \phi') / (1 - \sin \phi')$$

For $\phi' = 30^\circ$, K_a is one third and K_p is three. Passive resistance is not a reduction of vertical pressure. In an anchored wall, local movement can differ along the depth, so parts of the wall may mobilise different stress conditions during the same stage. Examine displacement, stresses and contact state together.

G3 Soil strength and wall interface strength

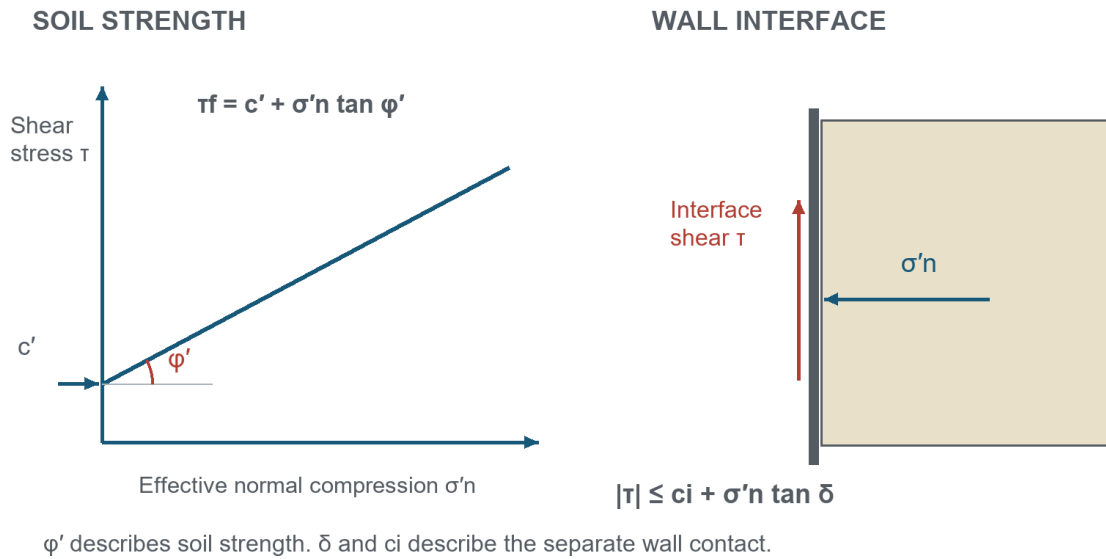


Figure G3 Separate soil and contact strength envelopes

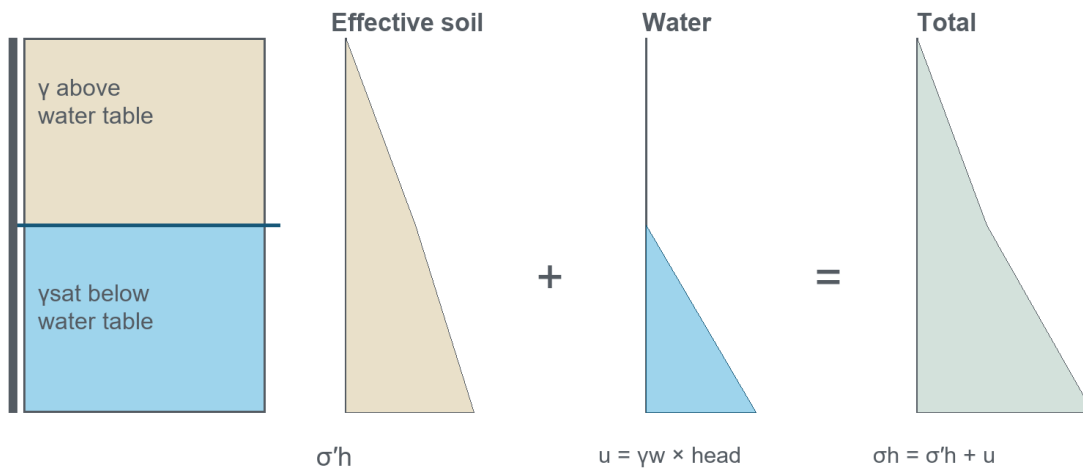
The drained soil friction angle sets the slope of the effective normal stress–shear strength envelope: that slope is $\tan \phi'$. Cohesion is its intercept. The friction angle is not a universal physical fracture angle for brittle rock. Mohr-circle sketches can explain how changing stress reaches a strength limit, but ShoreKALC evaluates the full principal stress state in its plane-strain material update.

$$\tau_f = c' + \sigma'n \tan \phi'; \quad |\tau_{interface}| \leq c_i + \sigma'n \tan \delta$$

For Frictional contact, the layer friction ratio multiplies $\tan \phi'$ and the adhesion ratio multiplies c' . Blank ratios use wall Rinter. For Undrained B, friction is zero and interface adhesion scales S_u . Rinter = 1 remains a frictional interface if Frictional mode is selected. Bonded instead shares translations and prevents relative slip and opening.

G4 Groundwater and surcharge interpretation

SOIL PRESSURE AND WATER PRESSURE



Compression-positive sketch; ShoreKALC soil stress output uses tension-positive signs.

Figure G4 Effective soil pressure and hydrostatic pressure are distinct contributions

For drained hand calculations, integrate total vertical self-weight and subtract hydrostatic pore pressure to obtain effective vertical stress. Below a water table, a conventional hydrostatic calculation uses submerged unit weight equal to saturated unit weight minus water unit weight. Add water pressure separately to effective lateral soil pressure. Avoid using submerged weight and subtracting the same water pressure twice.

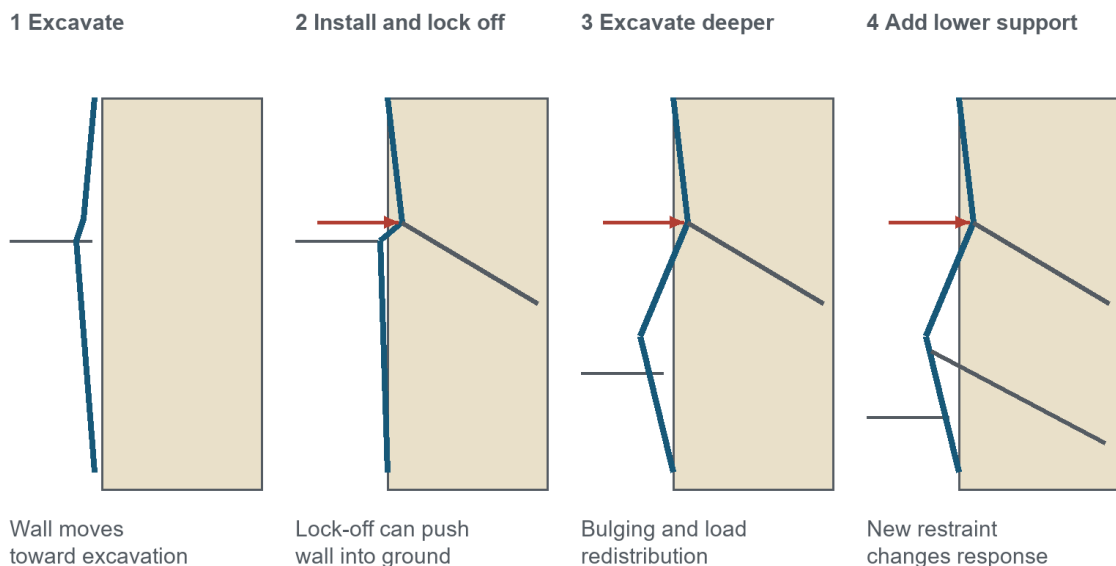
$$u = \gamma_w \times \max(0, h_w - z); \quad \sigma_h = \sigma'h + u$$

The sketch uses compression-positive magnitudes. ShoreKALC's soil stress results use tension-positive signs; total normal stress is effective normal stress minus positive pore pressure. Undrained total-stress hand equations using S_u need a consistent interpretation and should not be combined blindly with drained effective-stress expressions.

A uniform surcharge adds K_a times q to a classical fully active pressure diagram under its assumptions. A finite strip or buried surcharge in ShoreKALC acts through the continuum and construction sequence; it need not produce a uniform lateral increment. Specify each load's width, elevation and active stages.

ShoreKALC prescribes heads; it does not calculate seepage, pumping rates or consolidation.

G5 Excavation and anchor sequence



Schematic shapes only; arrows show anchor action, not computed pressure magnitudes.

Figure G5 Excavation and lock-off change restraint and wall movement

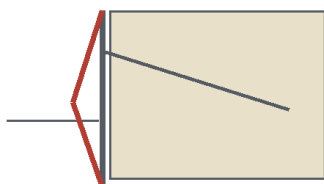
Excavate to expose a support head, install the support, apply anchor lock-off at the intended stage, then continue excavation. Subsequent phases inherit stress, plastic strain, displacement and support references. Final geometry alone does not define the force history.

Anchor lock-off can move the wall into retained ground and raise local contact pressure. Later excavation can create bulging between restraints and transfer load to anchors and embedded ground. These are mechanisms to inspect in ShoreKALC; the schematic shapes do not prescribe a pressure envelope or predict a particular project's movement.

The model anchor is a tension-only tendon acting against a fixed remote anchorage. Free length and EA set its stiffness; spacing converts between member force and force per metre of wall. The fixed remote point does not simulate the bond zone, ground pullout, or adjacent foundation movement. Actual bonded length and location must be designed separately.

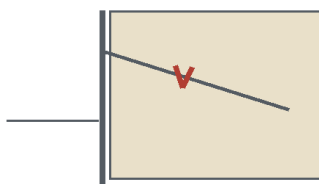
G6 Failure mechanisms and model coverage

Wall bending



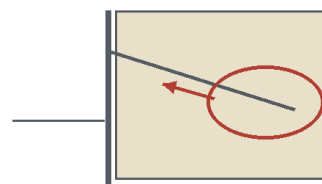
Elastic wall: section capacity checked separately

Tendon tensile limit



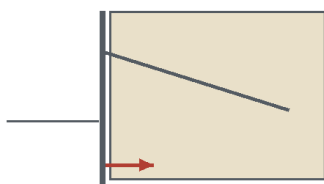
Entered tensile cap; verify actual tendon design

Anchor bond or pullout



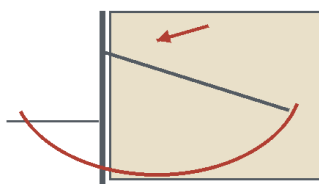
Not calculated by ShoreKALC

Insufficient embedment



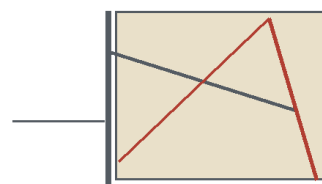
Response can indicate demand; no embedment safety factor

Overall ground movement



No global stability factor is calculated

Rock block or wedge



Explicit joints and blocks are outside the continuum

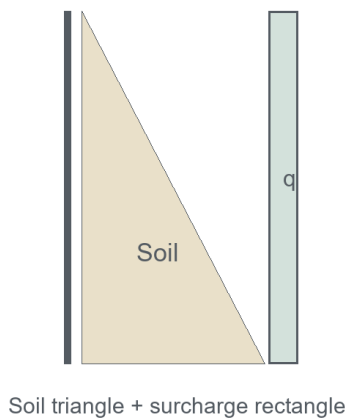
Figure G6 Examples of mechanisms requiring engineering assessment

The wall remains elastic: computed moment, shear and axial demand require separate section resistance checks. Strut resistance is screened only against an entered value; buckling and connections are not designed. An anchor tensile cap limits the tendon force in the model, but does not establish bond or pullout capacity.

Soil yielding, wall movement and contact slip can identify response requiring attention. They do not establish a global stability factor, an adequate embedment safety margin or hydraulic safety. Assess overall instability, basal heave, uplift and piping using appropriate independent methods. A joint-controlled rock wedge is outside the isotropic continuum idealisation.

G7 Two simple hand checks

A DRY SMOOTH WALL



B WATER TABLE AT MIDHEIGHT

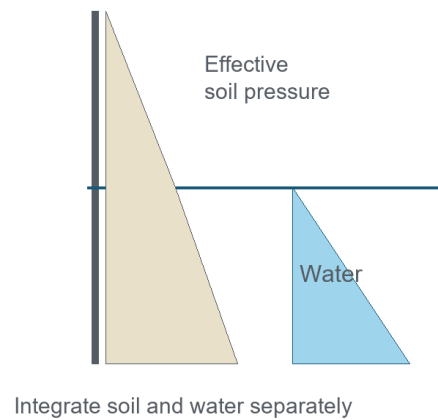


Figure G7 Pressure diagrams for explicitly assumed active conditions

Dry soil with a uniform surcharge

Assume a 6 m high smooth vertical wall, level homogeneous drained soil, $c' = 0$, $\phi' = 30^\circ$, unit weight 18 kN/m^3 and a uniform surcharge of 10 kPa extending over the retained ground. Assume fully active conditions. K_a is one third. The soil triangle has base pressure 36 kPa and resultant 108 kN/m , acting 2 m above the base. The surcharge rectangle is 3.33 kPa , giving 20 kN/m at midheight.

$$P_{a, \text{soil}} = \frac{1}{2} K_a \gamma H^2 = 108 \text{ kN/m}; \quad P_{a, q} = K_a q H = 20 \text{ kN/m}$$

Total horizontal resultant is 128 kN/m . Its moment about the base is $276 \text{ kN}\cdot\text{m/m}$ and its height above the base is approximately 2.16 m . This is the moment of the pressure resultant, not automatically the maximum bending moment in an embedded or supported ShoreKALC wall.

Water table at midheight

Use the same 6 m wall and strength assumptions, with no surcharge, bulk unit weight 18 kN/m^3 above a water table 3 m below ground, saturated unit weight 20 kN/m^3 below it, and water unit weight 9.81 kN/m^3 . The effective vertical stress at the base is 84.57 kPa , effective active lateral pressure is 28.19 kPa , and water pressure is 29.43 kPa . The total lateral base pressure is 57.62 kPa .

$$\sigma'_{v, \text{base}} = 18 \times 3 + (20 - 9.81) \times 3 = 84.57 \text{ kPa}$$

Integrating the two soil-pressure segments gives 96.29 kN/m . The water triangle adds 44.15 kN/m . The total resultant is 140.43 kN/m , with moment $248.43 \text{ kN}\cdot\text{m/m}$ and application height approximately 1.77 m above the base. Values are rounded from unrounded calculations.

G8 Applying independent checks to ShoreKALC

The hand checks in G7 test arithmetic, units, hydrostatic loading and classical limiting pressure magnitudes. A meaningful comparison requires matching geometry, soil state, drainage, surcharge extent, water heads and contact assumptions. Active conditions need sufficient appropriate movement; a supported staged model may not mobilise them everywhere. It should not be forced to match a prescribed triangular diagram.

Compare effective soil and water contributions, total resultants and resultant locations before comparing detailed peaks. Examine moment, support force and displacement by stage. A force envelope combines extrema from different stages and does not represent a simultaneous pressure state. Differences may arise from restraints, stress history, interface behaviour, soil stiffness, or numerical resolution.

For comparison with an independently defined calculation, match wall movement or support conditions and examine mesh and domain sensitivity. The simple hand examples illustrate the assumed mechanics and units; their pressure diagrams must be interpreted within those assumptions.



Figure G8 Real excavation and support – Project in Lidcombe 2019

The photograph supplies context only.

Appendix H Benchmark validation

9 October 2026 | Engine native-lapack-q8-t6-segmented-contact-20261009

This report records numerical verification and comparison of two staged-excavation benchmarks using Solver 1 (Q8 quadrilaterals) and Solver 2 (T6 triangles). Both options complete the reported construction stages at the stated equilibrium tolerance. Solver 1 remains the default because its refined Benchmark4 response is more stable. Solver 2 is an alternative for sensitivity assessment; the evidence does not establish general superiority or mesh independence.

H1 Scope and validation basis

Verification tests check whether the implemented equations are solved and assembled correctly. Published comparisons examine agreement with independently defined excavation examples. Equilibrium convergence, a successful elastic patch and agreement with an approximate reference are different kinds of evidence. The present report covers dry drained Mohr–Coulomb examples; it does not validate every drainage condition, ground type, contact mode, construction history or safety assessment.

Evidence	Result	Scope
Regression tests	9,033 assertions and 30 linear algebra cases pass	Material, continuum, contact and quadratic mesh tests
Independent T6 elastic assembly	Maximum difference 4.6×10^{-14} m	Five-stage bonded Benchmark4; independently derived polynomial interpolation
T6 topology	Paired interior edges, shared midsides and exact domain area	Reported meshes; intentional wall slit excluded from ordinary edge pairing
Current benchmark runs	All reported stages complete; zero cutbacks	Residual $\leq 10^{-6}$; finite displacements and bounded anchor forces
Local web service	Benchmark3 T6 completes 6 stages in 14.94 s	960-node model; recorded separately from native stage timings

The 9,033 assertions comprise 6,764 material/continuum checks, 668 segmented-contact checks and 1,601 quadratic-mesh checks, including two additional Q8 coarsened-wall regression checks. Independent elastic agreement does not independently validate the shared nonlinear Mohr–Coulomb law.

H2 Benchmark3 tied back excavation

The source is the Seequent PLAXIS 2D 2023.1 Mohr–Coulomb tied-back excavation tutorial. It provides approximate final checkpoints, not raw wall-profile exports or formal tolerances. The model has a 100 m × 60 m domain, a wall at $x = 15$ m with a 25 m toe, and excavation to 15 m. Two inclined anchors lock off at 300 kN. Initial equilibrium plus five construction phases correspond to six ShoreKALC stages.

Input	Adopted value
Strata / E	0/–15/–25/–45/–60 m; 60,000/100,000/130,000/480,000 kPa
Soil strength and weight	$\nu = 0.2$; $c = 1$ kPa; $\phi = 35^\circ$; $\psi = 5^\circ$; $\gamma = 18$ kN/m ³ ; drained
Wall	EA = 20,000,000 kN/m; EI = 1,670,000 kNm ² /m
Wall contact	Frictional; upper/middle sand strength ratios 0.6; penalty factor 10
Anchors	Heads –5/–10 m; free length 18.0278 m; inclination 33.6901°; EA 170,000 kN; spacing 1 m; cap 605 kN
Mesh controls	General spacing 10 m; wall spacing 1 m; local spacing 2.5, 2 and 1.5 m

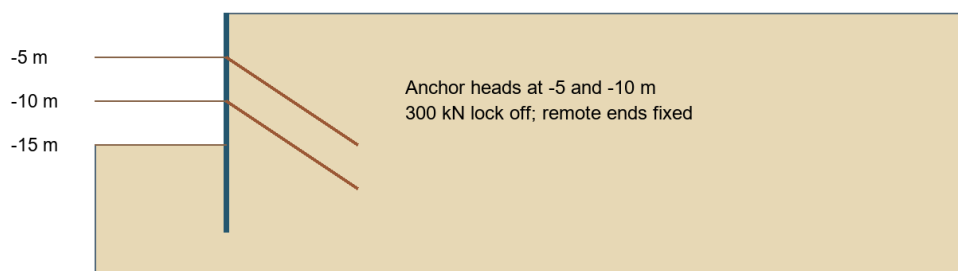
The comparison uses fixed remote tendon ends. The source includes grout-body extension and moving-soil coupling, which are omitted here. Source wall self-weight and plate Poisson effects are also omitted in this benchmark model. Geometry, material parameters, EA/EI and strength are not calibrated to published results. Solver 1 and Solver 2 use identical physical input data but different element connectivity, node counts and wall-tip discretisation.

Solver / local	Nodes	Moment kNm/m	Wall mm	Upper / lower kN	Heave mm
1 Q8 / 2.5	743	318.97	3.53	342.58/341.01	58.36
1 Q8 / 2.0	862	314.99	3.51	342.13/340.63	58.19
1 Q8 / 1.5	1065	313.66	3.66	341.90/340.49	58.07
2 T6 / 2.5	960	328.08	5.12	342.00/342.35	57.71
2 T6 / 2.0	1109	315.73	4.97	341.55/341.63	57.66
2 T6 / 1.5	1386	316.15	4.84	341.79/341.81	57.69
Published	—	~350	—	~330 each	50–60

The finest Q8 and T6 runs give 313.66 and 316.15 kNm/m, respectively: –10.38% and –9.67% relative to the approximate 350 kNm/m checkpoint. Both predict heave within 50–60 mm and anchor forces about 3–4% above 330 kN. The published example states that the lower anchor is slightly higher; refined T6 reproduces that ordering, while Q8 does not. No published scalar wall-displacement target is supplied for this comparison.

Within Solver 1, the 2 m to 1.5 m refinement changes moment by about 0.42% and peak wall movement by 4.41%. Solver 2 moment changes substantially from 2.5 m to 2 m and then changes little from 2 m to 1.5 m. This limited sequence supports useful agreement in final force/heave checkpoints, while movement and contact discretisation warrant further study. The remaining differences cannot be assigned solely to the nonlinear solver.

Benchmark3 problem and published reference mesh



100 m domain width; 60 m depth (upper 30 m shown)

Wall at $x = 15$ m; toe -25 m; final excavation -15 m

Dry model; side rollers and fixed base at full domain depth

Figure H1. ShoreKALC adopted Benchmark3 problem. Construction levels and principal dimensions are shown; the sketch shows the upper domain only. Full domains appear in the mesh figures.

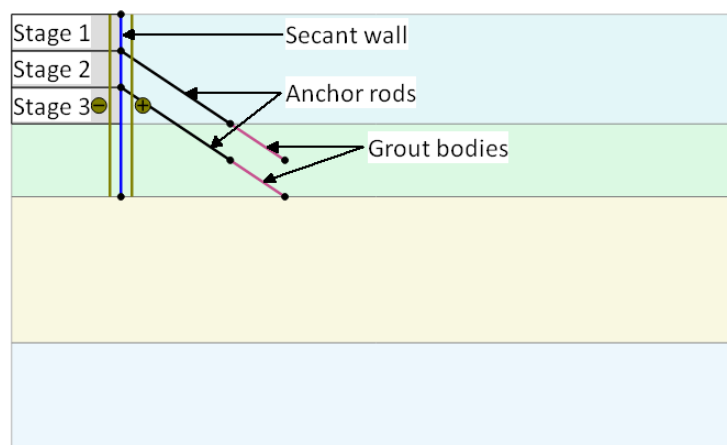


Figure H2. Published problem geometry. Source: Seequent PLAXIS 2D 2023.1 tied-back tutorial, Figure 1.1, p. 3. Grout bodies belong to the published model; ShoreKALC uses fixed remote anchor ends.

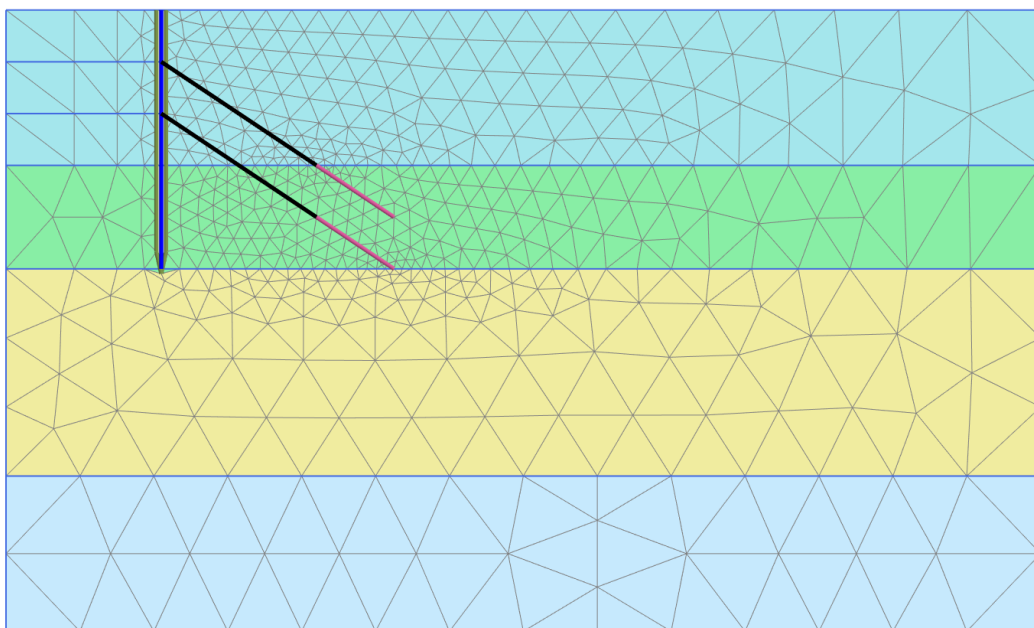


Figure H3. Published initial medium mesh before excavation. Source: the same Seequent tutorial, Figure 2.4, p. 10. The triangular topology and grout-body refinement differ from ShoreKALC.

Benchmark3 ShoreKALC verification meshes

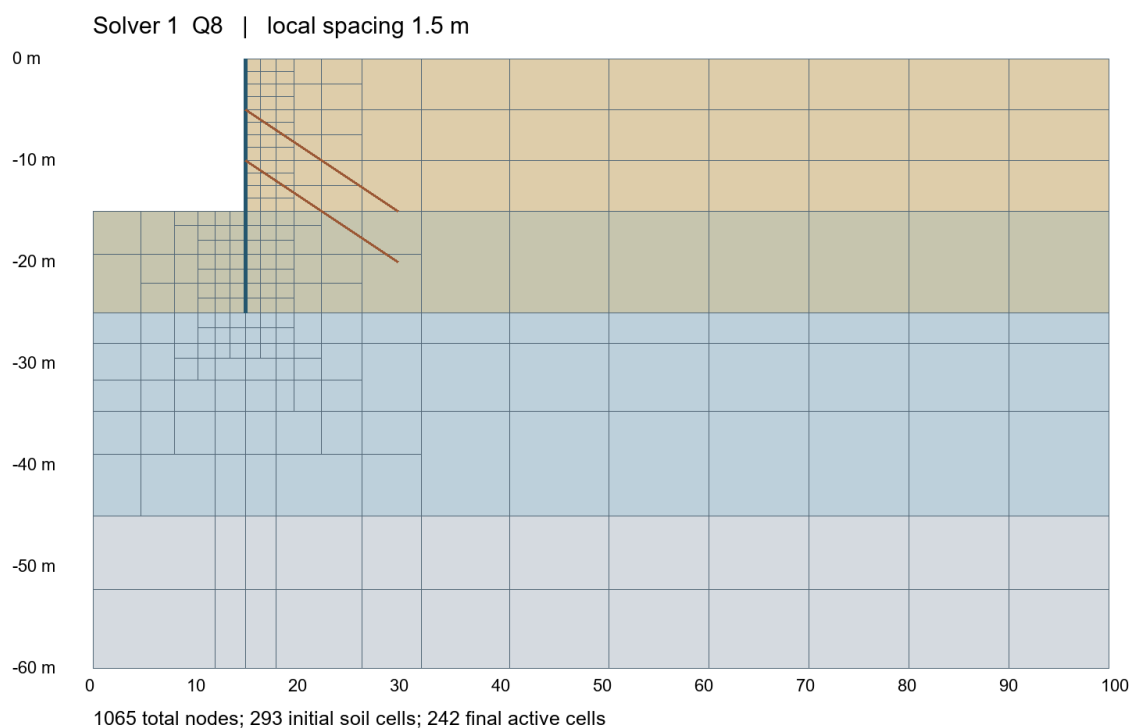


Figure H4. Solver 1 final active Q8 mesh, drawn from the archived verification result. Undeformed geometry; full domain and physical cell edges. Refinement transitions use interpolation constraints; midside nodes are omitted from the drawing.

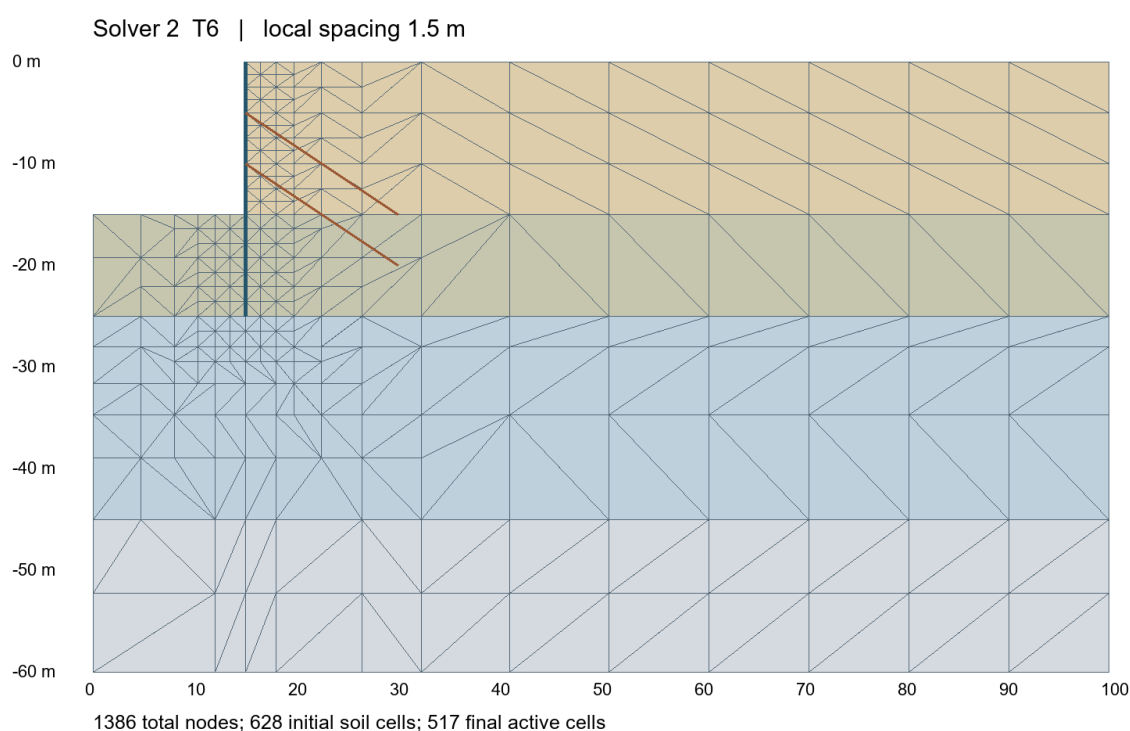


Figure H5. Solver 2 final active T6 mesh, drawn from the archived verification result. Undeformed geometry; shared corner and midside nodes form a conforming mesh. Midside node markers are omitted for readability.

These are the finest reported meshes for each solver. Requested local spacings and node counts differ where shown. The figures compare geometry and discretisation; they do not demonstrate mesh independence or equal accuracy.

H3 Benchmark4 dry cantilever excavation

Benchmark4 follows DIANA's published sheet-pile-wall verification example, Case A with drained Mohr–Coulomb soil. Its graphs contain PLAXIS Reference and DIANA curves. The final stage follows three excavation steps to 6 m. The comparison retains the 50 m × 30 m domain and uses initial equilibrium, wall/surcharge activation and three excavation stages.

Input	Adopted value
Soil	$E = 30,000 \text{ kPa}$; $\nu = 0.25$; $c = 1 \text{ kPa}$; $\phi = 30^\circ$; $\psi = 0^\circ$; $K_0 = 0.5$
Wall geometry and rigidity	$x = 10 \text{ m}$; toe -12 m ; $EA = 18,000,000 \text{ kN/m}$; $EI = 540,000 \text{ kNm}^2/\text{m}$
Weight and loading	$\gamma = 17.658 \text{ kN/m}^3$; wall weight 9.806076 kN/m height; 10 kPa surcharge from $x = 11$ to 32 m
Contact and water	Bonded shared soil/wall translations; dry
Mesh controls	General spacing 8 m ; wall follows soil edges; local spacing shown below

Source densities are converted using adopted $g = 9.81 \text{ m/s}^2$. Source wall weight is included explicitly while the wall is active. Nominal rectangular EA/EI are used without fitting a stiffness multiplier. DIANA's stiff elastic interface and tip connection approximate continuity; ShoreKALC uses shared-node bonding. Plate/beam and element formulations differ. Published curves are digitised rather than raw program exports.

Solver / local	Nodes	Wall mm	Moment kNm/m	Shear kN/m	Axial kN/m
1 Q8 / 1.50	548	28.51	281.05	88.71	127.19
1 Q8 / 1.00	762	30.93	285.24	91.03	130.47
1 Q8 / 0.75	1059	32.85	291.25	93.07	130.40
1 Q8 / 0.60	1504	34.04	293.24	95.13	121.97
2 T6 / 1.50	721	31.42	292.82	98.57	138.75
2 T6 / 1.00	995	28.06	279.86	89.47	125.82
2 T6 / 0.75	1391	31.76	289.41	93.42	132.58
PLAXIS	—	40.37	325.93	112.18	129.34
DIANA	—	35.83	307.41	100.37	122.32

Approximate two-pixel digitisation uncertainty is 0.37 mm movement, 3.70 kNm/m moment, 2.95 kN/m shear and 1.48 kN/m axial force. These uncertainty estimates describe curve extraction; they are not engineering acceptance tolerances. PLAXIS peaks exceed DIANA by about 12.7% in movement, 6.0% in moment, 11.8% in shear and 5.7% in axial force. Agreement with one program does not make it an exact truth standard.

At matching requested local spacing 0.75 m , Q8 gives 32.85 mm and 291.25 kNm/m ; T6 gives 31.76 mm and 289.41 kNm/m . Node counts differ, so this is matched spacing and physical inputs rather than an equal-degree-of-freedom comparison. T6's movement changes non-monotonically over its three meshes; its axial demand is also more sensitive.

Solver 1's finer meshes are better settled and support retaining it as the default. Neither sequence proves general mesh independence.

Benchmark4 problem and published reference mesh

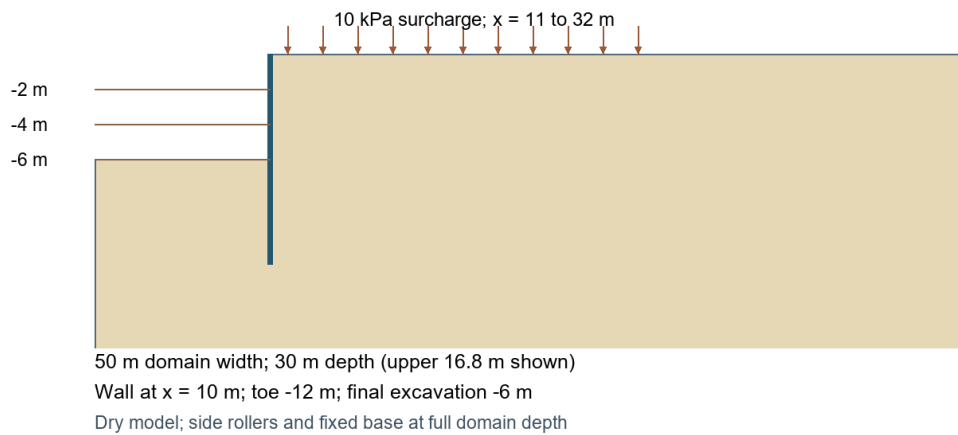


Figure H6. ShoreKALC adopted Benchmark4 problem. Construction levels and principal dimensions are shown; the sketch shows the upper domain only. Full domains appear in the mesh figures.

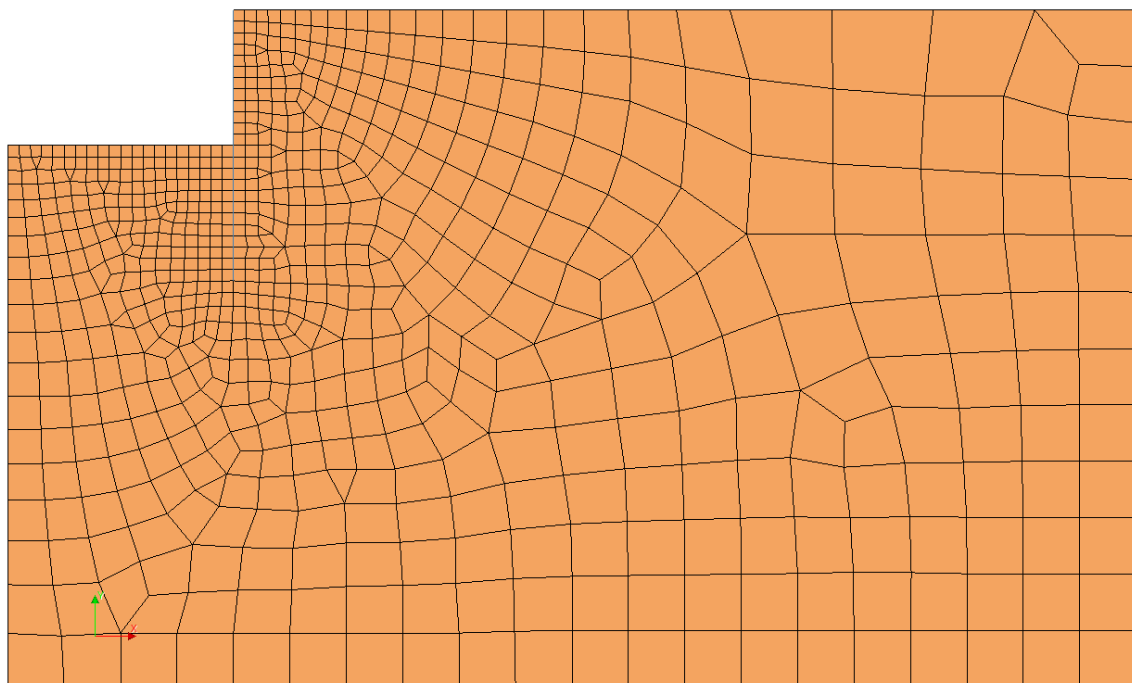


Figure H7. Published final excavation mesh, Case A. Source: DIANA 10.7 verification manual, Finite Element Model, Figure 4, third excavation (DIANA FEA BV). The source uses mostly quadratic quadrilaterals with graded sizes.

The DIANA publication provides the comparison curves for both DIANA and PLAXIS. This figure is the published DIANA mesh; it is not a PLAXIS mesh image. Source links are listed under Sources and reproducibility.

Benchmark4 ShoreKALC verification meshes

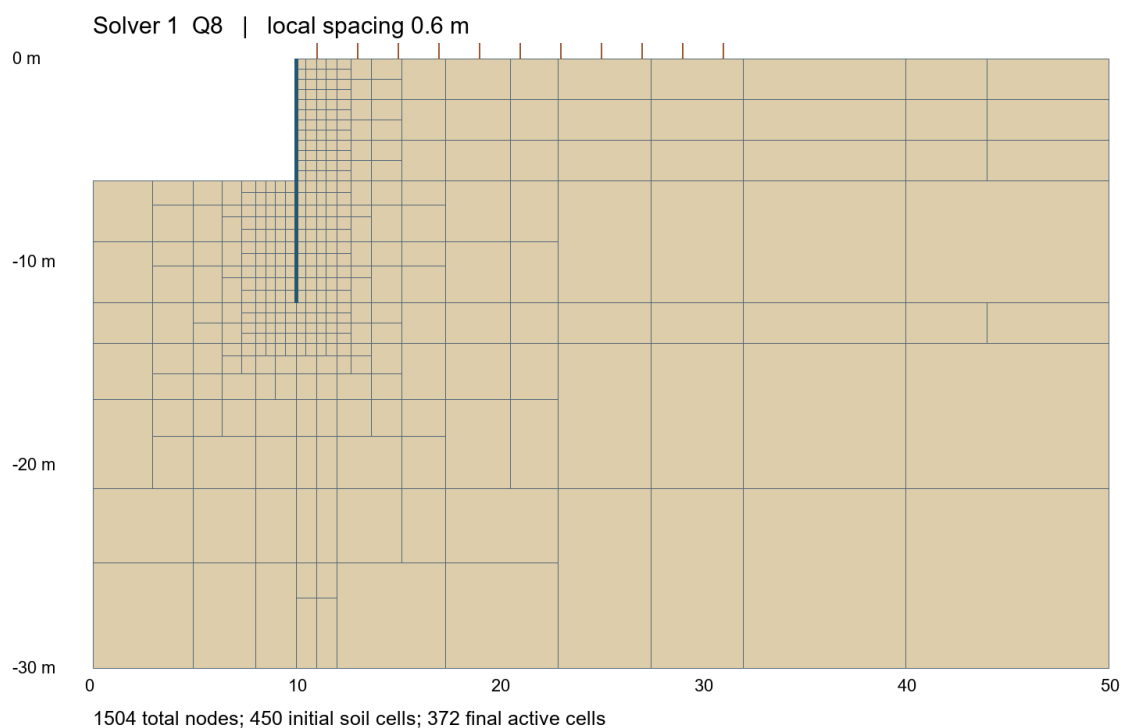


Figure H8. Solver 1 final active Q8 mesh, drawn from the archived verification result. Undeformed geometry; full domain and physical cell edges. Refinement transitions use interpolation constraints; midside nodes are omitted from the drawing.

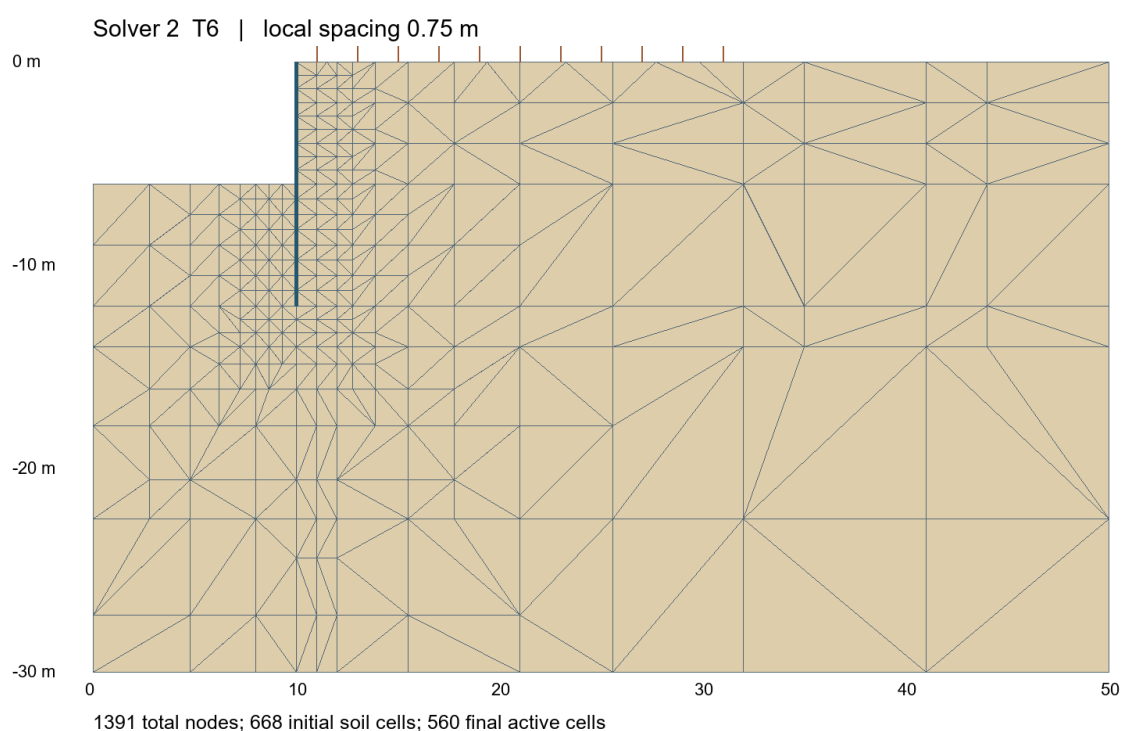
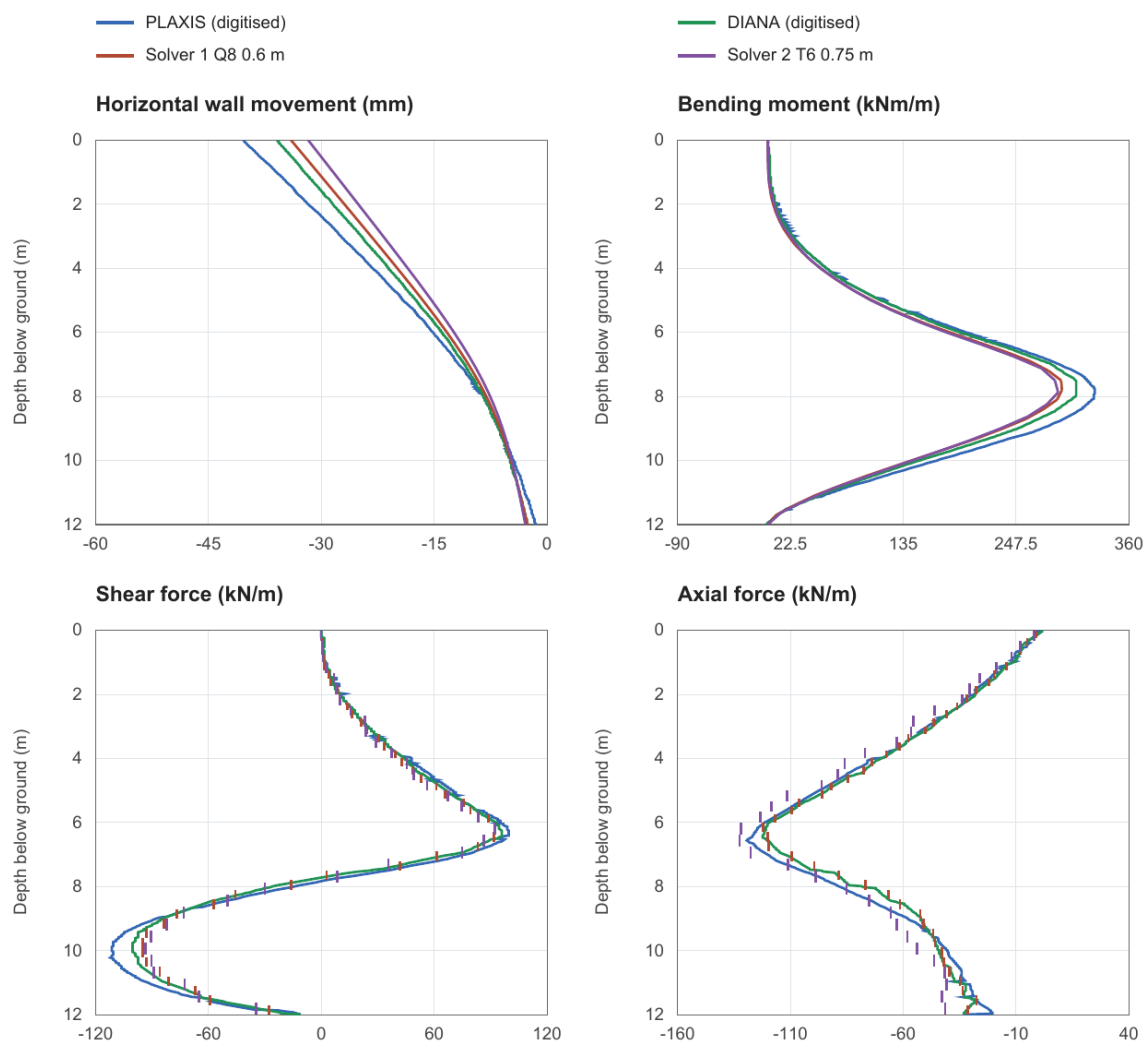


Figure H9. Solver 2 final active T6 mesh, drawn from the archived verification result. Undeformed geometry; shared corner and midside nodes form a conforming mesh. Midside node markers are omitted for readability.

These are the finest reported meshes for each solver. Requested local spacings and node counts differ where shown. The figures compare geometry and discretisation; they do not demonstrate mesh independence or equal accuracy.

Benchmark4 final wall profiles



Final-stage wall profiles for the finest reported Q8 and T6 meshes. Published PLAXIS and DIANA lines are digitised. Horizontal movement retains its signed direction; force signs follow the published curves. Different local spacings and node counts are stated explicitly. These profiles supplement the absolute peak tables and do not define a design action combination.

Benchmark4 shows good agreement with the published reference solutions. Both ShoreKALC solvers reproduce the overall wall deformation and force-profile shapes, including the bending-moment peak near 8 m depth and the shear reversal below excavation level. Agreement extends beyond isolated peak values to the distribution of response along the wall.

Solver 1's finest reported mesh gives peak wall movement, bending moment and shear approximately 5.0%, 4.6% and 5.2% below DIANA, respectively; peak axial force differs by approximately 0.3%. Both ShoreKALC solutions generally lie closer to DIANA than PLAXIS, which predicts larger movement and bending demand in this example.

This agreement supports confidence in ShoreKALC's representation of the principal soil-wall interaction mechanisms for this benchmark. Further refinement remains relevant, particularly for displacement and Solver 2's axial-force response.

H4 Numerical results and interpretation

Peak wall movement is the maximum absolute horizontal movement of active wall nodes relative to converged initial equilibrium.

Moment, shear and axial peaks are maximum absolute active beam end actions in the final stage. Anchor forces are axial forces per anchor at 1 m spacing.

Benchmark3 floor heave is maximum vertical movement at formation on the excavation side, relative to initial equilibrium. Peaks can occur at different locations; they do not form a single compatible wall design action set.

Case	Cells / records	Iterations	Max residual	Stage time s
B3 Q8 2.50	204 / 816	393	5.87e-07	8.76
B3 Q8 2.00	235 / 940	399	2.92e-07	9.24
B3 Q8 1.50	293 / 1172	446	6.26e-07	12.64
B3 T6 2.50	430 / 1290	383	1.31e-07	9.41
B3 T6 2.00	501 / 1503	404	4.06e-07	12.89
B3 T6 1.50	628 / 1884	403	1.86e-07	17.45
B4 Q8 1.50	157 / 628	271	8.76e-07	2.64
B4 Q8 1.00	217 / 868	278	5.59e-07	5.72
B4 Q8 0.75	305 / 1220	289	5.50e-07	8.26
B4 Q8 0.60	450 / 1800	370	3.14e-07	17.01
B4 T6 1.50	338 / 1014	278	7.02e-07	4.91
B4 T6 1.00	474 / 1422	301	5.55e-07	8.37
B4 T6 0.75	668 / 2004	333	5.56e-07	12.99

Every reported case completes six Benchmark3 stages or five Benchmark4 stages with zero cutbacks. Times sum native stage diagnostics and exclude preparation, web transfer and report generation. They depend on machine conditions and are not a controlled cross-product performance comparison. The default 58-second calculation budget remains a stop condition rather than an engineering acceptance criterion.

The published checkpoints have no agreed pass/fail tolerance. A numerical residual below 10^{-6} establishes the adopted equilibrium criterion, not an equivalent percentage error in movement or moment. Likewise, analytical regression tests cannot replace independent soil stress-path validation, field calibration or checking application-specific sensitivity.

H5 Applicability and remaining validation

The evidence supports use of the implemented quadratic formulations for the stated benchmark conditions with transparent reporting of model assumptions and convergence. It does not justify a blanket claim of agreement with PLAXIS or DIANA for all excavations. Solver 1 is the default; Solver 2 offers a conforming triangular alternative and should be compared with Solver 1 and further refinements where results control design.

Further validation should cover nonlinear material stress paths independently of the common implementation, wider mesh and boundary studies, penalty sensitivity, saturated/Undrained B benchmark cases, anchor-ground coupling where relevant, and the separate scope of strength-reserve checks. Wall section resistance, anchor pullout, hydraulic mechanisms, basal heave safety and joint-controlled rock failure require project design methods outside these dry benchmark comparisons.

H6 Sources and reproducibility

Benchmark3 source: Seequent, PLAXIS 2D 2023.1, Tied-back excavation with Mohr–Coulomb, updated December 2022; section 3.1 supplies approximate checkpoints.

<https://files.seequent.com/training/Data/PLAXIS/PLAXIS%20Fundamentals/Tied-back%2Bexcavation%2B%28MC%29%2B%5BPLAXIS%2B2D%2B2023%5D.pdf>

Benchmark4 model: DIANA 10.7 verification manual, Finite Element Model.

<https://manuals.dianafea.com/d107/en/1092500-1093607-finite-element-model.html>

Benchmark4 results: DIANA 10.7 verification manual, Mohr–Coulomb Model.

<https://manuals.dianafea.com/d107/en/1092500-1093608-mohr-coulomb-model.html>

Benchmark4 geometry and loading: DIANA verification example.

<https://manuals.dianafea.com/d106/Verify/Verifyse68.html>

Numerical evidence is archived under Release-Validation-20261009. The manifest records exact settings, stage metrics, input/result SHA-256 hashes, engine identity and source/binary hashes.

Published-reference digitisation and its uncertainty remain separate from calculated output.

Reproduction requires the recorded input files and corresponding solver build; preserving only rounded tables is insufficient.

Appendix J Benchmark4 Detailed Results



ShoreKALC Analysis Report

Staged excavation · plane-strain analysis

CONSTRUCTION
CONVERGED

Report generated by (account ID): admin@rkalc.com

PROJECT

Benchmark4 - production Q8 DIANA verification

SUBTITLE / JOB NUMBER

Mohr-Coulomb Case A; published domain ·
BENCHMARK4

PREPARED BY

ShoreKALC benchmark

GENERATED (SYDNEY TIME)

09/10/2026, 3:46:09 pm

SOIL INFORMATION

DIANA 10.7 dry Mohr-Coulomb Case A:
<https://manuals.dianafea.com/d107/en/1092500-1093608-mohr-coulomb-model.html>. Includes the published wall weight, 9.806076 kN/m height. Reference curves are digitised.

ANALYSIS COMPLETION

5 of 5 stages converged

Construction convergence establishes equilibrium. Engineering verdicts are listed separately for each stage. Movement and support demand are checked against entered limits; governing support resistance is supplied by the engineer. Optional soil and toe-ground branches verify a strength-reduction target in the model. They do not calculate a limiting factor of safety or required embedment depth. Use wall movement, bending, shear and axial demands for external section and reinforcement design. Basal heave, hydraulic uplift, piping and rock-joint stability are outside the calculation scope.

1 · Model definition

DOMAIN

x 0 to 50 m; base -30 m

INITIAL STRESS

K0

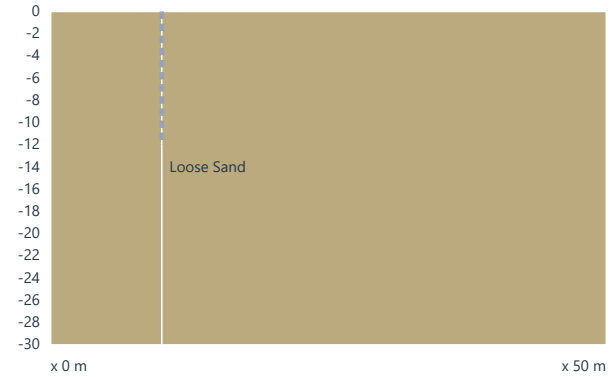
UNITS / DATUM

m · kN · kPa; ground surface 0 m

GROUNDWATER

Dry soil

Initial model



Undeformed section. Loose Sand: 0 to -30 m

Soil profile and strength

Layer	Top m	Base m	γ kN/m ³	γ_{sat} kN/m ³	c' kPa	ϕ' °	ψ °
Loose Sand	0	-30	17.658	19.62	1	30	0

Layer	E' kPa	ν'	Drainage	Su kPa	ν_u	K_0
Loose Sand	30,000	0.25	Drained	—	—	0.5

Wall and supports

WALL

Bonded cantilever wall; x 10 m; top 0 m; toe -12 m

WALL WEIGHT

9.806 kN/m of height per metre of wall width

WALL STIFFNESS

EA 18,000,000 kN/m; EI 540,000 kN-m²/m

WALL THICKNESS / INTERFACE

0.6 m; Rinter 1

DESIGN ACTIONS

Wall demands for external section and reinforcement design; support checks use entered resistance

RETAINED SURFACE SETTLEMENT LIMIT

Not entered

Anchor	Level m	Angle °	Free length m	EA kN	Spacing m	Lock-off kN	Capacity kN
--------	---------	---------	---------------	-------	-----------	-------------	-------------

Strut	Level m	Remote x m	EA kN	Spacing m	Preload kN	Compression resistance kN
-------	---------	------------	-------	-----------	------------	---------------------------

Surcharge	Start x m	End x m	Elevation m	Pressure kPa
Retained ground surcharge	11	32	0	10

Engineering assessment criteria

WALL HORIZONTAL SLS LIMIT Not entered	SOIL STRENGTH-REDUCTION TARGET Not entered
TOE GROUND STRENGTH-REDUCTION TARGET Not entered	ENTERED CRITERIA / SOURCE Not entered

Anchor	Model tensile cap kN/member	Entered governing design resistance kN/member
--------	-----------------------------	---

Strength-reserve targets hold loads and pore pressures fixed and do not establish the limiting factor of safety or required embedment depth. Governing support resistances are supplied by the engineer on the same basis as the analysed actions.

Wall–soil contact inputs

MODE Bonded	PENALTY FACTOR 10
----------------	----------------------

Layer	tan δ / tan φ	Adhesion / c
Loose Sand	1	1

Frictional contact has zero tensile normal capacity and no interface dilation. In Undrained B, adhesion scales Su and friction is zero. Ratios do not change a bonded wall.

Stage wall stiffness

Stage	EA factor	EI factor	EA kN/m	EI kNm²/m
Initial - K0 equilibrium	1	1	18,000,000	540,000
Install wall and apply 10 kPa surcharge	1	1	18,000,000	540,000
Excavate to -2 m	1	1	18,000,000	540,000
Excavate to -4 m	1	1	18,000,000	540,000
Excavate to -6 m	1	1	18,000,000	540,000

Factors apply to original wall rigidities; blanks carry forward from 1. Values are configured rigidities; inactive walls contribute no stiffness. Changes rescale elastic forces at existing deformation and re-equilibrate with the original installation reference.

2 · Construction sequence

Stage	Excavation m	Wall	Active surcharges	Water left/right m	Installed supports	Locked anchors
00 · Initial - K0 equilibrium	0	Inactive	—	Dry	—	—
01 · Install wall and apply 10 kPa surcharge	0	Active	Retained ground surcharge	Dry	—	—
02 · Excavate to -2 m	-2	Active	Retained ground surcharge	Dry	—	—

Stage	Excavation m	Wall	Active surcharges	Water left/right m	Installed supports	Locked anchors
03 · Excavate to -4 m	-4	Active	Retained ground surcharge	Dry	—	—
04 · Excavate to -6 m	-6	Active	Retained ground surcharge	Dry	—	—

Support and lock-off columns describe cumulative state. The initial groundwater head is common to both sides. Subsequent heads are prescribed independently.

3 · Analysis and convergence

MESH 1504 nodes · 450 soil cells · 44 wall beams	REQUESTED SPACING General 8 m; local 0.6 m; wall 0 m (0 = soil rows)
FORMULATION Q8 quadratic quadrilaterals, 2x2 Gauss integration; Small-strain effective-stress plane strain; drained Mohr-Coulomb or Undrained B (specified Su, effective stiffness, no-flow fluid storage). Prescribed hydrostatic groundwater; no consolidation or seepage.	OUTCOME All continuum stages converged.

Stage	Status	Stage change %	Residual	Iterations	Steps	Retries	Time s
00 · Initial - K0 equilibrium	Converged	100	7.43e-15	0	1	0	0.1
01 · Install wall and apply 10 kPa surcharge	Converged	100	2.16e-10	38	20	0	4.7
02 · Excavate to -2 m	Converged	100	2.76e-9	82	20	0	9
03 · Excavate to -4 m	Converged	100	1.71e-7	103	20	0	8.7
04 · Excavate to -6 m	Converged	100	3.14e-7	147	20	0	12

Stage change is the achieved fraction of the phase force change, not a fraction of excavation depth. Failed stages and subsequent stages have no completed result plots. Prior converged results remain valid as results of those earlier stages.

4 · Wall and support force envelopes

Across all converged stages. Signed minimum and maximum at each station; inactive members are excluded.



No active anchors or struts.

Stage 00 · Initial - K0 equilibrium

CALCULATION STATUS

Converged

EXCAVATION / WALL

0 m / inactive

INSTALLED SUPPORTS

—

LOCKED-OFF ANCHORS

—

ACTIVE SURCHARGES

—

Stage geometry

Undeformed geometry; inactive / removed soil excluded.

Wall deformed shape

Wall displacement from initial equilibrium

Dashed: original wall · scale ×30

Wall is inactive in this stage.

Wall section forces



Engineering assessment

ASSESSMENT SUMMARY — 0 passed; 0 failed; 1 not assessed. Verdicts cover the assessed checks only. Omitted optional limits are not failures.

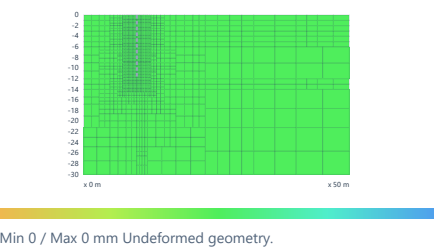
Check	Result	Detail / action
Soil stability — strength reserve	NOT APPLICABLE	No active retaining wall with excavation in this stage.
Toe ground — strength reserve	NOT APPLICABLE	No active retaining wall with excavation in this stage.
Soil yielding	OBSERVATION	0 of 1800 active integration points currently yielding. Use the strength-reserve verdict to assess the requested margin; yielding alone does not establish failure.
Yielding below formation	OBSERVATION	0 of 576 excavation-side elements between formation and toe currently yielding. This is a geometric count, not a passive wedge or resistance calculation.
Retained ground surface settlement	NOT ASSESSED	0 mm downward from initial equilibrium; enter the project SLS settlement limit. No 25 mm or rock-footing percentage is assumed. Immediate free-field surface movement only; consolidation, foundation movement and differential settlement are not assessed.
Wall horizontal movement	NOT APPLICABLE	No active wall elements.

Anchor and strut forces

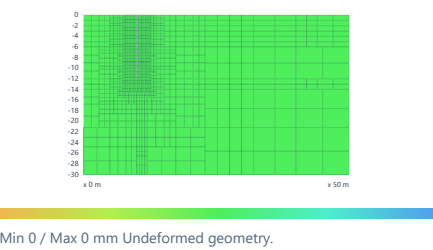
No active anchors or struts.

Soil results · selected stage only

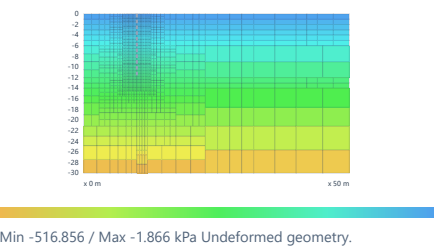
Horizontal displacement Ux



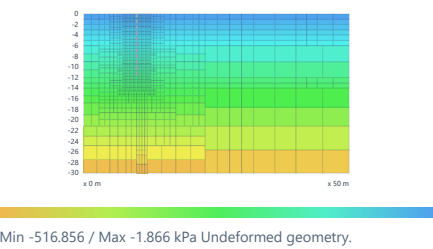
Vertical displacement Uz



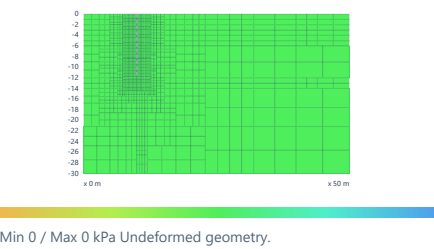
Vertical effective stress σ_z'



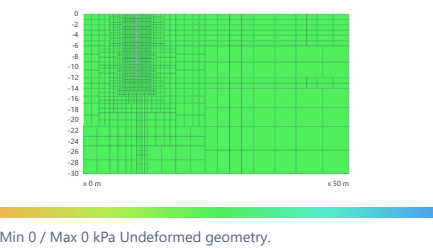
Vertical total stress σ_z



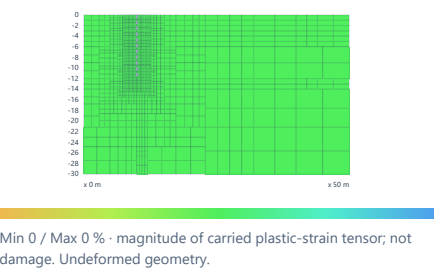
Total pore pressure



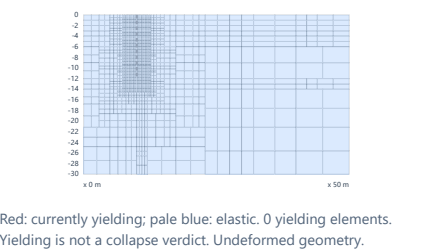
Excess pore pressure



Plastic strain magnitude



Current soil yielding



Stage 01 · Install wall and apply 10 kPa surcharge

CALCULATION STATUS

Converged

EXCAVATION / WALL

0 m / active

INSTALLED SUPPORTS

—

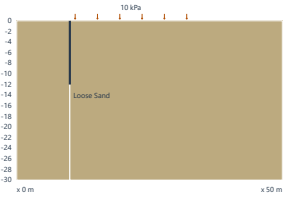
LOCKED-OFF ANCHORS

—

ACTIVE SURCHARGES

Retained ground surcharge

Stage geometry



Undeformed geometry; inactive / removed soil excluded.

Wall deformed shape



Dashed: original wall · scale ×30

Wall Ux range -0.402 ... 0.163 mm.

Wall section forces

Wall bending moment



Min -0 / Max 13.956 kN-m/m

Wall shear force



Min -6.096 / Max 2.366 kN/m

Wall axial force



Min -49.172 / Max -0.532 kN/m

Segment	Top m	Base m	M top/base kN-m/m	V top/base kN/m	N top/base kN/m
1	0	-0.25	-0 / 0.443	-1.772 / -1.772	-0.532 / -0.532
2	-0.25	-0.5	0.443 / 1.624	-4.723 / -4.723	-2.567 / -2.567
3	-0.5	-0.75	1.624 / 2.998	-5.497 / -5.497	-4.619 / -4.619

Segment	Top m	Base m	M top/base kN-m/m	V top/base kN/m	N top/base kN/m
4	-0.75	-1	2.998 / 4.522	-6.096 / -6.096	-6.687 / -6.687
5	-1	-1.25	4.522 / 6.017	-5.979 / -5.979	-9.026 / -9.026
6	-1.25	-1.5	6.017 / 7.409	-5.569 / -5.569	-11.253 / -11.253
7	-1.5	-1.75	7.409 / 8.719	-5.242 / -5.242	-13.577 / -13.577
8	-1.75	-2	8.719 / 9.847	-4.511 / -4.511	-15.747 / -15.747
9	-2	-2.25	9.847 / 10.875	-4.11 / -4.11	-18.024 / -18.024
10	-2.25	-2.5	10.875 / 11.702	-3.311 / -3.311	-20.054 / -20.054
11	-2.5	-2.75	11.702 / 12.431	-2.914 / -2.914	-22.252 / -22.252
12	-2.75	-3	12.431 / 12.97	-2.155 / -2.155	-24.109 / -24.109
13	-3	-3.25	12.97 / 13.418	-1.793 / -1.793	-26.216 / -26.216
14	-3.25	-3.5	13.418 / 13.697	-1.118 / -1.118	-27.885 / -27.885
15	-3.5	-3.75	13.697 / 13.898	-0.804 / -0.804	-29.897 / -29.897
16	-3.75	-4	13.898 / 13.956	-0.23 / -0.23	-31.373 / -31.373
17	-4	-4.25	13.956 / 13.948	0.031 / 0.031	-33.288 / -33.288
18	-4.25	-4.5	13.948 / 13.822	0.503 / 0.503	-34.568 / -34.568
19	-4.5	-4.75	13.822 / 13.644	0.714 / 0.714	-36.385 / -36.385
20	-4.75	-5	13.644 / 13.372	1.089 / 1.089	-37.465 / -37.465
21	-5	-5.25	13.372 / 13.058	1.253 / 1.253	-39.181 / -39.181
22	-5.25	-5.5	13.058 / 12.673	1.541 / 1.541	-40.058 / -40.058
23	-5.5	-5.75	12.673 / 12.257	1.665 / 1.665	-41.67 / -41.67
24	-5.75	-6	12.257 / 11.787	1.877 / 1.877	-42.336 / -42.336
25	-6	-6.3	11.787 / 11.195	1.974 / 1.974	-43.991 / -43.991
26	-6.3	-6.6	11.195 / 10.552	2.143 / 2.143	-44.498 / -44.498
27	-6.6	-6.9	10.552 / 9.89	2.207 / 2.207	-46.139 / -46.139
28	-6.9	-7.2	9.89 / 9.2	2.3 / 2.3	-46.302 / -46.302
29	-7.2	-7.5	9.2 / 8.501	2.33 / 2.33	-47.763 / -47.763
30	-7.5	-7.8	8.501 / 7.793	2.363 / 2.363	-47.544 / -47.544
31	-7.8	-8.1	7.793 / 7.083	2.366 / 2.366	-48.803 / -48.803
32	-8.1	-8.4	7.083 / 6.378	2.35 / 2.35	-48.148 / -48.148
33	-8.4	-8.7	6.378 / 5.678	2.331 / 2.331	-49.172 / -49.172
34	-8.7	-9	5.678 / 4.996	2.275 / 2.275	-47.998 / -47.998
35	-9	-9.3	4.996 / 4.325	2.237 / 2.237	-48.737 / -48.737
36	-9.3	-9.6	4.325 / 3.682	2.144 / 2.144	-46.918 / -46.918
37	-9.6	-9.9	3.682 / 3.055	2.088 / 2.088	-47.298 / -47.298
38	-9.9	-10.2	3.055 / 2.469	1.954 / 1.954	-44.612 / -44.612
39	-10.2	-10.5	2.469 / 1.906	1.877 / 1.877	-44.459 / -44.459
40	-10.5	-10.8	1.906 / 1.399	1.691 / 1.691	-40.595 / -40.595
41	-10.8	-11.1	1.399 / 0.923	1.587 / 1.587	-39.801 / -39.801
42	-11.1	-11.4	0.923 / 0.533	1.301 / 1.301	-33.561 / -33.561
43	-11.4	-11.7	0.533 / 0.189	1.145 / 1.145	-29.428 / -29.428

Segment	Top m	Base m	M top/base kN-m/m	V top/base kN/m	N top/base kN/m
44	-11.7	-12	0.189 / -0	0.63 / 0.63	-20.984 / -20.984

Engineering assessment

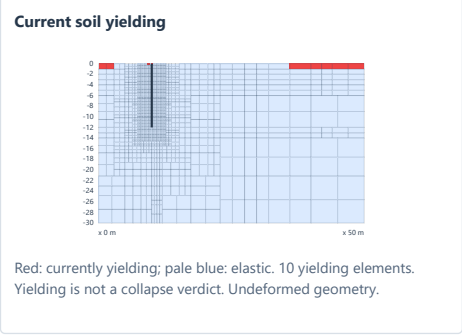
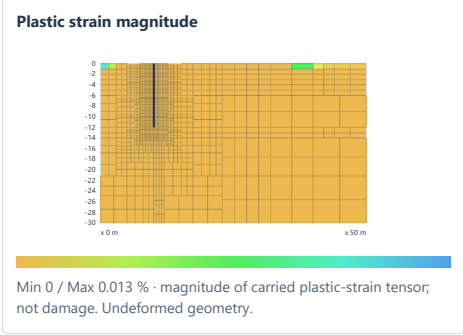
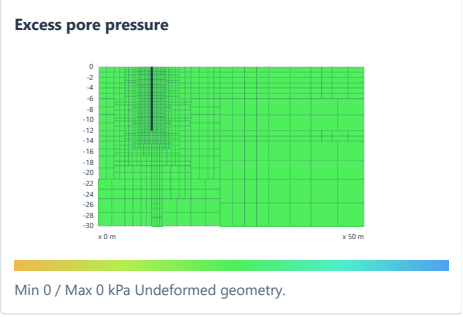
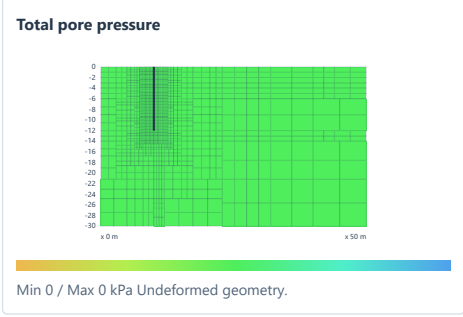
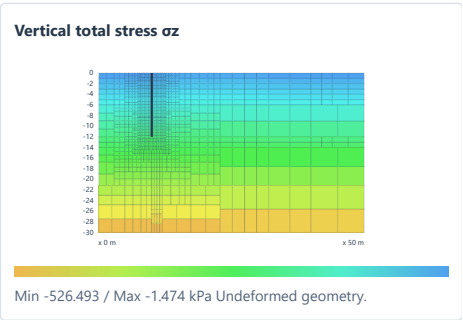
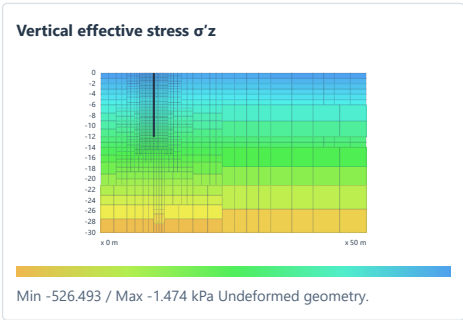
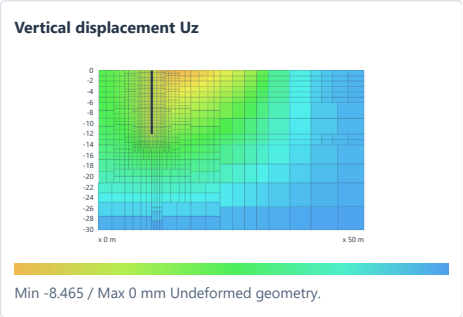
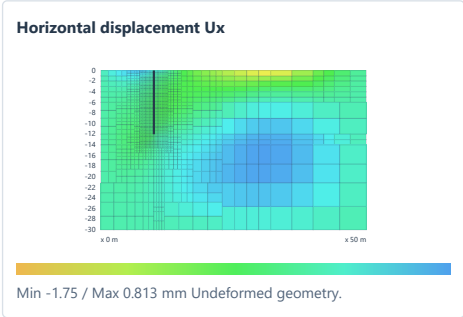
ASSESSMENT SUMMARY — 0 passed; 0 failed; 2 not assessed. Verdicts cover the assessed checks only. Omitted optional limits are not failures.

Check	Result	Detail / action
Soil stability — strength reserve	NOT APPLICABLE	No active retaining wall with excavation in this stage.
Toe ground — strength reserve	NOT APPLICABLE	No active retaining wall with excavation in this stage.
Soil yielding	OBSERVATION	10 of 1800 active integration points currently yielding. Use the strength-reserve verdict to assess the requested margin; yielding alone does not establish failure.
Yielding below formation	OBSERVATION	4 of 576 excavation-side elements between formation and toe currently yielding. This is a geometric count, not a passive wedge or resistance calculation.
Retained ground surface settlement	NOT ASSESSED	8.465 mm downward from initial equilibrium at x = 15.2 m; enter the project SLS settlement limit. No 25 mm or rock-footing percentage is assumed. Immediate free-field surface movement only; consolidation, foundation movement and differential settlement are not assessed.
Wall horizontal movement	NOT ASSESSED	0.4021 mm maximum absolute horizontal movement from initial equilibrium; enter the project wall movement limit.

Anchor and strut forces

No active anchors or struts.

Soil results · selected stage only



Stage 02 · Excavate to -2 m

CALCULATION STATUS

Converged

EXCAVATION / WALL

-2 m / active

INSTALLED SUPPORTS

—

LOCKED-OFF ANCHORS

—

ACTIVE SURCHARGES

Retained ground surcharge

Stage geometry

Undeformed geometry; inactive / removed soil excluded.

Wall deformed shape

Wall displacement from initial equilibrium

Dashed: original wall · scale x30

Wall Ux range -2.496 ... 2.054 mm.

Wall section forces

Wall bending moment

Min -9.68 / Max 32.61 kN-m/m

Wall shear force

Min -14.525 / Max 9.619 kN/m

Wall axial force

Min -28.935 / Max 7.779 kN/m

Segment	Top m	Base m	M top/base kN-m/m	V top/base kN/m	N top/base kN/m
1	0	-0.25	0 / 0.038	-0.151 / -0.151	-1.03 / -1.03
2	-0.25	-0.5	0.038 / 0.007	0.125 / 0.125	-4.928 / -4.928
3	-0.5	-0.75	0.007 / -0.046	0.21 / 0.21	-8.047 / -8.047

Segment	Top m	Base m	M top/base kN-m/m	V top/base kN/m	N top/base kN/m
4	-0.75	-1	-0.046 / -0.217	0.683 / 0.683	-10.705 / -10.705
5	-1	-1.25	-0.217 / -0.552	1.343 / 1.343	-14.075 / -14.075
6	-1.25	-1.5	-0.552 / -1.398	3.384 / 3.384	-16.99 / -16.99
7	-1.5	-1.75	-1.398 / -2.593	4.778 / 4.778	-20.489 / -20.489
8	-1.75	-2	-2.593 / -4.841	8.992 / 8.992	-25.081 / -25.081
9	-2	-2.25	-4.841 / -7.245	9.619 / 9.619	-25.977 / -25.977
10	-2.25	-2.5	-7.245 / -9.329	8.334 / 8.334	-28.935 / -28.935
11	-2.5	-2.75	-9.329 / -9.68	1.403 / 1.403	-25.706 / -25.706
12	-2.75	-3	-9.68 / -8.34	-5.359 / -5.359	-25.488 / -25.488
13	-3	-3.25	-8.34 / -6.255	-8.338 / -8.338	-22.731 / -22.731
14	-3.25	-3.5	-6.255 / -3.365	-11.559 / -11.559	-20.598 / -20.598
15	-3.5	-3.75	-3.365 / -0.318	-12.188 / -12.188	-19.719 / -19.719
16	-3.75	-4	-0.318 / 3.122	-13.763 / -13.763	-18.071 / -18.071
17	-4	-4.25	3.122 / 6.633	-14.043 / -14.043	-17.792 / -17.792
18	-4.25	-4.5	6.633 / 10.264	-14.525 / -14.525	-15.316 / -15.316
19	-4.5	-4.75	10.264 / 13.871	-14.427 / -14.427	-15.169 / -15.169
20	-4.75	-5	13.871 / 17.349	-13.911 / -13.911	-11.903 / -11.903
21	-5	-5.25	17.349 / 20.684	-13.341 / -13.341	-12.186 / -12.186
22	-5.25	-5.5	20.684 / 23.632	-11.792 / -11.792	-8.026 / -8.026
23	-5.5	-5.75	23.632 / 26.314	-10.728 / -10.728	-8.009 / -8.009
24	-5.75	-6	26.314 / 28.45	-8.543 / -8.543	-3.354 / -3.354
25	-6	-6.3	28.45 / 30.574	-7.08 / -7.08	-2.275 / -2.275
26	-6.3	-6.6	30.574 / 31.767	-3.976 / -3.976	1.542 / 1.542
27	-6.6	-6.9	31.767 / 32.553	-2.622 / -2.622	1.825 / 1.825
28	-6.9	-7.2	32.553 / 32.61	-0.189 / -0.189	4.66 / 4.66
29	-7.2	-7.5	32.61 / 32.335	0.917 / 0.917	4.404 / 4.404
30	-7.5	-7.8	32.335 / 31.463	2.907 / 2.907	6.527 / 6.527
31	-7.8	-8.1	31.463 / 30.324	3.795 / 3.795	5.969 / 5.969
32	-8.1	-8.4	30.324 / 28.711	5.376 / 5.376	7.528 / 7.528
33	-8.4	-8.7	28.711 / 26.89	6.07 / 6.07	6.709 / 6.709
34	-8.7	-9	26.89 / 24.709	7.271 / 7.271	7.779 / 7.779
35	-9	-9.3	24.709 / 22.375	7.78 / 7.78	6.729 / 6.729
36	-9.3	-9.6	22.375 / 19.793	8.606 / 8.606	7.354 / 7.354
37	-9.6	-9.9	19.793 / 17.116	8.924 / 8.924	6.09 / 6.09
38	-9.9	-10.2	17.116 / 14.315	9.336 / 9.336	6.297 / 6.297
39	-10.2	-10.5	14.315 / 11.487	9.429 / 9.429	4.83 / 4.83
40	-10.5	-10.8	11.487 / 8.694	9.308 / 9.308	4.632 / 4.632
41	-10.8	-11.1	8.694 / 5.957	9.125 / 9.125	2.962 / 2.962
42	-11.1	-11.4	5.957 / 3.532	8.081 / 8.081	2.404 / 2.404
43	-11.4	-11.7	3.532 / 1.312	7.403 / 7.403	0.653 / 0.653

Segment	Top m	Base m	M top/base kN-m/m	V top/base kN/m	N top/base kN/m
44	-11.7	-12	1.312 / -0	4.372 / 4.372	-0.376 / -0.376

Engineering assessment

ASSESSMENT SUMMARY — 0 passed; 0 failed; 4 not assessed. Verdicts cover the assessed checks only. Omitted optional limits are not failures.

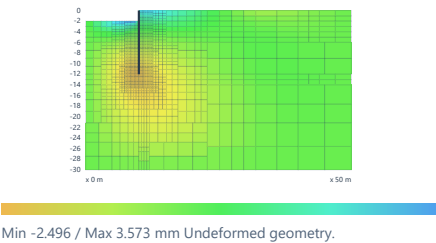
Check	Result	Detail / action
Soil stability — strength reserve	NOT ASSESSED	Enter the project-required strength-reduction target under Engineering assessment and reanalyse.
Toe ground — strength reserve	NOT ASSESSED	Enter the project-required strength-reduction target under Engineering assessment and reanalyse.
Soil yielding	OBSERVATION	73 of 1696 active integration points currently yielding. Use the strength-reserve verdict to assess the requested margin; yielding alone does not establish failure.
Yielding below formation	OBSERVATION	46 of 472 excavation-side elements between formation and toe currently yielding. This is a geometric count, not a passive wedge or resistance calculation.
Retained ground surface settlement	NOT ASSESSED	5.637 mm downward from initial equilibrium at x = 25.19 m; enter the project SLS settlement limit. No 25 mm or rock-footing percentage is assumed. Immediate free-field surface movement only; consolidation, foundation movement and differential settlement are not assessed.
Wall horizontal movement	NOT ASSESSED	2.496 mm maximum absolute horizontal movement from initial equilibrium; enter the project wall movement limit.

Anchor and strut forces

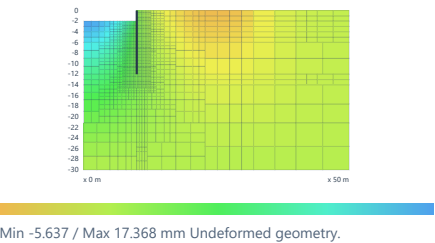
No active anchors or struts.

Soil results · selected stage only

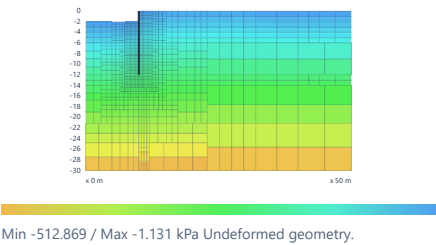
Horizontal displacement Ux



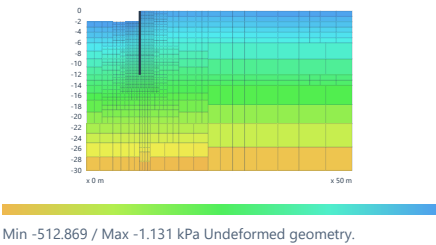
Vertical displacement Uz



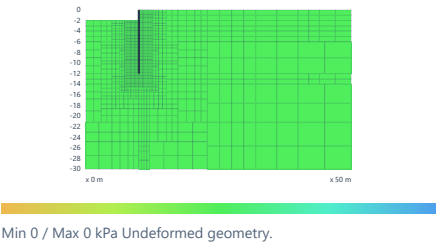
Vertical effective stress σ'_z



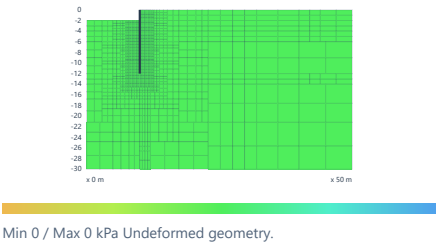
Vertical total stress σ_z



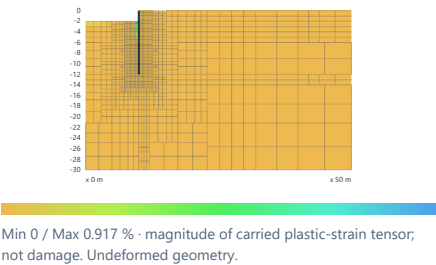
Total pore pressure



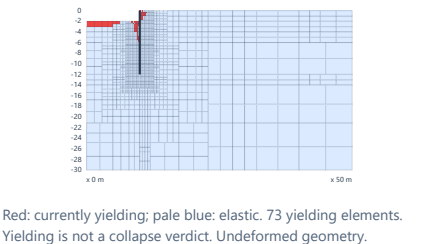
Excess pore pressure



Plastic strain magnitude



Current soil yielding



Stage 03 · Excavate to -4 m

CALCULATION STATUS

Converged

EXCAVATION / WALL

-4 m / active

INSTALLED SUPPORTS

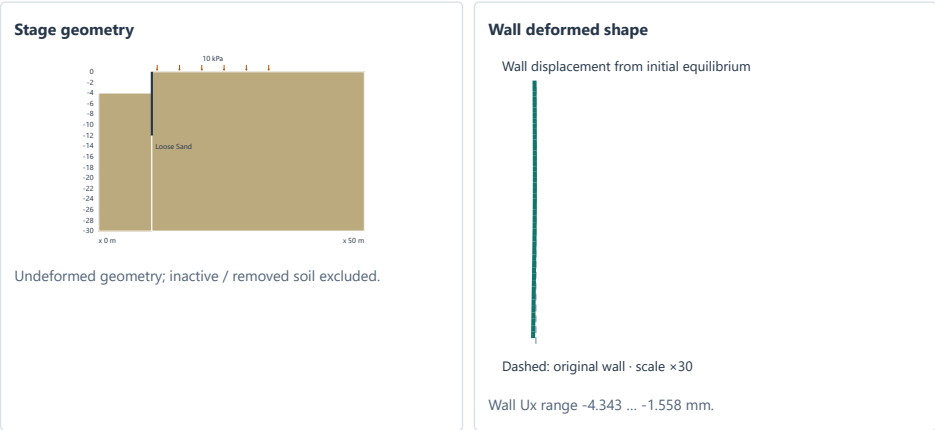
—

LOCKED-OFF ANCHORS

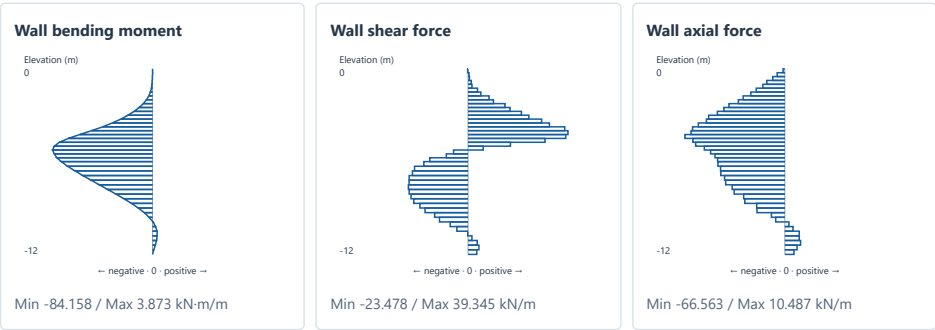
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ACTIVE SURCHARGES

Retained ground surcharge



Wall section forces



Segment	Top m	Base m	M top/base kN-m/m	V top/base kN/m	N top/base kN/m
1	0	-0.25	0 / 0.038	-0.151 / -0.151	-1.163 / -1.163
2	-0.25	-0.5	0.038 / -0.057	0.381 / 0.381	-5.115 / -5.115
3	-0.5	-0.75	-0.057 / -0.192	0.537 / 0.537	-8.087 / -8.087

Segment	Top m	Base m	M top/base kN-m/m	V top/base kN/m	N top/base kN/m
4	-0.75	-1	-0.192 / -0.507	1.26 / 1.26	-12.042 / -12.042
5	-1	-1.25	-0.507 / -0.895	1.556 / 1.556	-14.648 / -14.648
6	-1.25	-1.5	-0.895 / -1.829	3.733 / 3.733	-19.057 / -19.057
7	-1.5	-1.75	-1.829 / -3.09	5.047 / 5.047	-22.683 / -22.683
8	-1.75	-2	-3.09 / -5.156	8.264 / 8.264	-27.76 / -27.76
9	-2	-2.25	-5.156 / -7.656	9.999 / 9.999	-30.954 / -30.954
10	-2.25	-2.5	-7.656 / -11.299	14.571 / 14.571	-37.245 / -37.245
11	-2.5	-2.75	-11.299 / -15.438	16.555 / 16.555	-40.657 / -40.657
12	-2.75	-3	-15.438 / -20.694	21.025 / 21.025	-44.975 / -44.975
13	-3	-3.25	-20.694 / -26.682	23.953 / 23.953	-50.766 / -50.766
14	-3.25	-3.5	-26.682 / -33.926	28.976 / 28.976	-52.24 / -52.24
15	-3.5	-3.75	-33.926 / -41.936	32.04 / 32.04	-57.632 / -57.632
16	-3.75	-4	-41.936 / -51.456	38.08 / 38.08	-61.481 / -61.481
17	-4	-4.25	-51.456 / -61.292	39.345 / 39.345	-62.494 / -62.494
18	-4.25	-4.5	-61.292 / -70.908	38.463 / 38.463	-66.563 / -66.563
19	-4.5	-4.75	-70.908 / -78.487	30.316 / 30.316	-61.286 / -61.286
20	-4.75	-5	-78.487 / -82.662	16.699 / 16.699	-59.426 / -59.426
21	-5	-5.25	-82.662 / -84.158	5.984 / 5.984	-53.629 / -53.629
22	-5.25	-5.5	-84.158 / -82.732	-5.704 / -5.704	-49.448 / -49.448
23	-5.5	-5.75	-82.732 / -80.596	-8.541 / -8.541	-46.553 / -46.553
24	-5.75	-6	-80.596 / -76.827	-15.076 / -15.076	-44.825 / -44.825
25	-6	-6.3	-76.827 / -71.607	-17.403 / -17.403	-44.581 / -44.581
26	-6.3	-6.6	-71.607 / -65.289	-21.06 / -21.06	-42.829 / -42.829
27	-6.6	-6.9	-65.289 / -58.718	-21.903 / -21.903	-42.672 / -42.672
28	-6.9	-7.2	-58.718 / -51.766	-23.171 / -23.171	-40.172 / -40.172
29	-7.2	-7.5	-51.766 / -44.805	-23.204 / -23.204	-39.432 / -39.432
30	-7.5	-7.8	-44.805 / -37.762	-23.478 / -23.478	-35.125 / -35.125
31	-7.8	-8.1	-37.762 / -30.811	-23.17 / -23.17	-33.789 / -33.789
32	-8.1	-8.4	-30.811 / -24.078	-22.444 / -22.444	-27.439 / -27.439
33	-8.4	-8.7	-24.078 / -17.669	-21.36 / -21.36	-26.716 / -26.716
34	-8.7	-9	-17.669 / -11.985	-18.948 / -18.948	-18.779 / -18.779
35	-9	-9.3	-11.985 / -6.907	-16.926 / -16.926	-18.583 / -18.583
36	-9.3	-9.6	-6.907 / -2.965	-13.142 / -13.142	-8.963 / -8.963
37	-9.6	-9.9	-2.965 / 0.409	-11.246 / -11.246	-6.092 / -6.092
38	-9.9	-10.2	0.409 / 2.517	-7.028 / -7.028	2.727 / 2.727
39	-10.2	-10.5	2.517 / 3.838	-4.402 / -4.402	5.459 / 5.459
40	-10.5	-10.8	3.838 / 3.873	-0.117 / -0.117	9.583 / 9.583
41	-10.8	-11.1	3.873 / 3.41	1.544 / 1.544	9.598 / 9.598
42	-11.1	-11.4	3.41 / 2.319	3.636 / 3.636	10.487 / 10.487
43	-11.4	-11.7	2.319 / 1.03	4.295 / 4.295	8.146 / 8.146

Segment	Top m	Base m	M top/base kN-m/m	V top/base kN/m	N top/base kN/m
44	-11.7	-12	1.03 / 0	3.434 / 3.434	6.069 / 6.069

Engineering assessment

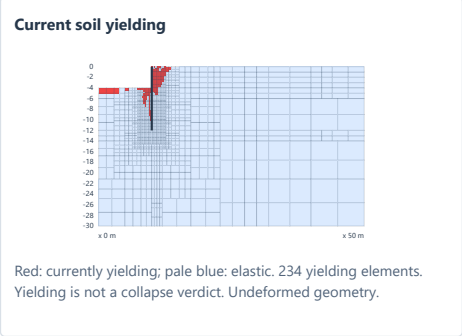
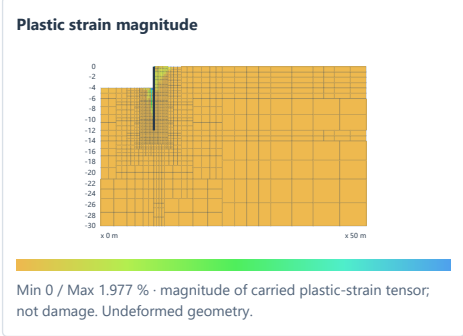
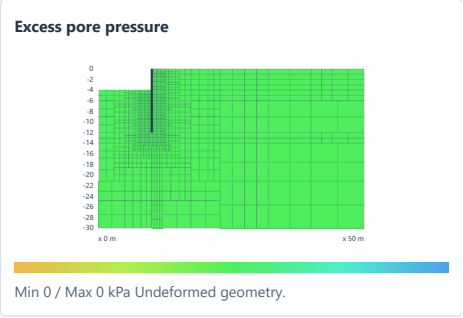
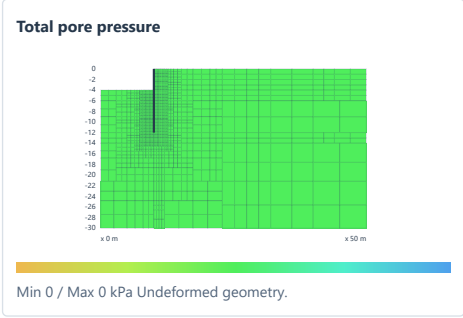
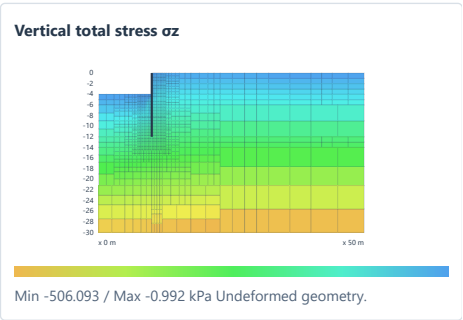
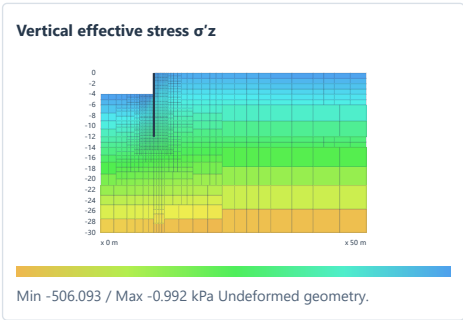
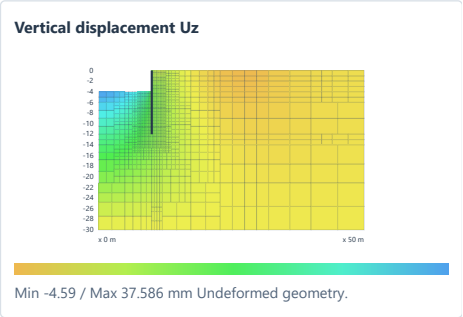
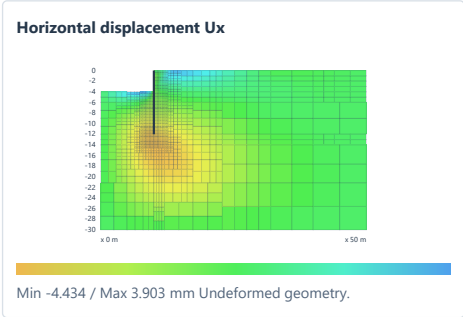
ASSESSMENT SUMMARY — 0 passed; 0 failed; 4 not assessed. Verdicts cover the assessed checks only. Omitted optional limits are not failures.

Check	Result	Detail / action
Soil stability — strength reserve	NOT ASSESSED	Enter the project-required strength-reduction target under Engineering assessment and reanalyse.
Toe ground — strength reserve	NOT ASSESSED	Enter the project-required strength-reduction target under Engineering assessment and reanalyse.
Soil yielding	OBSERVATION	234 of 1592 active integration points currently yielding. Use the strength-reserve verdict to assess the requested margin; yielding alone does not establish failure.
Yielding below formation	OBSERVATION	79 of 368 excavation-side elements between formation and toe currently yielding. This is a geometric count, not a passive wedge or resistance calculation.
Retained ground surface settlement	NOT ASSESSED	4.59 mm downward from initial equilibrium at x = 27.49 m; enter the project SLS settlement limit. No 25 mm or rock-footing percentage is assumed. Immediate free-field surface movement only; consolidation, foundation movement and differential settlement are not assessed.
Wall horizontal movement	NOT ASSESSED	4.343 mm maximum absolute horizontal movement from initial equilibrium; enter the project wall movement limit.

Anchor and strut forces

No active anchors or struts.

Soil results · selected stage only



Stage 04 · Excavate to -6 m

CALCULATION STATUS

Converged

EXCAVATION / WALL

-6 m / active

INSTALLED SUPPORTS

—

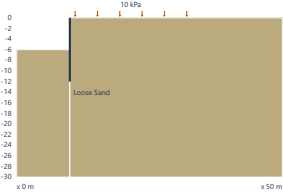
LOCKED-OFF ANCHORS

—

ACTIVE SURCHARGES

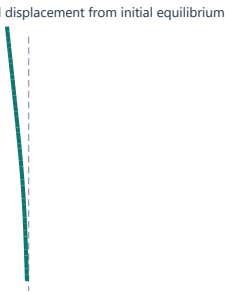
Retained ground surcharge

Stage geometry



Undeformed geometry; inactive / removed soil excluded.

Wall deformed shape



Dashed: original wall · scale ×30

Wall Ux range -34.039 ... -2.587 mm.

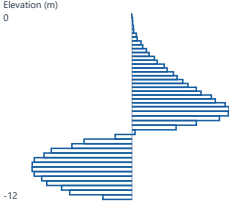
Wall section forces

Wall bending moment



Min -293.237 / Max 0.039 kN-m/m

Wall shear force



Min -95.129 / Max 92.397 kN/m

Wall axial force



Min -121.969 / Max -1.197 kN/m

Segment	Top m	Base m	M top/base kN-m/m	V top/base kN/m	N top/base kN/m
1	0	-0.25	0 / 0.039	-0.156 / -0.156	-1.197 / -1.197
2	-0.25	-0.5	0.039 / -0.067	0.425 / 0.425	-5.118 / -5.118
3	-0.5	-0.75	-0.067 / -0.215	0.59 / 0.59	-8.106 / -8.106

Segment	Top m	Base m	M top/base kN-m/m	V top/base kN/m	N top/base kN/m
4	-0.75	-1	-0.215 / -0.536	1.286 / 1.286	-12.024 / -12.024
5	-1	-1.25	-0.536 / -0.926	1.558 / 1.558	-14.31 / -14.31
6	-1.25	-1.5	-0.926 / -1.948	4.088 / 4.088	-19.803 / -19.803
7	-1.5	-1.75	-1.948 / -3.17	4.889 / 4.889	-22.107 / -22.107
8	-1.75	-2	-3.17 / -5.304	8.538 / 8.538	-27.817 / -27.817
9	-2	-2.25	-5.304 / -7.848	10.173 / 10.173	-31.737 / -31.737
10	-2.25	-2.5	-7.848 / -11.278	13.723 / 13.723	-36.072 / -36.072
11	-2.5	-2.75	-11.278 / -15.344	16.262 / 16.262	-40.718 / -40.718
12	-2.75	-3	-15.344 / -20.659	21.261 / 21.261	-46.595 / -46.595
13	-3	-3.25	-20.659 / -26.647	23.952 / 23.952	-50.141 / -50.141
14	-3.25	-3.5	-26.647 / -34.303	30.624 / 30.624	-57.798 / -57.798
15	-3.5	-3.75	-34.303 / -42.648	33.38 / 33.38	-61.575 / -61.575
16	-3.75	-4	-42.648 / -52.512	39.456 / 39.456	-67.633 / -67.633
17	-4	-4.25	-52.512 / -63.243	42.923 / 42.923	-74.027 / -74.027
18	-4.25	-4.5	-63.243 / -75.328	48.339 / 48.339	-77.47 / -77.47
19	-4.5	-4.75	-75.328 / -88.622	53.176 / 53.176	-84.578 / -84.578
20	-4.75	-5	-88.622 / -103.917	61.182 / 61.182	-91.751 / -91.751
21	-5	-5.25	-103.917 / -120.335	65.672 / 65.672	-95.907 / -95.907
22	-5.25	-5.5	-120.335 / -139.224	75.553 / 75.553	-106.264 / -106.264
23	-5.5	-5.75	-139.224 / -159.046	79.29 / 79.29	-109.461 / -109.461
24	-5.75	-6	-159.046 / -181.227	88.723 / 88.723	-116.688 / -116.688
25	-6	-6.3	-181.227 / -208.946	92.397 / 92.397	-121.969 / -121.969
26	-6.3	-6.6	-208.946 / -236.445	91.663 / 91.663	-120.012 / -120.012
27	-6.6	-6.9	-236.445 / -261.413	83.227 / 83.227	-119.618 / -119.618
28	-6.9	-7.2	-261.413 / -279.794	61.271 / 61.271	-109.371 / -109.371
29	-7.2	-7.5	-279.794 / -292.377	41.941 / 41.941	-99.412 / -99.412
30	-7.5	-7.8	-292.377 / -293.237	2.867 / 2.867	-88.706 / -88.706
31	-7.8	-8.1	-293.237 / -288.412	-16.082 / -16.082	-76.901 / -76.901
32	-8.1	-8.4	-288.412 / -274.712	-45.666 / -45.666	-66.652 / -66.652
33	-8.4	-8.7	-274.712 / -257.528	-57.279 / -57.279	-61.493 / -61.493
34	-8.7	-9	-257.528 / -234.454	-76.916 / -76.916	-52.483 / -52.483
35	-9	-9.3	-234.454 / -209.314	-83.799 / -83.799	-51.106 / -51.106
36	-9.3	-9.6	-209.314 / -181.396	-93.061 / -93.061	-46.704 / -46.704
37	-9.6	-9.9	-181.396 / -152.89	-95.018 / -95.018	-45.868 / -45.868
38	-9.9	-10.2	-152.89 / -124.352	-95.129 / -95.129	-42.966 / -42.966
39	-10.2	-10.5	-124.352 / -96.411	-93.137 / -93.137	-42.034 / -42.034
40	-10.5	-10.8	-96.411 / -70.612	-85.996 / -85.996	-39.561 / -39.561
41	-10.8	-11.1	-70.612 / -46.244	-81.224 / -81.224	-34.894 / -34.894
42	-11.1	-11.4	-46.244 / -26.126	-67.061 / -67.061	-33.683 / -33.683
43	-11.4	-11.7	-26.126 / -8.328	-59.326 / -59.326	-27.499 / -27.499

Segment	Top m	Base m	M top/base kN-m/m	V top/base kN/m	N top/base kN/m
44	-11.7	-12	-8.328 / 0	-27.76 / -27.76	-31.322 / -31.322

Engineering assessment

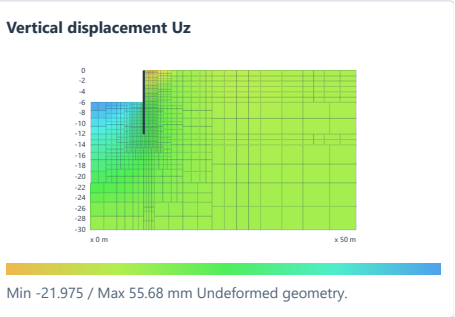
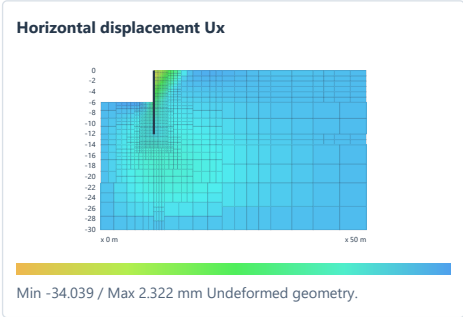
ASSESSMENT SUMMARY — 0 passed; 0 failed; 4 not assessed. Verdicts cover the assessed checks only. Omitted optional limits are not failures.

Check	Result	Detail / action
Soil stability — strength reserve	NOT ASSESSED	Enter the project-required strength-reduction target under Engineering assessment and reanalyse.
Toe ground — strength reserve	NOT ASSESSED	Enter the project-required strength-reduction target under Engineering assessment and reanalyse.
Soil yielding	OBSERVATION	481 of 1488 active integration points currently yielding. Use the strength-reserve verdict to assess the requested margin; yielding alone does not establish failure.
Yielding below formation	OBSERVATION	116 of 264 excavation-side elements between formation and toe currently yielding. This is a geometric count, not a passive wedge or resistance calculation.
Retained ground surface settlement	NOT ASSESSED	21.98 mm downward from initial equilibrium at x = 11.25 m; enter the project SLS settlement limit. No 25 mm or rock-footing percentage is assumed. Immediate free-field surface movement only; consolidation, foundation movement and differential settlement are not assessed.
Wall horizontal movement	NOT ASSESSED	34.04 mm maximum absolute horizontal movement from initial equilibrium; enter the project wall movement limit.

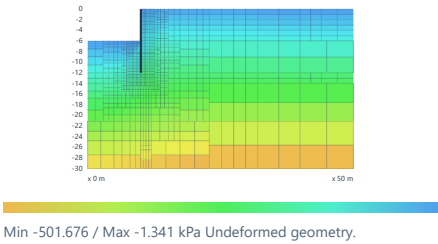
Anchor and strut forces

No active anchors or struts.

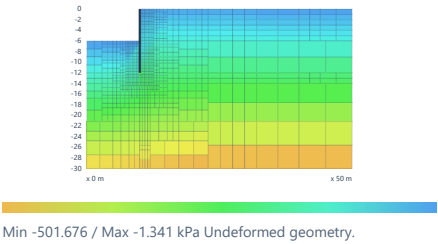
Soil results · selected stage only



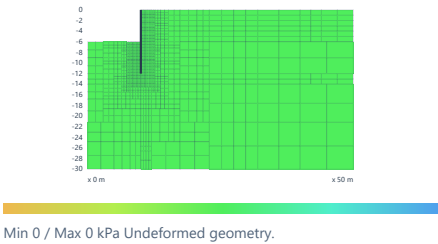
Vertical effective stress σ'_z



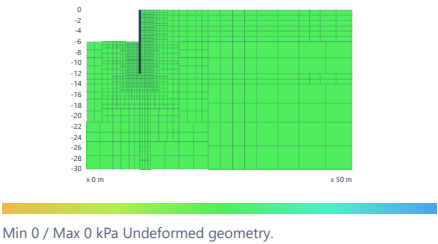
Vertical total stress σ_z



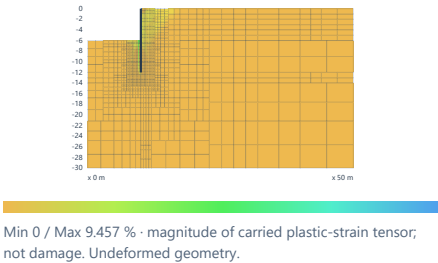
Total pore pressure



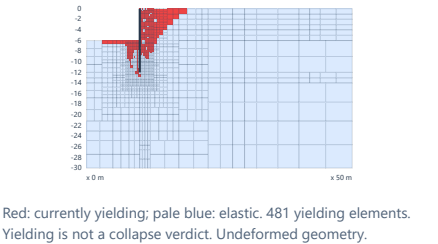
Excess pore pressure



Plastic strain magnitude



Current soil yielding



5 · Calculation notes and limitations

- Dry soil.
- K0 effective gravity stresses (Jaky automatic or specified per layer), followed by equilibrium of stage-0 loads.
- Elastic bonded wall; compression-only supports to fixed anchors.
- Development mesh: maximum 1600 nodes. Check mesh/boundary sensitivity.
- Quadratic Q8 soil cells with four independent integration points and consistent distributed loads; wall beams follow midside nodes unless separate wall spacing is entered.
- Wall weight = 9.806076 kN/m height per metre of wall width, applied only while the wall is active. EA/EI remain explicit inputs.

- Graded mesh: local spacing 0.6 m beside both wall faces and through the wall / excavation depth; general spacing 8 m away from this zone. Layer, support and excavation boundaries are preserved. Far-field cells coarsen locally; layer, excavation and load boundaries remain aligned. Q8 uses quadratic hanging-edge interpolation; T6 triangulates transitions with shared nodes.
- Soil stresses and plastic-strain history carry forward between stages. Displacement is measured from initial equilibrium. Negative normal stress denotes compression; pore pressure is compression positive.
- Soil contours show the selected stage on its undeformed active mesh. The wall deformation graphic uses the stated magnification.
- Wall end actions use the same signed convention as the results view. Wall actions and support forces are per metre out of plane unless labelled per member.
- Current yielding identifies plastic response in the final accepted increment. Plastic-strain magnitude is the norm of the carried strain tensor, not accumulated equivalent strain or damage; it may decrease on reversal.
- A converged calculation is not a capacity assessment, mesh-convergence study or independent verification. Wall resistance, strut buckling, ground pullout and overall soil factor of safety are not assessed.
- The report is a snapshot. Download the calculation data for the full mesh, nodal results and element histories.

