GEM4D DOCUMENTATION

BEM Stress Analysis

User Guide

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Contents

Part 1 — Getting started 5
1. What the BEM module does 5
2. Quick start: your first model 6
Step 1 — Enter the inputs 6
Step 2 — Build the model 7
Step 3 — Solve 7
Step 4 — Calculate the stresses around the excavation 7
Step 5 — Display the results 7
3. Key concepts 8
3.1 In-situ stress and induced stress 8
3.2 How the BEM models an excavation 9
3.3 Two kinds of element: FF and DD 9
3.4 Two kernels: Kelvin and Mindlin 9
3.5 Conventions 9
3.6 Words used in this guide 10
Part 2 — Building and solving a model 10
4. The BEM ribbon tab 10
5. Setup (Inputs) 11
5.1 Coordinate System 12
5.2 Rock Properties 12
5.3 In-Situ Stress 12
5.4 Kernel & solver 16
5.5 Field-point handling 17
5.6 Buttons, and saving a setup 17
6. Preparing meshes for BEM 18
6.1 What a good BEM mesh looks like 18
6.2 The repair tools 18
6.3 Remesh for BEM analysis 20
6.4 Balloon wrap for BEM 20
6.5 Refine for BEM (keep shape) 21
6.6 Choosing the element size 23
7. Adding meshes (Add FF and DD objects) 23
7.1 The mesh table 23
7.2 Choosing the Type: FF or DD 24
7.3 DD rows: Width and element size 24
7.4 Mining steps 25
7.5 What GEM4D does to your triangles 25
7.6 Checks when you build 25
7.7 The completion summary 26
7.8 The quality grade and notes 27

7.9 After you change the Setup ... 29
7.10 What the table remembers ... 29
8. Mining sequences ... 29
8.1 How a sequence works ... 30
8.2 Additive mining (the default) ... 30
8.3 From a Deswik mining schedule ... 30
8.4 As-mined snapshots ... 30
8.5 Which mode the table opens in ... 31
8.6 Checks in both modes ... 32
8.7 Results of a sequence ... 32
9. Running, stopping and saving ... 32
9.1 Run model ... 32
9.2 Which method runs ... 32
9.3 Reading the status area ... 33
9.4 How long will it take? ... 33
9.5 Stop and Clear ... 34
9.6 Saving and reloading a solved model ... 34
Part 3 — Getting and viewing results ... 35
10. Mapping results ... 35
10.1 Choosing what to calculate ... 35
10.2 Map to Grid ... 36
10.3 Map to Octree ... 36
10.4 Map to datagrid ... 37
10.5 σ1 arrows and critical-plane discs ... 37
10.6 Mapping a sequence ... 37
11. The BEMResult panel ... 38
11.1 Loading data ... 38
11.2 Points ... 38
11.3 Colours ... 38
11.4 Iso-surfaces and mesh colouring ... 39
11.5 Scalar bar and legend ... 40
11.6 The histogram ... 41
11.7 BEM filters ... 41
12. Stepping through a sequence ... 41
12.1 The controls ... 41
12.2 What changes at each step ... 42
12.3 Colouring the steps ... 42
12.4 Picking up a session later ... 42
Part 4 — Interpreting results ... 43
13. Stress, displacement and the Status column ... 43
13.1 What the columns are ... 43
13.2 Displacement components ... 43

13.3 The Status column 43
13.4 Points inside excavations 44
13.5 Reading stress results 44
13.6 Checking the result 44
14. Kirsch tangential stress and RCF 45
14.1 What it measures 45
14.2 How to get it 46
14.3 The columns 46
14.4 Reading the wall stress 46
14.5 Reading the RCF 46
14.6 Setting F and UCS by area 46
14.7 Points to note 47
15. Excess shear stress (ESS) 47
15.1 What it measures 47
15.2 Two kinds of ESS 47
15.3 The parameters 48
15.4 Checking a fault: plane-specific ESS 48
15.5 Mapping the hazard volume: Coulomb ESS 49
15.6 Limits 49
16. Stored energy 49
16.1 What it measures 49
16.2 Which energy output do you need? 49
16.3 On the walls: Energy ▸ Stored on surfaces 50
16.4 Through the rock: the SED checkbox 50
16.5 Reading it 50
16.6 Limits 50
17. Released energy 50
17.1 What it measures 50
17.2 How to get it 51
17.3 Two normalisations 51
17.4 Comparing with published ERR 51
17.5 What a sequence can and cannot show 51
17.6 As-mined bookkeeping 52
17.7 Limits 52
18. Tabular reefs (DD) 52
18.1 When to use DD 52
18.2 Building a reef model 52
18.3 The results 53
18.4 Which area to use for ERR 53
18.5 Choosing the DD element size 54
18.6 The touchdown advisory 54
18.7 Limits 54

Part 5 — Reference 54
19. Automating a run (macros) 54
19.1 What is recorded 55
19.2 The Macros tab 55
19.3 Recording and replaying a BEM run 55
19.4 What Run BEM reproduces 56
19.5 Parameters 56
19.6 What a macro file holds 56
20. Assumptions and limitations 56
21. Troubleshooting 57
21.1 Setup and building the model 57
21.2 Solving 58
21.3 Mapping 60
21.4 Energy 60
21.5 Stepping through a sequence 60
21.6 Macros 61
21.7 DD preparation notes 61
22. Output column dictionary 62
22.1 Map to Grid and Map to Octree — single model 62
22.2 Map to Grid and Map to Octree — sequence 63
22.3 Map to datagrid — single model 63
22.4 Map to datagrid — sequence 64
22.5 Energy outputs 64
22.6 Mapping objects 64
23. Glossary 64
24. References 66
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This guide shows you how to build, solve and read a BEM stress model in GEM4D. Its companion, *GEM4D — BEM Stress Analysis: Theory and Verification*, explains how the method works inside, how it was checked, and works three results through by hand.

> **Scope and engineering responsibility.** GEM4D's BEM module is a **linear-elastic** stress-analysis tool. It shows where stress would concentrate, how much elastic energy is stored and released, and how close a plane of weakness is to slipping — **if the rock stayed elastic**. It does not model yield, joints or faults as separate blocks, backfill, pore pressure or dynamic loading; Chapter 20 lists every assumption. The interpretation bands quoted for RCF, ESS and ERR come from the published literature. They are **starting points to calibrate against your own site**, not design limits. Results are only as good as the geometry, rock properties and in-situ stress you supply. What a result means for support, yield or a mining sequence remains the judgement of a competent geotechnical engineer.
>
> **Models solved before 5 October 2026 — re-run them.** They used BEM library versions before 1.2.1.0, whose results are superseded: every fictitious-force (FF) model moved, by about 1 % or less on bulky stopes and by several percent on thin ones, and the per-element energy maps, Mindlin (half-space) models and iterative solves above 6 700 elements moved more. No later library version has superseded a result. *Theory and Verification*, Chapter 9, lists what changed in each version.

How to use this guide

If you want to…	Read
Understand what the module can do	Chapter 1
Get a first result quickly	Chapter 2 — a 15-minute walk-through
Learn the few ideas you need	Chapter 3
Build and solve a real model	Part 2 (Chapters 4–9)
Get results out and display them	Part 3 (Chapters 10–12)
Know what a result means	Part 4 (Chapters 13–18)
Fix a problem, or look up a column or term	Part 5 (Chapters 19–24)

Part 1 — Getting started

1. What the BEM module does

The **BEM** ribbon tab runs a three-dimensional stress analysis around underground excavations. It uses the **Boundary Element Method (BEM)**, the same family of methods as Map3D and Examine3D.

You supply three things:

1. **The excavation geometry** — closed triangulated meshes, already loaded in the scene.
2. **The rock properties** — Young's modulus and Poisson's ratio of the rock mass.
3. **The in-situ stress** — the stress in the ground before any mining.

GEM4D then calculates the **total stress** and the **elastic displacement** at any points you choose in the rock. *Total* means the in-situ stress plus the change caused by mining.

The results are the principal stresses σ1, σ2 and σ3 (MPa) and the displacement (mm), with the full stress tensor if you ask for it. They go to CSV files, or straight into the BEMResult table, where you can colour, filter, contour and export them like any other GEM4D data.

Typical questions it answers

- Where does mining concentrate stress, and how high does it get? (abutments, pillars, intersections)

- Where does the rock destress? (stope backs and walls, shadowed ground)
- How will nearby voids change the stress at a planned excavation?
- How does the stress change as a mining sequence advances?
- Which parts of a fault are close to slip?
- How much elastic energy does each mining step release?

What it does not do. The model is elastic, uniform and dry. It does not show where rock yields or fails, it does not let blocks slide on joints, and it does not include backfill or water. Chapter 20 gives the full list.

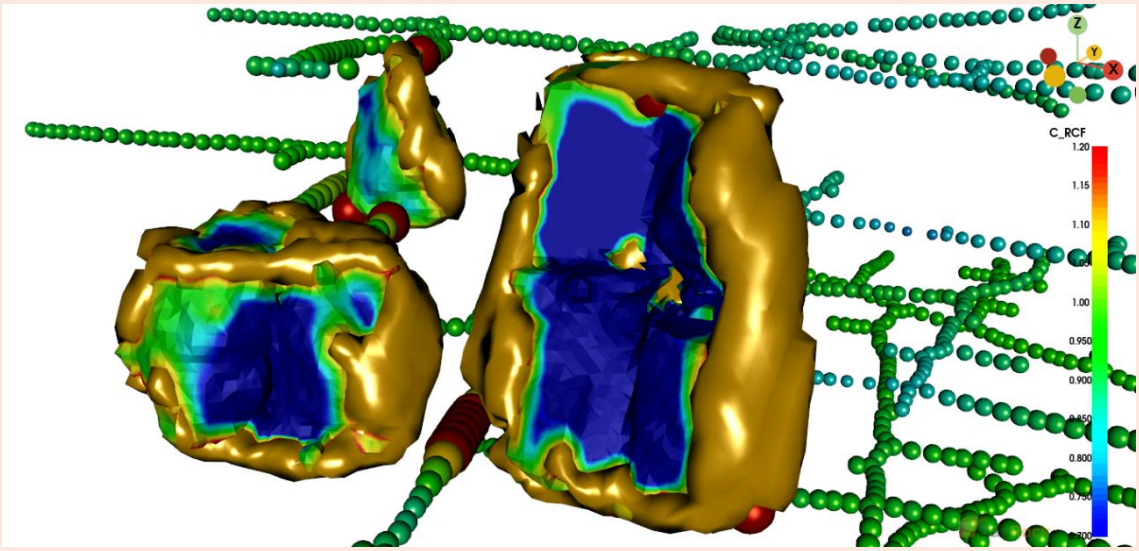


Figure 1 — The Major Principal Stress (Sigma1) was used to colour the stopes and create the iso-surfaces, and the development is represented by Minodes coloured and scaled on the Rockmass Condition Factor (RCF).

2. Quick start: your first model

This walk-through takes a single stope (or a stope with its access drive) from mesh to coloured stress contours. It takes about 15 minutes.

Before you start

- Load the excavation mesh into the scene, for example with **Mesh tab** → **Load DXF**. Make sure it is visible.
- The mesh must be **closed** — a solid with no holes. An open surface cannot form a void.
- For a fast first run, keep the mesh under about **6 700 triangles**. It will then solve in seconds to minutes. To reduce a detailed mesh, use **Toolbox 1** → **Reduce polygon count**.

Step 1 — Enter the inputs

1. Select the **BEM** tab.
2. Click **Inputs**. The *BEM Analysis — Setup* dialog opens.
3. Under *Rock Properties*, click **Hard Rock** (E = 70 GPa, v = 0.25).
4. Under *In-Situ Stress*, keep **Uniform**. Enter the vertical stress at your mining depth — for example 27 MPa at 1 000 m. Then enter the two horizontal stress ratios (kH, kh) and the trend of the major horizontal stress, in degrees clockwise from North.
5. Under *Kernel & solver*, keep **Kelvin** (right for deep workings).
6. Click **OK**.

Step 2 — Build the model

1. Click **Add FF and DD objects**. The mesh table opens, with your visible meshes ticked.
2. Check that the **Type** column reads **FF** for each excavation. (The **Shape** column should read *Solid*.)
3. Click **Build model**.
4. Read the summary. A coloured badge gives the model's quality grade, and the text opens with *"Added N FF triangles to the BEM model. Ready to solve."* A blue or green grade is fine for a first run; §7.8 explains the grade and the notes below it.

A transparent orange copy of the model now appears in the scene. This is the BEM overlay — what the solver will see.

Step 3 — Solve

1. Click **Run model**. The status area on the ribbon shows the progress.
2. Wait until it reads **Solved — N el**.
3. Click **Save model** and choose a file name. The `.bem4d` file stores the solution, so you can reload it later without solving again.

Step 4 — Calculate the stresses around the excavation

1. Click **Map to Octree**.
2. Keep the cell sizes the dialog suggests. When the number of points shows under them, click **OK**.
3. The *Map BEM field points* dialog opens. Keep the defaults and click **Map**.
4. When the calculation finishes, choose a file name for the results (the default is `BEM_OctreePoints.csv`).

An octree places many points close to the excavation, where the stress changes quickly, and few points far away.

Step 5 — Display the results

1. With the BEM tab selected, the left panel shows *BEM result settings and data*. Right-click its table and choose **Load data from CSV-file**. Pick the file from Step 4.
2. Under *Colour mode*, set the column to **S1_MPa**. The points take on the colours of σ1.
3. Under *Iso-surface and Colour mapping*, tick **Iso-surface** and enter a stress value. A 3D contour shell appears at that value of σ1.

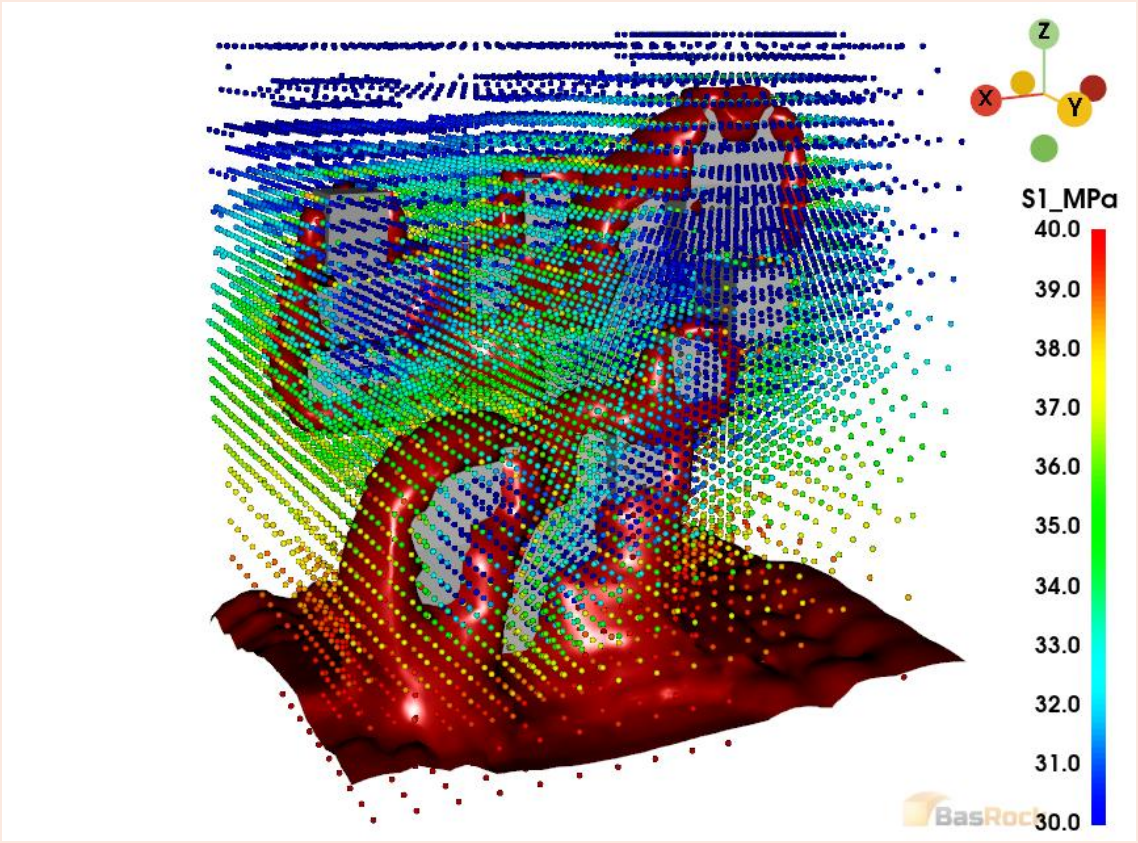


Figure 2 — The quick-start result: an octree point cloud coloured by S1_MPa, with one σ_1 iso-surface around the stope.

Where to go next

- Read the stress at your own points — instrument locations, planned development — with **Map to datagrid** (Chapter 10).
- Model a mining sequence (Chapter 8).
- Check faults for slip with excess shear stress (Chapter 15), or look at stored and released energy (Chapters 16–17).

3. Key concepts

You need only a few ideas to use the module well. This chapter explains them in plain terms. The *Theory and Verification* companion gives the mathematics.

3.1 In-situ stress and induced stress

Rock at depth is stressed before any mining. The weight of the rock above produces a **vertical stress** that grows with depth. Tectonic history adds **horizontal stresses**, usually given as ratios of the vertical: **kH** = σH/σv for the major horizontal direction, and **kh** = σh/σv for the minor one.

When you mine, the rock that carried load is removed, and the stress flows around the opening. It **concentrates** in some places (abutments, pillars) and **relaxes** in others (backs, walls). The BEM calculates this redistribution. Every stress it reports is the **total** stress: in-situ plus the change caused by mining.

3.2 How the BEM models an excavation

Most stress programs (FLAC3D, RS3, Abaqus) divide the whole rock volume into millions of small cells. The BEM divides only the **excavation surfaces**. Each triangle of your mesh becomes one **element** of the model. The rock around them, out to infinity, is handled exactly by the mathematics of elasticity. So:

- your existing meshes **are** the model — there is nothing else to build;
- there is no artificial outer boundary;
- models are small: thousands to hundreds of thousands of triangles, not millions of cells.

The price is that the rock must be **linear-elastic and the same everywhere** (homogeneous). For mine-scale stress screening this is the standard, accepted approach.

3.3 Two kinds of element: FF and DD

Each mesh you add is one of two types. You choose it in the **Type** column of the mesh table; GEM4D pre-sets it for you.

Type	Use it for	What it does
FF (fictitious force)	Closed solids: stopes, drives, voids	Makes the excavation walls free of load, as a real open void is.
DD (displacement discontinuity)	A reef or seam: a flat or folded surface, or a thin closed solid	Treats the orebody as a single surface that the rock on either side can close across. This is the classic approach for narrow tabular mining.

Chapter 7 explains how GEM4D chooses the type, and Chapter 18 covers reefs in detail.

3.4 Two kernels: Kelvin and Mindlin

The **kernel** is the elasticity solution the elements are built from. You choose it in Setup.

Kernel	The rock is…	Use it for
Kelvin (default)	Infinite in all directions	Deep excavations — more than a few excavation spans below surface
Mindlin	A half-space with a load-free ground surface at the RL you set	Shallow workings, open-pit interaction, anywhere the ground surface matters

Mindlin runs are somewhat slower. For deep workings Kelvin is simpler and slightly more accurate near the walls. DD reefs need Kelvin.

3.5 Conventions

- **Compression is positive**, and σ1 ≥ σ2 ≥ σ3. So σ1 is the major (most compressive) principal stress.
- **Coordinates are mine coordinates** in metres (Easting, Northing, RL), the same as everywhere else in GEM4D.
- **Stress is in MPa and displacement in mm** in every table and file.
- **Trend** is in degrees clockwise from North.
- **Points inside an excavation** have no rock, so their values mean nothing. GEM4D marks them `Interior` and leaves their values blank (Chapter 13).

3.6 Words used in this guide

Term	Meaning
mesh table	The table that **Add FF and DD objects** opens (title *BEM — Model from Meshes*). You tick meshes, set their Type and assign mining steps here.
BEMResult table	The data table in the left panel when the BEM tab is selected. The ribbon calls it the *datagrid* (**Map to datagrid**).
element	One triangle of the model.
status area	The read-only text on the BEM ribbon that reports progress.
step	One stage of a mining sequence.

Chapter 23 is a full glossary.

Part 2 — Building and solving a model

4. The BEM ribbon tab

The work runs from left to right across the BEM tab.

Group	Button	What it does	Chapter
Model setup	**Inputs**	Opens the Setup dialog: rock properties, in-situ stress, kernel and solver options.	5
Model setup	**Clear**	Deletes the BEM model and its results. Your Setup values are kept. To end a run without losing the model, use **Stop** instead.	9
Meshes	**Add FF and DD objects**	Opens the mesh table, where you choose the meshes, set each one's Type and assign mining steps. This is the one place the model is built.	7, 8
Model solution	**Run model**	Solves the model in the background. A sequence is solved one step at a time.	9
Model solution	**Stop**	Ends the running task and keeps the model.	9
Model solution	**Save model** / **Load model**	Saves or reloads a solved model as a `.bem4d` file. Reloading skips the solve.	9
Save and export	**Map to Grid**	Calculates results on a regular 3D grid and saves them to CSV.	10
Save and export	**Map to Octree**	Calculates results on an adaptive grid — dense near the excavations, coarse far away — and saves them to CSV.	10
Save and export	**Map to datagrid**	Calculates results at the points in the BEMResult table and adds them as new columns.	10
Save and export	**Energy ▸ Stored on surfaces**	Maps the stored elastic energy on the excavation walls.	16
Save and export	**Energy ▸ Released on surfaces**	Calculates the energy released by each mining step.	17, 18
Mining steps	**Prev** / **Next >** / **Play steps**	Steps through a mining sequence.	12

Group	Button	What it does	Chapter
Status area	*(read only)*	Shows what is running and how far it has got.	9
BEM filters	*(several)*	Filters the rows of the BEMResult table.	11
Scalar bar settings, General settings	*(several)*	Legend colours and labels, colour scheme, log scale, glyph resolution, decimals.	11

The buttons enable in order. **Run model** needs a model; the **Map** and **Energy** buttons need a solved (or reloaded) model.

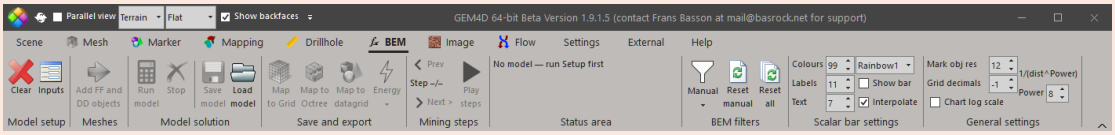


Figure 3 — The BEM ribbon tab, with the groups labelled from left to right: Model setup, Meshes, Model solution, Save and export, Mining steps, Status area, BEM filters, Scalar bar settings and General settings.

5. Setup (Inputs)

Click **Inputs** to open the *BEM Analysis — Setup* dialog. The dialog only records your choices. An existing model does not change until you click **Add FF and DD objects** again (§7.9).

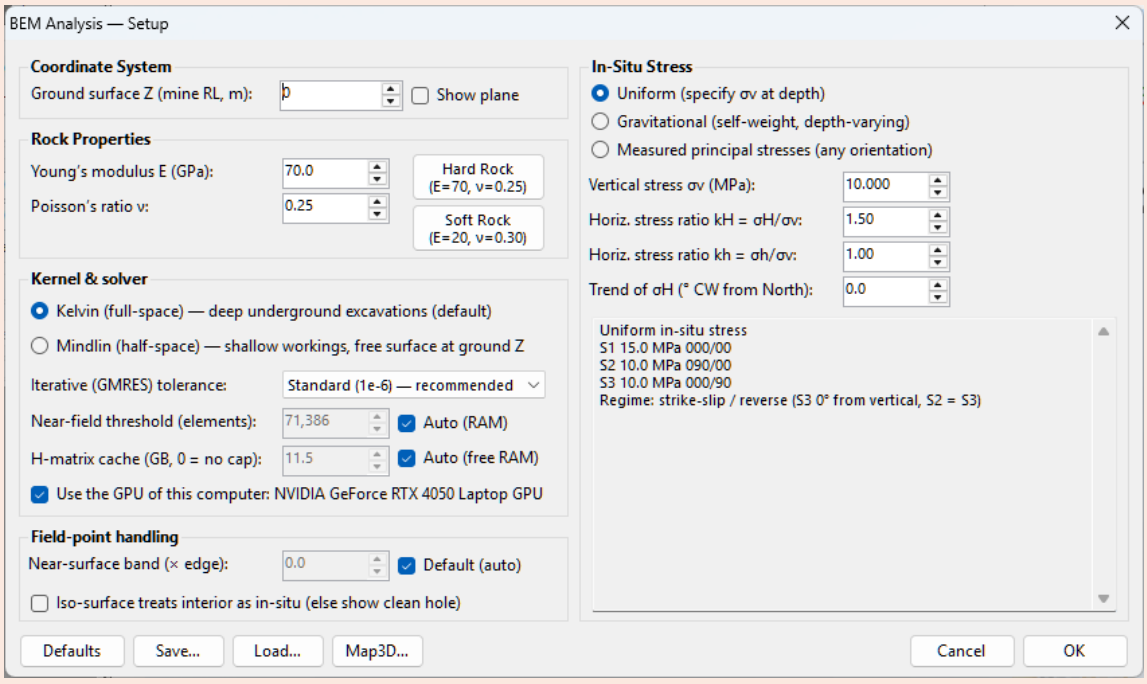


Figure 4 — The BEM Analysis — Setup dialog, showing the Coordinate System, Rock Properties, Kernel & solver, Field-point handling groups & In-Situ Stress.

5.1 Coordinate System

Field	What it is	Default
Ground surface Z (mine RL, m)	The RL of the natural ground surface. The Mindlin kernel uses it as the free surface; the Gravitational and Measured stress options measure depth from it.	0
Show plane	Draws a see-through green plane at the ground surface Z, so you can check it against your meshes. It is a display aid only and never part of the model.	Off

Set the ground surface Z to the real surface RL — on a mine grid where the surface sits at RL 5000, enter 5000. Where the ground is very uneven, use a representative average; §7.6 explains what happens to meshes that reach above it.

The **Show plane** box acts straight away, while the dialog is open, and the plane follows the Z value as you type. **Cancel** restores what was there before. The box also ticks itself when GEM4D draws the plane to flag meshes above the surface (§7.6); untick it to hide the plane.

5.2 Rock Properties

Field	What it is	Range	Default
Young's modulus E (GPa)	Rock-mass stiffness	0.1–1000	70
Poisson's ratio v	Lateral strain ratio	0.01–0.49	0.25

The **Hard Rock** button fills in E = 70 GPa and v = 0.25; **Soft Rock** fills in E = 20 GPa and v = 0.30. Use rock-mass values, not intact-core values.

In a uniform elastic model the **stresses barely depend on E** — the geometry and the in-situ stress drive them. E mainly scales the **displacements** and the **energies**.

5.3 In-Situ Stress

Choose one of three descriptions. The first two give one vertical and two horizontal principal stresses; the third takes measured principal stresses of any orientation.

Uniform (specify σv at depth) — one stress state everywhere. Use it when the excavations span a limited depth range. It is the simplest and most common choice.

Field	What it is	Default
Vertical stress σv (MPa)	The vertical stress at your mining horizon	10
Horiz. stress ratio kH = σH/σv	Major horizontal ÷ vertical	1.5
Horiz. stress ratio kh = σh/σv	Minor horizontal ÷ vertical	1.0
Trend of σH (° CW from North)	Direction of the major horizontal stress	0

Gravitational (self-weight, depth-varying) — the stress grows with depth below the ground surface Z. Use it when the model spans a large depth range, such as a whole mine, or for shallow workings.

Field	What it is	Default
Unit weight γ (kN/m³)	Overburden unit weight; σv = γ × depth	27
kH, **kh**, **Trend**	As above, at every depth	1.5 / 1.0 / 0

For a stress that does not start from zero at the ground surface, such as Examine3D's and RS3's locked-in horizontal stresses, use measured principal stresses with *Linear: a + b × depth* (*Stresses from other programs*, below).

Measured principal stresses (any orientation) — three principal stresses with the directions of their axes, as a stress-measurement report gives them (overcoring, hollow-inclusion cells and the like). No axis needs to be vertical.

Field	What it is	Default
Stress (MPa), **Trend (°)**, **Plunge (°)** — three rows	Each principal stress and the direction of its axis. Enter them in any order: the label beside each row (*Row 1: S1*) says which is the largest, middle and smallest, and follows the magnitudes as you type. Plunge is measured below horizontal; a negative plunge is read as the same line pointing down (trend + 180°).	the default Setup's stresses
Gradient	Read only: how much each row's stress grows per metre of depth with the chosen *Change with depth* (0, or stress ÷ depth). With *Linear: a + b × depth* the column becomes **b** and you enter it (below).	—
Derive	Tick it on one row to take that row's direction from the other two (perpendicular to both). Use it when a report gives only two of the directions.	Off
Measured at RL (m)	The RL of the measurement. Its depth below the ground surface Z shows beside it. Not used by *Linear: a + b × depth*.	the model centre
Change with depth	How the stresses change away from the measurement RL — see the next table.	Proportional to depth
γ kN/m³	The unit weight, beside *Change with depth*: the yardstick for σv in the summary (σv against γ × depth).	27
Trends measured from	**Mine grid north**, or **True north**. With True north, enter **grid N (°E)** beside it — the bearing of mine-grid north, measured clockwise (east) from true north — and GEM4D turns the trends to mine grid.	Mine grid north

Change with depth	The stresses…	Use it when
None (constant)	are the same at every depth, as entered.	the workings span a limited depth range around the measurement
Proportional to depth	grow in proportion to depth — zero at the ground surface — keeping their directions and ratios. With vertical and horizontal axes this is exactly the Gravitational description.	you would otherwise use Gravitational
Linear: a + b × depth	follow each row's own straight line, σ = a + b × depth: a constant **a** (MPa, the value at the ground surface) plus a gradient **b** (MPa per metre of depth). The directions stay fixed; the stresses and the measurement RL are not used.	your best estimate is a stress–depth relation with a constant term, such as σ1 = 6.5 + 0.054 × depth from a regional stress database or a site regression

Linear: a + b × depth in detail. The first two columns become **a (MPa)** and **b (MPa/m)**, and each row keeps its trend and plunge. When you first choose it, GEM4D fills b with the rows' stresses ÷

measurement depth and a with 0 — the same field as *Proportional to depth* — so you change only what differs. The stresses you entered are kept and come back when you choose another option. The other options are special cases: a = 0 and b = stress ÷ depth is *Proportional*, b = 0 is *None (constant)*. Because each row has its own gradient, the S1 / S2 / S3 order can change with depth. The row labels hold where the summary is taken (the model centre), and a note gives the depth at which two rows change places when that lies within the model. Different gradients on tilted axes get the same sideways-force note as *Proportional*. The constants a never do: a constant stress is always in balance.

Tilted axes and the weight of the rock. A stress field that changes only with depth is in balance with the weight of the rock only when no shear stress on horizontal planes changes with depth. With tilted axes, *Proportional to depth* — and *Linear* with different gradients — does not quite do that: it implies a sideways body force that does not exist, about 3.8 kN/m³ in the example below (14 % of the rock's weight). The checks under the summary note it. It is small next to the uncertainty of most measurements. With one gradient for all three rows the balance holds for any orientation.

Squaring up the directions. Measured directions are rounded, so three axes are seldom exactly perpendicular. GEM4D turns them by the smallest rotation that makes them perpendicular, shared between all three axes. A correction above 0.5° is noted and one above 3° is a warning. Two directions more than 10° from perpendicular are refused: that points to a typing or transcription error, not rounding.

The summary under the inputs updates as you type, for all three descriptions. It gives the principal stresses where the stress indicator takes them (the model centre, else the scene centre, else 1 000 m below the ground surface Z) with their trend/plunge in mine grid. For measured stresses it adds σv against γ × depth — with *None (constant)*, whose stress is the same at every depth, at the measurement depth (*σv 23.6 MPa against γ·d 23.0 MPa at the measurement depth (+3 %)*). Last comes the stress regime: *normal* when S1 is the axis nearest vertical, *strike-slip* for S2, *reverse* for S3 — or *oblique* when no axis lies within 30° of vertical. When the vertical stress equals one of the others (kh = 1 makes σh = σv) the regime lies between two, and the summary names both, for example *strike-slip / reverse (…, S2 = S3)*. The checks follow:

Check	Kind	For example
Two directions more than 10° from perpendicular, or *Proportional to depth* with the measurement above the ground surface	Error: **OK** is refused until it is put right	*Rows 1 and 3 are 75.9° from perpendicular (at most 10° can be squared up).*
Directions squared up by more than 3° (0.5–3°: a note)	Warning	*The directions were squared up by up to 4.2° to make them perpendicular.*
Tension within the depth of the model — or of the visible meshes before you build one	Warning	*Tension (S3 below 0) in the in-situ field above 315 m depth.*
Measurement RL above the ground surface Z	Warning	
A negative plunge read as the same line pointing down	Note	*Row 1 read as 085/08 (an upward line is the same line pointing down).*
Proportional to depth with tilted axes	Note	*… implies a sideways body force of 3.8 kN/m³ …*
The Mindlin kernel with tilted axes and a stress at the ground surface (*None (constant)*, or *Linear* with constants)	Note	The half-space's ground surface carries no load, which the shear of such a stress puts on it; stresses close to the surface are approximate. *Proportional to depth* is zero at the surface, so it gets only the sideways-force note.

Check	Kind	For example
Linear: two rows change places in the S1 / S2 / S3 order within the model	Note	*Rows 1 and 2 change places in the S1 / S2 / S3 order at about 1,600 m depth, within the model; the row labels hold at the model centre.*
Linear: different gradients on tilted axes	Note	*Different gradients b on tilted axes imply a sideways body force of 3.9 kN/m³ …*

While the dialog is open, the **stress indicator** in the scene (below) shows the stress as you enter it, for all three descriptions, so you can check the directions against the mine before you click **OK**. **Cancel** puts it back.

Example. A measurement at RL −850, with the ground surface Z at 0, gave 45 MPa at 085/08, 30 MPa at 176/10 and 23 MPa at 318/77. GEM4D squares the directions up by at most 0.26°, to 084.8/07.9, 176.2/10.1 and 317.4/77.1. With *Proportional to depth*, the summary at RL −1000 reads S1 52.9 MPa 085/08, S2 35.3 MPa 176/10, S3 27.1 MPa 317/77, σv 27.8 MPa against γ·d 27.0 MPa (+3 %), regime reverse (S3 13° from vertical). *Theory and Verification* Appendix D works it through.

Stresses from other programs.

Program and stress option	Enter in GEM4D as
Examine3D / RS3 constant field (σ1, σ2, σ3 with trend and plunge)	Measured, *None (constant)*: the σ1 and σ3 rows with their directions, σ2 with **Derive**
Examine3D / RS3 gravity field (unit weight, K ratios)	Gravitational: γ, kH = the larger K, kh = the smaller, trend of the larger.
… with locked-in horizontal stresses	Measured, *Linear: a + b × depth*: the larger horizontal stress at its trend / 0, with a = its locked-in stress and b = its K × γ ÷ 1 000; the vertical stress at plunge 90, with a = 0 and b = γ ÷ 1 000; the smaller horizontal stress with **Derive**, a = its locked-in stress and b = its K × γ ÷ 1 000 (γ in kN/m³, b in MPa/m).
A Map3D model input file (`.inp`)	Click **Map3D…** (§5.6): it fills the measured rows, the ground surface Z and E and v from the file's host rock.
Map3D principal option with a horizontal σHmax	Measured, *Linear: a + b × depth*: σHmax at THmax / 0, σVert at plunge 90, σHmin with **Derive**. For each row b = − Map3D's gradient (Map3D's is per metre of elevation, GEM4D's per metre of depth) and a = the stress at the datum − b × the datum's depth below the ground surface Z.
A stress–depth regression (σ = a + b × depth for each principal stress, with directions)	Measured, *Linear: a + b × depth*, a and b as published. A regression against RL instead: b = − its slope, a = its value at the ground surface RL.
A full stress tensor (Map3D Cartesian, FLAC3D, 3DEC)	Not yet: enter its principal stresses and their directions. FLAC3D and 3DEC report compression as negative — change the signs.

With Gravitational stress, measured stresses that change with depth, or the Mindlin kernel, GEM4D checks that no excavation reaches above the ground surface Z when you build the model (§7.6).

The stress indicator. Once you click **OK**, a small indicator of the in-situ stress appears in the top-right corner of the scene whenever the BEM tab is selected. It sits just left of the orientation compass, which carries the N, E, S and W letters and the East / North / Up arrows (Scene Navigation and Picking manual, §7.1). It shows:

- a pair of arrows for each principal stress: S1 in magenta, S2 in violet and S3 in cyan. The arrows point inwards for compression and outwards for tension. Their lengths are in proportion to the stress, so S1 is always the longest;
- a faint ring for the horizontal plane, with a tick at North, and a faint vertical line;
- underneath, each principal stress in MPa with its trend/plunge, for example *S1 20.0 MPa 030/00*. The lines are right-aligned under the indicator, so the compass's Dip / Azimuth readout beside it always has room. On a short scene, the BEM-results colour legend on the right becomes shorter, so its title stays below these lines.

The indicator turns with the scene, in step with the compass beside it, so you can read the stress directions straight against the mine grid. When two principal stresses are equal (kh = 1 makes σh = σv), it draws one of them horizontal and the other vertical.

With **Gravitational** stress, or measured stresses that change with depth, the magnitudes depend on depth, so the first line of the readout says where they were taken:

First line	Taken at
At RL -750, model centre	the centre of the BEM model, once you have built one
At RL -500, scene centre	the centre of what the scene shows, before you build a model
At 1000 m depth	1 000 m below the ground surface Z, when the scene is empty
At RL 99, 1 m below datum	the centre lies above the ground surface Z (no in-situ stress there), so 1 m below it is used

With **Uniform** stress, or measured stresses with *None (constant)*, the first line reads *Uniform in-situ stress*.

The indicator stays in step with the scene in every view, including straight down. When an axis points almost straight at you, such as σv in a plan view, its label moves just off the centre, clear of the other arrows.

The indicator is a display aid only. It hides on every other tab and follows the Scene tab's **Show widget** box, which shows or hides both the indicator and the compass. **Clear** (and Scene ▸ **Reset all**) removes it. It returns when you next click **OK** in Setup, or once there is a model again (**Add FF and DD objects** or **Load model**). Clear does not reset the Setup values.

5.4 Kernel & solver

Choice	Use it for
Kelvin (full-space) — the default	Deep excavations, where the ground surface is far away compared with the size of the workings
Mindlin (half-space)	Shallow workings, where the ground surface takes part in the stress flow. Not available with DD rows.

GEM4D picks the numerical method by itself for each solve: an exact direct method up to 6 700 elements, and an iterative method above that (§9.2). There is nothing to choose. The three fields below only matter for the iterative method.

Field	What it does	Default
Iterative (GMRES) tolerance	How closely the iterative solver must converge. **Standard (1e-6)** is right for production work. **Coarse (1e-4)** is quicker, for scoping runs on very large models. A setup or model saved with the former **Fine** tolerance (1e-8) opens as Standard (*Theory and Verification* §5.7).	Standard

Field	What it does	Default
Near-field threshold (elements)	How the solver keeps the near field — the influence of nearby elements on each other — when it runs on the processor. On **Auto (RAM)** it gives the H-matrix cache to the far field first and keeps as much of the near field as the rest holds; the remainder is recalculated at every iteration. With the H-matrix cache at **0** (no cap), Auto instead keeps the whole near field in memory below an element count set from your computer's memory, and recalculates all of it above. A number entered here instead keeps the whole near field in memory below that element count and recalculates all of it above (*Theory and Verification* §5.4).	Auto
H-matrix cache (GB, 0 = no cap)	How much RAM the solver may use to store its working data. **Auto (free RAM)** uses the memory free when each step starts, less a reserve of 6 GB — more for steps above about 100 000 elements (*Theory and Verification* §5.3). The value shown is an estimate for the model's largest step. Enter a number to cap it, or **0** to remove the cap for a model you know fits. More cache means faster iterations.	Auto

Leave all three on their defaults unless you have a reason to change them. Nothing is ever written to the hard drive, whatever you choose. *Theory and Verification*, Chapter 5, explains exactly how these settings interact.

Use the GPU of this computer — ticked whenever GEM4D finds a graphics processor (GPU): a graphics card, or graphics built into the processor. The iterative solve, the maps (Chapter 10) and Stored and Released energy (Chapters 16–17) then do their long sums on the GPU, for every kind of model — full space (Kelvin), half-space (Mindlin) and models with DD elements. They run many times faster (§9.4; *Theory and Verification* §5.7) and need far less RAM: the near-field threshold and the H-matrix cache then play no part (the tolerance still does). The box names the GPU, or says that none was found (it is then cleared and greyed, and the BEM calculates on the processor).

The box is **not saved**, neither in the setup file nor on the computer: it is ticked again each time GEM4D starts, and a box you clear stays clear, for every model you open, until you close GEM4D. Clear it to calculate on the processor only — for example, to repeat an earlier result exactly. Results on the GPU differ slightly from those on the processor, and are the closer to the exact answer (*Theory and Verification* §5.7). If the GPU fails, GEM4D finishes on the processor by itself, and a warning says so (§21.2).

5.5 Field-point handling

Field	What it does	Default
Near-surface band (× edge)	Points within this many element-edge lengths of a wall are flagged `NearSurface` (Chapter 13). It is a flag only; the values are not changed. With **Default (auto)** the band is 0 for Kelvin (no flagging) and 2 for Mindlin.	Default (auto)
Iso-surface treats interior as in-situ (else show clean hole)	Unticked, the **Map** buttons leave points inside an excavation blank, so iso-surfaces built from them show a clean hole. Ticked, they fill those points with the in-situ stress, so iso-surfaces close smoothly across the void (§13.4). It takes effect at the next map.	Off

5.6 Buttons, and saving a setup

- **Defaults** restores every field. **OK** keeps your changes; **Cancel** discards them.

- **Save…** writes the current values to a small `.bemset` file — useful for sharing a site's standard rock properties and stress field. A setup with measured principal stresses is saved as `.bemset` version 2 (a solved model as `.bem4d` version 6). GEM4D versions from before measured stresses refuse those files rather than read them as another stress field; Uniform and Gravitational setups are saved exactly as before.
- **Load…** reads a `.bemset` file back into the dialog. Click **OK** to apply it. **Load…** also accepts a solved model (`.bem4d`) and takes just its setup, so any earlier model can serve as a template.
- **Map3D…** reads the in-situ stress and rock properties of the host rock (material 1) from a Map3D model input file (`.inp`); the file dialog opens on the last Map3D file loaded on the Mesh tab (Mesh ▸ Load other formats ▸ Other formats ▸ **Map3D (INP)**, as one object per mining step or as the as-mined snapshots of §8.4 — *Import and Export* manual, §8). Like **Load…** it only fills the dialog; click **OK** to apply it.
  - It selects **Measured principal stresses** with **Linear: a + b × depth** and sets the **Ground surface Z** to Map3D's datum (Surf). Each row's **a** is Map3D's stress at the datum and **b** is minus Map3D's gradient (Map3D's is per metre of elevation, GEM4D's per metre of depth), so below the datum the stresses are exactly Map3D's. A file whose stresses do not change with depth gives **Constant**, and the ground surface Z stays as it was.
  - Row 1 is σ1 at Map3D's trend and plunge, row 3 is σ3 at Map3D's trend with its plunge set square to σ1 (Map3D gives σ3's trend only), and row 2 is derived. **E** and **v** are Map3D's peak values (E converted from MPa to GPa).
  - Above the datum GEM4D holds the stresses at their datum values. Map3D does the same with NDATUM 1; with NDATUM 0 it keeps the gradients going, which matters only where blocks rise above the datum (topography), where Map3D's own field turns tensile. A note after the read says this for the file at hand, and warns when **Mindlin** is ticked, because the free surface moves to the datum.
  - Where Map3D's datum is a reference level with stresses that are not zero, the summary's σv check against γ·d reads high, because its depth is measured from the datum; the stresses are still Map3D's.

6. Preparing meshes for BEM

A BEM model is only as good as its meshes. This chapter describes a good mesh, the tools that repair or refine one, and how to choose the element size. When you build the model, its quality grade and notes say what is left to fix (§7.8).

6.1 What a good BEM mesh looks like

- **Closed** — each excavation is a solid without holes.
- **No internal walls** — one skin per excavation, without walls left inside it from the CAD model.
- **No overlaps** — solids do not run into each other.
- **Well-shaped triangles** — no needle-thin slivers. Prefer triangles no more elongated than about 3 : 1 near where you will read stresses, but element size matters more than shape (§6.6).
- **A sensible size** — a few thousand to a few tens of thousand elements is comfortable. The solver handles 250 000 elements and more: in about a minute on a GPU, in up to half an hour on the processor (§9.4).

6.2 The repair tools

All of these tools work on the **visible** meshes only.

Tool	Where	What it does	Use it when
Remesh for BEM analysis	Toolbox 1 ▸ Prepare meshes for BEM	Rebuilds the visible meshes as clean, closed, consistently facing surfaces. Each group of touching bodies is remeshed on its own, at about a third of its narrowest thickness. You give either the **largest** edge length allowed or a **triangle budget** (§6.3). Bodies with no volume are dropped. The run can be cancelled.	A mesh has mixed normals, holes, overlaps or slivers — including thin CAD stopes made of long needle triangles
Balloon wrap for BEM	Toolbox 1 ▸ Prepare meshes for BEM	Fills the visible meshes on a grid of small cubes, rolls a "balloon" over the outside and wraps what it cannot reach in one closed surface, at the number of triangles or the element length you set. Gaps narrower than the balloon are sealed; internal walls and holes go. The report says what it added and how closely the wrap follows the surveys. See §6.4.	Survey scans that are open, overlapping, inside out or stored as loose wall sheets; stope layouts with gaps or internal walls; when you want one clean wrap with a known element count
Refine for BEM (keep shape)	Toolbox 1 ▸ Prepare meshes for BEM	Refines the visible meshes without changing their shape: every flat face stays flat, corners stay sharp and no point leaves its face. The meshes are refined together, so a face two objects hold — a wall between two mining steps, or a face several as-mined snapshots share — gets the same triangles in each. Elements are small at edges and corners and across narrow pillars and openings, and grow away from them. Each mesh comes back as a new object with its name, colour and attributes. See §6.5.	Angular models of large flat faces — Map3D models, CAD stope models, mining-step objects — whose triangles are much larger than the distance from the walls at which you read stresses
Remesh and/or smooth → Remesh and smooth	Toolbox 1	Remeshes at the edge length you enter, flipping edges to remove slivers.	One mesh has slivers. Use the mesh's current element size.
Reduce polygon count	Toolbox 1	Reduces the number of triangles.	A mesh is far more detailed than the analysis needs
Break combined meshes apart ▸ Into closed solids and open surfaces	Toolbox 1	Splits a mesh into one mesh per closed solid.	One mesh holds bodies that need different element sizes
Remove internal surfaces	Toolbox 1	Keeps only the outer skin, removing walls buried inside the excavation.	A development model has internal walls between segments

Tool	Where	What it does	Use it when
Boolean union overlapping solids	Split & Boolean	Joins solids that overlap or share a wall exactly, keeping the original triangles away from the joins. The wall between two solids is removed. Only closed solids are joined: open surfaces among the visible meshes (faults, topography, pit shells) are left as they are.	Overlapping or adjacent solids, where exact dimensions matter. Walls that nearly, but not exactly, coincide are not joined — use **Remesh for BEM analysis** for those.

The completion dialog of each tool reports what it did and anything it skipped.

> **Do not coarsen a thin body past its thickness. Remesh and smooth** at an edge length larger than a stope's thickness cannot keep its shape — it can lose half the volume. **Remesh for BEM analysis** samples a thin body at about a third of its thickness and keeps its shape. It is the right tool for thin stopes.

6.3 Remesh for BEM analysis

Use it when a mesh has mixed normals, holes, overlaps or slivers, including thin CAD stopes made of long needle triangles.

The element size. Choose one of two. **Maximum element edge** is the largest cube of the grid the surface is built on; thin bodies refine below it, down to an eighth, so the result often has several times the triangles that size implies. **Triangle budget** remeshes the same surface to the number of triangles you ask for, within 5 % where it can, and repairs it as the balloon wrap does. Each body keeps elements no longer than half its thickness, which keeps 99 % of its volume (*Theory and Verification* §8.3). If the budget is too small for that, one size is used for all and thin bodies lose volume — on a mine with 2.5 m stopes, 150 000 triangles kept 85 % — and the report says how many triangles would keep every body. The report also gives the volume kept, the skins of open sheets it left out, any crossing triangles left where a stope is narrower than the elements, and how far the count ends from the budget when it is more than 5 % off. The same meshes give the same surface on every run.

6.4 Balloon wrap for BEM

Use it for survey scans that are open, overlapping, inside out or stored as loose wall sheets, for stope layouts with gaps or internal walls, and when you want one clean wrap with a known element count. This tool does not repair the meshes; it wraps them. It works in three steps.

1. **Fill.** Each visible mesh is filled on a grid of small cubes (voxels) of size *h*. Open scans, scans stored as loose wall sheets, stopes facing inwards, stopes with a face missing and stopes divided into cells by internal walls are all filled. A single flat sheet is not, because it encloses nothing.
2. **Balloon.** A ball of radius *R* is rolled over the outside. Whatever it cannot reach becomes solid. Gaps between surveys narrower than 2*R* are sealed, and internal walls and enclosed holes disappear. **Rock pillars and skins thinner than 2*R* are filled in too.**
3. **Wrap.** The solid is wrapped and remeshed to the number of triangles you ask for (within 5 %; when the count ends farther off, the report says how far, and whether the remesh missed it or the repair after the remesh moved it), or to the element length *L*. Every body is closed and faces outwards. Self-intersections and slivers are repaired. Where a stope is narrower than the elements are long, some can remain; the completion report counts them.

The dialog suggests *h*, *R* and the smallest body to keep from the element size. It shows how much memory the run needs and refuses a run that does not fit in the free memory, and a balloon radius of more than 250 voxels (use a larger voxel or a smaller balloon). The run can be cancelled.

One object comes back, kept in place: **the wrap**, named and coloured after the first visible mesh. The source meshes are hidden. The same meshes and settings give the same wrap on every run.

The completion report gives the volume before and after the balloon, the five largest additions (with their coordinates), how closely the wrap follows the surveys, and how much of the wrap lies more than 1 m from every survey (on an open pit, mostly the lid over its open top). It also counts the bodies too small for the element length that the remesh dropped (*Lost in the remesh*; shorter elements or a higher triangle count keep them), the bodies smaller than the smallest body you keep, mostly flat pieces, that were removed after the repair (*Removed after the repair*), and pairs of faces lying on top of each other, for information.

To see where the wrap leaves the surveys — a lid, a sealed gap, a filled pillar or a wrong fill — show the source meshes again, choose **Colour Palette 1 ▸ Colour on closest distance from mesh**, set the range to 0 – 5 m and pick the wrap. It is coloured by its distance to the surveys.

Choose the size with care:

- **Elements longer than a drive or stope is narrow round it off or lose it.** The dialog warns when the elements are longer than the thinnest closed survey body is thick. The wrap is also left with self-intersecting triangles there: narrow stopes wrapped at 2.8 m elements kept about 120 of 150 000. If the report counts more than a few, use shorter elements.
- **The voxel sets the finest detail.** Positions are held to about half a voxel. On narrow stopes, a 1 m voxel changed the filled volume by up to 5 % when the grid moved by half a voxel. Use a voxel of a quarter of the narrowest width or less.
- **It works at one size for everything visible.** Grade a model as in §6.6: wrap one group of meshes at a time.
- **Stopes divided into cells by internal walls are filled whole.** The flat walls between the cells are set aside when the inside of a stope is found. If the report still says more than 5 % of the wrap is far from the surveys, run **Remove internal surfaces** first and wrap its result.

6.5 Refine for BEM (keep shape)

Use it for angular models whose triangles are much larger than the distance from the walls at which you read stresses. A Map3D block or a CAD stope has few corners: each face is two triangles, often 20–100 m across. GEM4D's BEM takes every triangle as one element, so the stresses near such a wall are coarse. On a small test model of five bricks, σ1 2 m from a wall was 22 % off as loaded, against a 0.25 m mesh of the same bricks. This tool refines such a model and keeps its shape exactly.

1. The visible meshes are grouped by the flat planes they lie in. In each plane the faces are cut where the objects' triangles begin and end, so a face held by several objects is one face, held by each of them.
2. Every edge is divided once, so the faces on both sides share its points. Then every face is meshed once inside its edges, and each object that holds it gets the same triangles. A wall between two mining steps stays an identical pair that cancels in the solve, and the snapshots of an as-mined sequence share their elements.
3. A wall inside one object (two of its faces back to back) is removed, and a corner that lies on another face's edge is joined in.

The element size follows the geometry, so that the answer is good enough anywhere, not only where you looked first.

Setting	Default	What it does
At edges and corners (m)	2	The element size where the surface bends by more than 20°, or ends
Growth away from them (m per m)	0.3	10 m from an edge, the elements are up to 2 + 3 = 5 m
Largest element (m; 0 = no limit)	16	
Smallest element (m; 0 = no limit)	0	
Rock between two walls: element up to its width ÷	2	A 4 m pillar gets elements of up to 2 m on both its walls
Opening between two walls: element up to its width ÷	0.5	A 3 m drive gets elements of up to 6 m on its walls
Triangle budget	off	Every size is scaled so that the count meets the budget

The pillar and opening rules never ask for less than a quarter of the size at edges, nor below the smallest element. **Map3D…** opens a Map3D input file and takes two values from its control line. Its AL (the minimum element side) becomes the size at edges and corners and the smallest element. Its DON (the element-to-element D / L) becomes both width ratios. The other settings stay as they are; **Defaults** puts the first six settings of the table back (the triangle budget stays as set). Map3D's block WIDTH (the largest element on a block) is not read.

The dialog estimates the number of triangles as you change the settings. On the models measured it came within a quarter of the count the tool then made, mostly above it. The tool reads the visible objects as **as-mined snapshots** (each holds everything mined by its step) when a quarter or more of their face area lies in two objects facing the same way. Each step is then solved alone, so the figure is for the largest object and the budget aims at it. With snapshots, a pillar's width is measured only between faces of one step. For any other objects, the figure and the budget are for all of them together. A budget can ask for more triangles than the smallest element allows (after **Map3D…** the smallest element is AL): the estimate then says *short of the budget: the Smallest element (… m) limits it*, and the tool makes the elements that size everywhere. Lower the smallest element to reach the budget. Meshes that are not closed are listed in red: they are refined as they are and stay open.

Each visible mesh comes back as a new object, in the same order, with its name, colour and attributes. A Deswik step object keeps the schedule that fills BEM *Mined at* (§8.3). The new objects are saved in one DXF and kept in place, and only the refined meshes are hidden. The tool does not run in clipping mode. The report gives:

- the triangles before and after, against the estimate;
- the largest change of volume of a closed object;
- the open edges before and after;
- the faces that could not be refined (they keep their own corners — a sliver of a face, for example);
- the most elongated triangle.

The run can be cancelled at either of its two stages.

Measured on two Map3D models loaded as as-mined snapshots (§8.4): a stope model of 984 merged blocks went from 22 220 to 91 608 triangles in 21 s, closed and with its volume unchanged; a model of 20 snapshots, at its file's own AL and DON (10 m, 0.8), went from 24 414 to 48 778 triangles in 6 s, every snapshot closed, and solved in 69 s on the GPU.

6.6 Choosing the element size

Element size belongs to each mesh, not to the model. A graded model — fine elements near the area of interest, coarse ones further away — is normal BEM practice. It is how a large mine stays at a sensible element count.

Because the tools work on visible meshes, you grade a model by visibility. Show one group of meshes, remesh it at that group's size, then move on to the next group. **Never remesh the whole model at one size** — one size is always wrong at one end of the scale.

Four rules of thumb:

1. **Distant excavations can be coarse.** An element can be up to about a third of its distance from the nearest point where you read results. If a distant mesh has no quality notes, leave it alone.
2. **Thin stopes need elements no larger than their thickness.** There is no minimum size. Results on a thin body settle once its elements are no larger than its thickness; coarser than that, they can be several percent out.
3. **Size matters more than shape.** A long thin triangle is calculated less accurately at points close to it, but on a mine model with four triangles in ten more elongated than 3 : 1, this typically changed the stresses far less than halving the element size did (*Theory and Verification* §8.2, §8.7). Remesh for shape only when a mesh has quality notes or the solve stalls.
4. **Refine only as far as the results you need.**

A common layout. A mine with bulk stopes in the core and narrow stopes on the edges needs detail at the narrow stopes only:

- Leave the coarse bulk stopes alone if their notes are clean.
- Regularise the narrow stopes with **Remesh for BEM analysis** if their triangles are poor.
- If both kinds are in one mesh, split it first with **Break combined meshes apart ▸ Into closed solids and open surfaces**, then hide one group while you remesh the other.
- A mining step can include several meshes. "Bulk, step 3" and "narrow stopes, step 3" can both carry step 3, so there is no need to recombine them.

Checking the result. To see where a coarse mesh limits the answer, map with the D/L column and refine where it is below 1 (§13.6).

7. Adding meshes (Add FF and DD objects)

Click **Add FF and DD objects** to open the *BEM — Model from Meshes* dialog. This guide calls it **the mesh table**. Here you choose which meshes go into the model, what type each one is and, for a mining sequence, when each one is mined. **Build model** then builds the model.

7.1 The mesh table

There is one row per loaded mesh.

Column	What it shows
Use	Tick to include the mesh. Meshes that are visible in the scene arrive ticked.
Mesh (layer)	The layer name of the mesh. Where two rows would read the same, the file name follows in brackets: *Stopes (Step 1.dxf)*. Hover over the cell for the file and its full path.
Tris (source)	The number of triangles in the mesh.
Shape	What GEM4D measured the mesh to be (§7.2). Hover over the cell for the measurement.
Type	**FF** or **DD** (§7.2).

Column	What it shows
Width (m)	The mining width of a DD row (§7.3). Greyed on FF rows.
Mined at / Steps	The mining step(s) of the mesh (§7.4).

Below the table is the **DD element size (m)** box with its **Suggest** button (§7.3). Above it, two buttons choose how mining steps are entered (Chapter 8).

7.2 Choosing the Type: FF or DD

When the table opens, GEM4D measures every mesh and sets its Type:

- **every closed solid** → **FF**, a thin one included;
- an **open surface** → **DD**;
- **closed sheets with no thickness** → **DD**.

FF cannot model an open surface or sheets with no thickness, so those start as DD. Every solid starts as FF, because DD is an approximation that only you can judge. DD suits a narrow reef or seam whose width is small compared with the distance at which you want results — South-African-style narrow tabular mining of about 1 to 3 m. A bulk stope set to DD gives wrong results near the stope, and nothing warns you. A thin reef built as FF gives correct results, but needs more elements.

The **Shape** column shows what GEM4D measured:

Shape	Meaning
Surface	An open surface with a rim
Thin solid 1.92 m	A thin closed solid — no thicker than about 15 % of its width **and** no thicker than 5 m — with its measured thickness. DD suits it.
Solid	A closed, volumetric solid. A bulk stope shaped like a plate, such as a 20 m sublevel-shrinkage block, is a *Solid*; the tooltip gives its thickness.
Sheets	Closed, but with no thickness at all
Mixed	Thin and volumetric parts in one mesh — split the mesh first

To model a thin solid as a reef, set its Type to **DD**: its measured thickness fills the **Width**. For many rows at once, right-click the table and choose **Set every ticked thin solid to DD**. **Set every ticked solid to FF** sets them all back.

A few small holes in a closed solid do not make it a *Surface*. A stope left with a hole and some cracks after remeshing is still treated as the solid it is, and the tooltip counts the holes.

You decide. Change the Type if you disagree. The cell turns **amber** when the Type does not suit the shape: an open surface or sheets set to FF, or a solid other than a thin solid set to DD.

When you click **Build model**, GEM4D asks before it builds a choice that is likely to be a mistake:

- **An open surface set to FF.** An open surface cannot bound a void. **Yes** sets these rows to DD, **No** keeps them as FF, and **Cancel** returns you to the table.
- **A solid set to DD** that is not a thin solid. The same question in reverse. A thin solid set to DD is not questioned.
- **Mixed normals** (§7.8). **OK** builds anyway; **Cancel** returns you to the table.

7.3 DD rows: Width and element size

A DD row needs two more values.

Width (m) is the mining width. It is used **only** to flag where the reef closes completely (the touchdown advisory, Chapter 18) and to report the mined volume — it never reaches the solver. A thin closed solid set to DD fills it in with its measured thickness. For an open surface, type it in. A DD row without a width is refused when you click **Build model**.

DD element size (m) is the target edge length of the DD triangles, one value for all DD rows. A surface coarser than this is refined to it. A finer surface is used exactly as it is — GEM4D never coarsens a surface for you. **Suggest** fills in about one twentieth of the largest reef's shorter span, rounded to a value such as 1, 2, 5, 10 or 20 m — so between about span/35 and span/14; Chapter 18 explains why. The box takes this suggestion by itself, for all the DD rows together: when the table opens with a DD row, and again each time you set rows to DD or back to FF, or tick or untick a DD row. Once you type a size, the box keeps it, as it keeps a size set earlier in the session; **Suggest** puts the suggestion back, and the box follows the rows again. The label beside the box estimates the number of elements as you type.

A model with any DD row must use the **Kelvin** kernel. With Mindlin, **Build model** refuses and says why; the table stays open.

7.4 Mining steps

For a single excavation state, set every step to **1**. For a mining sequence, see Chapter 8. In short:

- In **Additive mining** mode (the default) the column is headed **Mined at**. Give each mesh the one step at which it is mined.
- In **As-mined snapshots** mode the column is headed **Steps**. Give each mesh the steps it belongs to, such as `1-3` or `2+`.

In both modes new rows are numbered 1, 2, 3, … down the ticked rows. Switching modes changes how the column is read, never what it holds: edit the rows yourself.

The table ticks the mode the meshes look like (§8.5), and fills **Mined at** from a Deswik schedule (§8.3).

7.5 What GEM4D does to your triangles

When you click **Build model**, GEM4D prepares each ticked mesh for you:

1. It turns any four-sided faces into triangles, and drops stray lines and points.
2. It joins vertices that almost coincide, which is common in DXF files.
3. It makes all the triangles face the same way. You do not need to fix their winding yourself.
4. It drops triangles with no area, and tells you how many.
5. **FF rows:** every remaining triangle becomes one FF element.
6. **DD rows:** the surface is refined to the DD element size if it is coarser. A thin closed solid is first reduced to its mid-surface, and each element takes the roof-to-floor gap under it as its width.

Theory and Verification, Chapter 3, describes these steps in detail.

7.6 Checks when you build

Replacing a model. If a model already exists, GEM4D asks before replacing it. **Add FF and DD objects** always builds a new model from scratch with the **current** Setup. It never adds to the old one.

Clipping. If a clip section is active, GEM4D leaves clipping first. A clipped mesh is an open fragment and cannot form a void.

Meshes above the ground surface. With a stress that changes with depth — **Gravitational**, or **Measured** with a change with depth — or the **Mindlin** kernel, every mesh should lie at or below the

ground surface Z. If any reaches above it, GEM4D lists those meshes, draws the surface as a see-through plane in the scene, and then:

- with **such a stress and the Kelvin kernel**, warns you. The ground surface is only the depth reference here. Above it the in-situ stress stays at its ground-surface value — zero for Gravitational — so results near those elements are unreliable, but the model is valid. On uneven ground, where the surface you entered is an average, click **Proceed anyway**. Enter and Esc both cancel.
- with the **Mindlin** kernel, refuses. The surface is the model's real boundary, so nothing may lie above it. Move or trim the meshes, raise the ground surface Z — or, on uneven ground, change to Kelvin with Gravitational stress.

The plane stays in the scene after the dialog closes, so you can see where it cuts your meshes. It is deleted with the model. The **Show plane** box in Setup hides it (§5.1).

7.7 The completion summary

A summary opens when the model is built. At the top, a coloured badge gives the model's **quality grade**, in the order of GEM4D's rainbow legends:

Badge	Grade	What it means
Blue	**High**	No defects found.
Green	**Acceptable**	Minor defects only. Results can differ a little right next to them.
Yellow	**Some defects**	It should still solve, but results near the logged places can be off.
Red	**Too many defects**	The solve may fail, or results be wrong over large areas. Fix the meshes before relying on the results.

The grade is also written in words, so the colour is not the only sign. Below it, the text starts with the outcome, for example:

"Added 4,812 FF triangles to the BEM model. Ready to solve."

A model with DD rows adds a line for its DD elements. A mining sequence starts with *"Built K additive steps from M meshes (…). Ready to solve."*, then one line per step: its element count, whether it is watertight, and its own grade. The badge shows the worst step.

The notes come last, grouped as **Serious defects** (red), **Defects to check** (yellow), **Minor** (green) and **For information**, which never lower the grade. A sequence that looks built in the wrong step mode gets one more line before them, under **Check the step mode** (§8.6). Each note is one line with a count. §7.8 explains each note and what to do about it. The exact locations go to `GEM4D_diag.log`.

A see-through orange copy of the model now shows in the scene. It is clipped along with everything else when you take a section. On a mining sequence it shows step 1 only — use **Next** to see what each later step mines (Chapter 12).

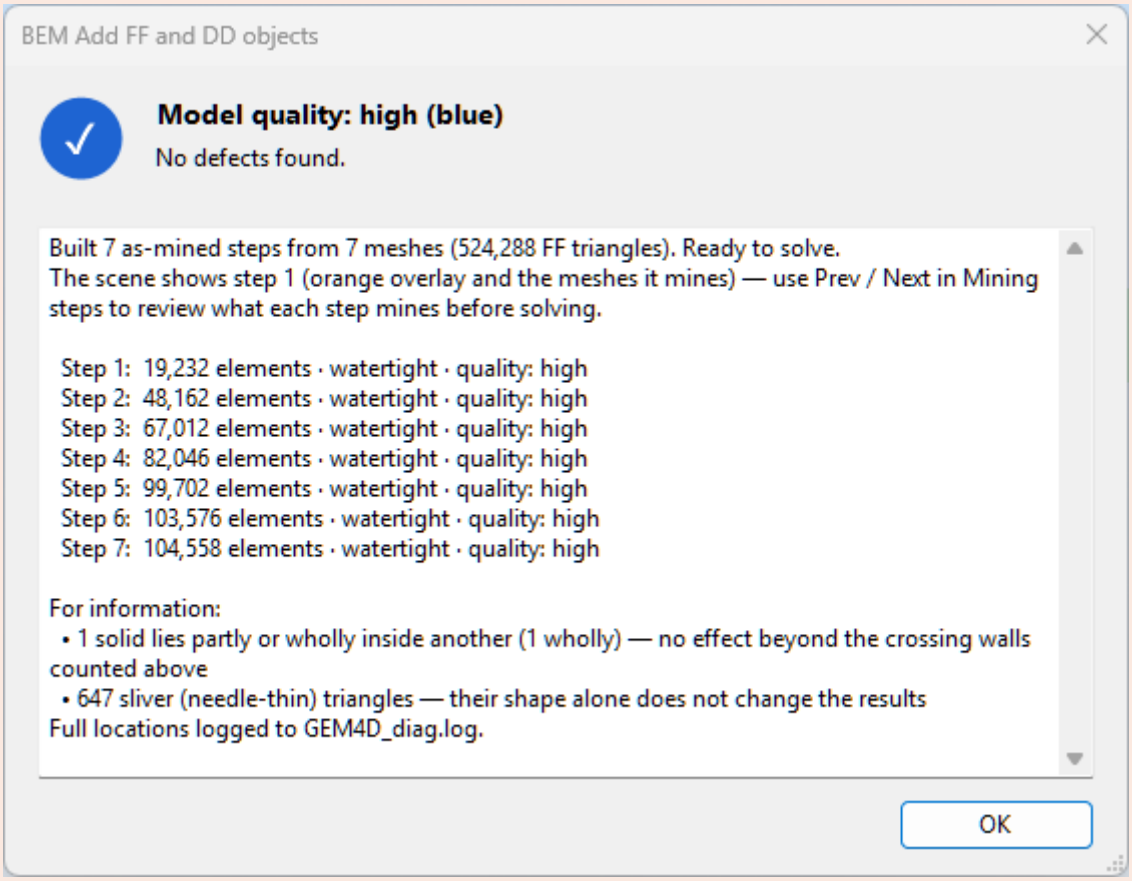


Figure 5 — The completion summary above a short Mesh-quality notes list.

7.8 The quality grade and notes

The summary's grade (§7.7) comes from a check of **all the FF meshes of the model together** — on a mining sequence, of each step's meshes. Walls of two meshes that cross, or a mesh that is in the model twice, are found as well as defects inside one mesh. The locations, in mine coordinates and with the meshes involved, go to `GEM4D_diag.log`.

Each note has a grade, and the summary takes the worst. Notes under **For information** never lower it.

Note	Grade	What it means	What to do
"N triangles cross another wall (x % of the model) — …; M of them cross another mesh"	Red at 10 % of the model's triangles or more, yellow from 2 %, green below	Walls drawn through each other — overlapping solids, a design solid with its own survey, a scan that crosses itself — or a surface folded over. There the walls do not separate rock from void.	Below 2 %, usually fine away from the logged places. Above that, wrap the meshes with **Balloon wrap for BEM** (§6.4), join overlapping solids with **Boolean union overlapping solids**, or leave out the surface that should not be there, such as a design under its survey.
"N triangles lie on top of another facing the same way (x % of the area) — a surface that is in the model twice"	Red at 25 % of the area or more, yellow from 5 %, green below	The same surface twice: a mesh loaded twice, or two meshes with a common face.	Untick or delete the second copy.

Note	Grade	What it means	What to do
"Mixed normals in K meshes: …"	Yellow	Some triangles face the wrong way, and internal walls stop GEM4D from turning them round. An element facing the wrong way gives wrong results near it. GEM4D also asks about this at **Build model**.	Rebuild the mesh with **Remesh for BEM analysis**, or wrap it with **Balloon wrap for BEM**, which does not depend on the triangles' facing. If the seams are internal development walls, run **Remove internal surfaces** first.
"N open surfaces built as FF …"	Green	You kept an open surface as FF (§7.2).	Set it to DD, unless you meant it.
"Not watertight: N open edges (holes)"	Green	Holes in the walls. Points near them may be put on the wrong side of the wall.	Usually fine. If results look wrong near a large hole, repair the mesh with **Remesh for BEM analysis** or **Balloon wrap for BEM** (§6.3, §6.4), or fix it in CAD.
"N triangles are walls two solids share, facing opposite ways (cells)"	Information	A stope stored as cells, or the two faces of a zero-volume sheet.	Nothing.
"N non-manifold edges …"	Information	Three or more triangles on one edge, usually at cell walls.	Nothing on their own.
"N solids lie partly or wholly inside another …"	Information	A solid inside another one's void: a design inside its survey, overlapping lifts. Where their walls cross, the crossing note counts them.	Nothing beyond the crossing note.
"N zero-volume bodies …"	Information	Closed bodies whose front and back faces lie on top of each other. Where the faces coincide they have no effect.	Nothing, unless the solve fails: then delete them at the logged coordinates (they enclose nothing).
"N sliver (needle-thin) triangles …"	Information	Triangles more than 100 times longer than they are high. On their own they have not been found to change the results (§6.6).	Usually nothing. If the solve stalls, remesh **only that mesh** with **Remesh and smooth** at its current element size, or with **Remesh for BEM analysis**.
"N source edges with triangles facing both ways — re-oriented automatically (no seams)"	Information	Some triangles faced the wrong way, and GEM4D turned them round.	Nothing.
"solid-inside-solid check skipped (N separate bodies)"	Information	With more than 1 500 bodies the check is not run.	If results look wrong, look for solids inside solids yourself.

Note	Grade	What it means	What to do
"The whole-model check stopped with an error … not counted"	Information	The check of all the meshes together failed, so crossings, duplicates and solids inside solids were not counted. The grade rests on the other notes only.	Send `GEM4D_diag.log` and the meshes to BasRock, and check the meshes yourself before relying on the grade.
"Skipped N zero-area triangles."	—	Triangles with no area were dropped.	Nothing, unless the count is a large part of the mesh.

Walls that only **touch** — meeting along an edge or lying side by side — are not counted as crossing. Nor is a wall two cells share, however each cell divides it into triangles.

What the grade rests on. The lines were set by solving models with each kind of defect and comparing their stresses with clean models of the same excavations. Crossing walls and duplicated surfaces moved the stresses by 9–20 % at 10–20 m from the walls, or stopped the solve converging. Shared cell walls, zero-volume sheets, slivers, holes up to 5 % of the triangles, open-topped survey shells and solids wholly inside another moved them by 0.5 % or less. The grade is a guide, not a guarantee (*Theory and Verification* §3.10).

The worst symptom of a bad mesh is a solve that ends with *"GMRES did not converge"*. If that happens, read these notes first.

7.9 After you change the Setup

The model keeps the Setup values that were current when you built it. If you then change the Setup — kernel, stress field, ground surface, rock properties — and click **Run model** or a **Map** button, GEM4D warns that the model is out of date:

- **Run model** lets you continue with the old values (for a change that does not matter), or cancel.
- The **Map** buttons insist that you rebuild with **Add FF and DD objects** first.

If the model came from a `.bem4d` file, there are no meshes to rebuild from. The warning then tells you to put the old Setup values back, or to reload the `.bem4d`, which restores the Setup it was solved with.

7.10 What the table remembers

For the rest of the session the table remembers its ticks, Types, widths, steps, element size and mode.

One rule applies to a remembered Type. If you **accepted** GEM4D's suggestion, the Type follows the classification: load a different mesh under the same name, or edit the mesh, and the row is classified afresh. If you set a Type **against** the suggestion, your choice stays, whatever the mesh measures later.

Deleting all meshes clears what the table remembers.

8. Mining sequences

A **mining sequence** solves the model at several stages of mining, so you can step through how the stress changes. You set it up in the mesh table (§7.4): choose a mode with the two buttons above the table (the table ticks the one the meshes look like, §8.5), then fill in the step column.

8.1 How a sequence works

Each step is the **complete excavation at that stage**, and each step is solved **on its own**. For an elastic model this is exact: the stress depends only on the excavation as it stands, not on the order in which it was mined. Both modes therefore behave the same once the steps are defined.

8.2 Additive mining (the default)

Use this mode for **separate solids mined one after another** — stopes and development headings. It matches the Map3D convention. The column is headed **Mined at**.

Give each mesh **one number: the step at which it is mined.** A mesh stays mined from that step to the end. Step k therefore contains every mesh mined at steps 1 to k.

Example: decline `1`, stope A `1`, stope B `2`, stope C `3`. This gives three steps; B appears at step 2 and C at step 3.

Rules:

- Every step needs at least one newly mined mesh. A step with nothing new would repeat the one before, so GEM4D reports it as a gap.
- A mesh must not repeat, or share walls with, a mesh from an earlier step. Surfaces lying on top of each other make the results unreliable. For a stope that grows into an earlier shape, use the as-mined mode.

8.3 From a Deswik mining schedule

Meshes loaded from a Deswik file with **One object per time step** carry their step (*Import and Export* manual §6.9). When such meshes are ticked, the table fills **Mined at** from the schedule:

- **The steps:** the steps of the ticked objects are numbered 1, 2, 3, … in date order, without gaps. A ticked mesh that is not in the schedule gets 1, as already mined.
- **Left out:** the hidden objects *… - no date* and *… - hidden by Deswik's filter* (figures the file's animation filters hide, such as unscheduled tasks) are not ticked, so they are not in the sequence. Tick one by hand and it counts as a mesh that is not in the schedule: it gets 1.
- **Hidden by the bar:** objects the player bar under the scene has hidden count as ticked, because only the step shown hides them.
- **Several schedules:** ticked together, they are put in one order by their start dates. If any of them has a step without a date, the column is numbered as usual, and `GEM4D_diag.log` says why.
- **The mode:** the table opens in **Additive mining**, and its title ends *Mined at from the Deswik schedule (K steps)*.
- **Remembered rows win:** a row the table remembers from earlier in the session (§7.10) keeps its own step.
- **Fewer solves:** each step is one solve. Load the file with longer steps — by the year rather than by the month — for fewer of them.

When you click **OK**, the BEM steps take over the scene from the bar (§12).

8.4 As-mined snapshots

Use this mode when **shapes grow or merge** — a stope that expands, pit pushbacks, or a scheduler's as-mined solids for each period. The column is headed **Steps**. Give each mesh **the steps it belongs to**:

Entry	Meaning
`1`	Step 1 only
`1,3`	Steps 1 and 3

Entry	Meaning
1-3	Steps 1 to 3
2+	Step 2 to the last step

The number of steps is the highest step you enter, and every step must have at least one mesh. To model a growing stope, swap shapes between steps: the small shape at 1, the full shape at 2+. A decline that is there throughout is 1+. Meshes within one step must not repeat each other or share walls.

Example: a scheduler's files *Step 1* to *Step 7*, each the whole mine at that step. The table numbers them 1 to 7 and ticks **As-mined snapshots** by itself, since each file holds the one before; each step is then its own file. Left in Additive mode, step 7 would hold all seven files together.

Starting from a Map3D model. Load it as as-mined snapshots. Loaded one object per step, a Map3D model whose blocks overlap does not solve, because faces inside other blocks are taken as surfaces in the void (Kate Stopes, 984 overlapping blocks: no progress as loaded, 101 iterations as mined).

1. Mesh ▸ Load other formats ▸ Other formats ▸ **Map3D (INP)**, and choose **As-mined snapshots, for the BEM** (*Import and Export* manual §8.5). Object k holds everything mined by Map3D's step k, its overlapping blocks merged into one closed surface.
2. Optionally, refine the snapshots' large faces (each brick face is two triangles) without changing their shape: Toolbox 1 ▸ Prepare meshes for BEM ▸ **Refine for BEM (keep shape)**, whose **Map3D…** button takes the file's AL and DON (§6.5).
3. In BEM **Inputs**, click **Map3D…** for the file's stresses and rock properties (§5.6).
4. Click **Add FF and DD objects**: the table ticks **As-mined snapshots** and starts every row as FF. Keep the rows numbered 1, 2, 3 ….
5. Click **Run model**.
6. To compare with Map3D, right-click the BEMResult table ▸ **Load Map3D grid points (INP)** (§11.1), then **Map to datagrid**.

8.5 Which mode the table opens in

GEM4D looks at the ticked meshes before the table opens and ticks the mode they look like:

- **Map3D objects** say what they are: objects loaded as *As-mined snapshots, for the BEM* open in **As-mined snapshots**, objects loaded *One object per mining step* in **Additive mining**.
- **Other meshes, by their shape:** in as-mined snapshots each step holds the step before — its bounding box contains the box of the step before, and its volume does not fall. When that is so at every step, with at least three steps, the table opens in **As-mined snapshots**. When it is so at no more than a quarter of the steps, the meshes are separate stopes and the table opens in **Additive mining**.
- **Anything else** — fewer than three steps, or a mixture — is left to you: the table opens in the mode you used last.
- **The title says so** when the guess ticks As-mined, or changes the mode you used last, for example *As-mined snapshots: each step holds the step before*.
- **Your choice wins:** a Deswik schedule opens the table in Additive mining (§8.3), and when the table remembers rows from earlier in the session, it opens in the mode you chose for them.

The guess uses what the table measures anyway, so it takes no time you would notice; it was right on all 15 real sets tested. Check the mode before you build: the summary after **Build model** still says when a sequence looks built in the wrong mode (§8.6).

8.6 Checks in both modes

Each step is checked on its own: its meshes together, as in §7.8. The summary gives each step's grade on its line, and each note gives its count from the step where it is worst, with the step number.

Is the step mode right? The summary also looks for a sequence built in the wrong mode, and says so first, under **Check the step mode**:

- **Additive mining, with later steps repeating the meshes of earlier steps** (5 % of a step's area or more, as duplicate walls or as solids lying wholly inside an earlier step's): the meshes look like as-mined snapshots, each the whole mine at its step. In Additive mode every earlier step's meshes stay in the model, so the snapshots lie on top of each other and the grade is usually red. Tick **As-mined snapshots** and build again. *Example:* seven scheduler files *Step 1* to *Step 7* built Additive repeated 40–80 % of each later step's area and graded red; built as As-mined snapshots, every step graded blue.
- **As-mined snapshots, with each mesh in one step only and no step repeating or containing another step's meshes:** the meshes look like separate stopes, each mined at its step. In As-mined mode a step's model holds only that step's meshes, so the earlier stopes would be missing from the later steps. Tick **Additive mining** and build again. This note needs the check for solids lying inside other solids, which is left out above 1 500 separate bodies in all the meshes together, so a larger model never gets it.

Separate stopes built Additive, and true snapshots built As-mined, get no such note. A mesh you put in several steps (a decline at 1+) is taken as a deliberate as-mined set.

There is no backfill. A shape that leaves a later as-mined step simply stops being part of the model.

8.7 Results of a sequence

The **Map** and **Energy** buttons work on a sequence as on a single model, repeated for every step at the same points: §10.6 describes the per-step columns and files, and Chapter 12 how to step through them.

9. Running, stopping and saving

9.1 Run model

Click **Run model**. The solve runs in the background, so you can keep working in GEM4D. The status area shows its progress.

On a mining sequence, **Run model** solves each step in turn, with `k/K ·` in front of each status line. Each step picks its own method and memory settings, as a single model of its size would (§9.2). **Stop** ends the whole run and keeps the model; the part-finished solution is discarded (§9.5).

9.2 Which method runs

GEM4D chooses the method for each solve, by element count:

Elements	Method	Notes
Up to 6 700	Direct (LU)	Exact, no iterations
Above 6 700	Iterative (GMRES)	Repeats until the result meets the GMRES tolerance (§5.4)

On large models, GEM4D also manages memory automatically. It stores as much of the solver's working data as fits in the free RAM, and recalculates the rest at each iteration. A large model therefore runs slower when RAM is short, rather than running out of memory. If a model is too large

for the free RAM even then, the status after the solve ends in · low RAM (§21.2). *Theory and Verification*, Chapter 5, explains how.

On a computer with a GPU (§5.4) the iterative method works differently: it stores only the influence of nearby elements, and recalculates everything else on the GPU at every iteration — which the GPU does many times faster than the processor can look it up. There is then no working data to fit into RAM. This holds for full-space (Kelvin), half-space (Mindlin) and DD models alike.

9.3 Reading the status area

The status area has room for only a short line, so its messages are brief:

Message	Meaning
Kelvin LU, Mindlin GPU, Kelvin+DD EBE, Kelvin GPU	At the start: the kernel, and the method (LU = direct; EBE = iterative, on the processor; GPU = iterative, on the GPU, §5.4). +DD means the model has DD elements.
GPU far field…, GPU far field ready	Preparing the GPU: the nearby elements are calculated once and the model is copied to the GPU. A few seconds.
GPU not used · CPU, GPU failed · CPU	The GPU could not be used, or failed during the solve; GEM4D solves on the processor instead, and a warning after the solve says why (§21.2).
GPU tolerance not met · CPU	The GPU could not reach the GMRES tolerance (§5.4), so GEM4D solves the step again on the processor. It can happen on openings much thinner than their elements.
H-matrix 8,192/12,480 blk (66%)	Building the solver's working data
H-mat 12,480 blk · 38 GB · 1,204 MF	Built: its size in RAM. A trailing · N MF means N far-field blocks did not fit and will be recalculated at each iteration (GEM4D_diag.log also counts the near-field blocks).
GMRES 184 · r/b 8.31E-05	Iteration 184. The second figure should fall steadily toward the tolerance.
Overlap stalled · block-Jacobi	On the processor, the iteration stopped improving with its default preconditioner, so it carries on with the simpler block-Jacobi one. The solve continues; GEM4D_diag.log has the details.
Solved — N el · k iter	Finished. The line below shows the start and end times and the duration. A trailing · GPU means every step was solved on the GPU.

On a mining sequence each line starts with the step, for example 2/5 · GMRES 184 · …. A sequence finishes with Solved S steps — N el · k iter. When that line ends in · low RAM (§21.2) or · GPU, the word *Solved* is left out to make room. Counts of a million or more are shortened in the status area, for example 1.05M el; the summaries and GEM4D_diag.log give the exact number.

9.4 How long will it take?

Models of up to 6 700 elements are solved by the direct method in seconds to a few minutes. Above that, the iterative solve is many times faster with a GPU (§5.4). Measured on a laptop with an NVIDIA RTX 4050 graphics chip, with BEM library 1.7.0.0 (*Theory and Verification* §5.7):

Elements	On the processor	On the GPU
19 000	4 s	2 s
67 000	30 s	9 s

Elements	On the processor	On the GPU
105 000	3.5 min	23 s
268 000 (BEM library 1.3.0.0)	29 min	76 s

On the same laptop's built-in Intel graphics the 105 000-element model took 2 minutes.

Half-space (Mindlin) and DD models gain as much: a 19 600-element half-space model solved in 3.3 s instead of 51 s, and a model of 10 800 FF and 8 000 DD elements in 2.0 s instead of 17 s (on the built-in Intel graphics 12 s and 7 s).

Mapping the results afterwards takes extra time, depending on the number of points. For a quick scoping answer, reduce the meshes (**Toolbox 1** → **Reduce polygon count**) or use the **Coarse** tolerance.

If a solve is much slower than this — tens of minutes on a few thousand elements, or the same model slower than before — see Chapter 21.

9.5 Stop and Clear

Stop ends the running task and **keeps your model**. It is lit only while something is running. It is not a pause — nothing resumes later.

- **Stopping a Map or Energy run** keeps the model **and** its solution. Click the button again when you are ready.
- **Stopping a solve** keeps your meshes, steps and Setup, but **discards the solution**. A solve writes into the model as it goes, so a half-finished solution cannot be trusted. Click **Run model** to start again.

Clear also ends a running task, but it deletes the model as well. You then need **Add FF and DD objects** again. Use **Clear** to start over and **Stop** to end the current run.

While a solve is running, **Run model** is greyed until the solve ends or you click **Stop**, and the **Map** buttons warn you rather than interrupt it.

9.6 Saving and reloading a solved model

The solve is the slow part. Once the status area shows **Solved**:

- **Save model** writes a `.bem4d` file. It holds the elements (in mine coordinates), the solution and your Setup.
- **Load model** restores all of it **without solving again**. You can map results straight away. Loaded into an empty scene, the view zooms to the model; loaded into an existing scene, the view is left alone.

A `.bem4d` file works in any session and on any computer. A good habit: solve a large model once — overnight if need be — save it, and come back to it as often as you like.

A model with DD elements uses a newer file layout, which older GEM4D versions refuse with a clear message rather than misread.

On a mining sequence, **Save model** stores every step — its elements, its solution and which meshes belong to it. **Load model** restores them all, ready to map, without solving again.

After a reload, GEM4D links each step to the meshes in the scene **by name** (*file* | *layer*). If one file holds several meshes with the same layer name, they are numbered `#2`, `#3`, … in load order, so each one steps on its own. If the original meshes are not loaded, the status area says how many are missing; the orange overlay still shows each step.

Part 3 — Getting and viewing results

10. Mapping results

Once a model is solved (or reloaded), the three **Map** buttons calculate the results at points in the rock.

Button	Where it calculates	Output	Best for
Map to Grid	A regular 3D grid of points	A CSV file	Even coverage; the fastest iso-surfaces
Map to Octree	An adaptive grid: dense near the excavations, coarse far away	A CSV file	Iso-surfaces, for the fewest points
Map to datagrid	The points already in the BEMResult table	New columns in that table	Your own points: instruments, minodes, fault facets, planned development

The energy outputs on the **Energy** dropdown are described in Part 4 (Chapters 16–18).

10.1 Choosing what to calculate

Each **Map** button first opens its options dialog — *Map BEM field points* for Grid and Octree, *Map BEM results to datagrid* for the datagrid; this guide calls both the Map dialog. Tick the outputs you want and click **Map**. The dialog remembers your choices for the session.

Checkbox	Adds	Available on
X/Y/Z, S1/S2/S3, Status (always)	The coordinates, the principal stresses and the Status column. Always written.	All maps
Displacement (U_mm)	The size of the displacement. Ticked by default.	All maps
…also Ux / Uy / Uz components	The displacement in the East, North and up directions (Chapter 13)	Datagrid, single model only
Full stress tensor (Sxx…Sxz)	The six stress components	All maps
Kirsch tangential + RCF, tunnel section	Wall stress of a drive along each row's direction, and the rock-wall condition factor (Chapter 14)	Datagrid only; needs Dip/DipDir columns
Excess Shear Stress on fault	How close each row's plane is to slipping (Chapter 15)	Datagrid only; needs Dip/DipDir columns
Coulomb ESS critical-plane Mapping discs (separate file)	The orientation-free excess shear stress, plus discs on its critical planes (§10.5, Chapter 15)	Grid and Octree only
Strain energy density at these points	The stored elastic energy (Chapter 16)	All maps
D/L: distance over the nearest element's length (D_over_L)	How far each point lies from the nearest element, in lengths of that element: where the stresses can be trusted (§13.6)	All maps
Sigma-1 orientation -> Mapping arrows (*… as Mapping arrows (separate file)* on Grid and Octree)	Arrows along σ1 (§10.5)	All maps
Write per-step full CSVs	One complete file per mining step (§10.6)	Sequences only

Options that do not apply to a map are greyed out. The two parameter groups on the right — **RCF parameters (Kirsch)** and **Excess Shear Stress parameters** (*Coulomb ESS parameters* on Grid and Octree) — are explained with their outputs in Chapters 14 and 15.

Large runs. A run of more than 1 000 000 point evaluations asks you to confirm first; it can take several minutes. On a sequence the count is the number of points times the number of steps. The status area shows progress, and **Stop** ends the run without touching the solution.

10.2 Map to Grid

1. Click **Map to Grid**. The *GEM4D 3D Grid parameters* dialog opens, already filled in for your model: the model's extent, extended on every side by 15 % of its largest dimension, with blocks about 8 % of that dimension.
2. Adjust **Model bounds**, the extension and **Block size** if you need to. (*Grid scope* and *Save and load the grid points as* do not apply to a BEM map.)
3. Click **Accept**, choose the outputs (§10.1) and click **Map**.
4. When the calculation finishes, save the CSV. The default name is `BEM_FieldPoints.csv`.

Watch the number of points: **halving the block size multiplies the points by eight.**

A grid CSV is already regular, so it can be displayed without interpolation — the fastest option (§11.4).

10.3 Map to Octree

1. Click **Map to Octree**. The *BEM — Map to Octree* dialog opens. It lays the model in cubic cells and puts one point at the centre of each. Four settings decide the cells:
   - **Finest cell, at the walls (m)** — the size of the cells next to the excavations.
   - **Coarsest cell, far from the walls (m)** — the size away from them. The cells halve from this size down to the finest. The line under it shows the sizes used: the finest cell × 2, 4, 8 … nearest to the value you enter.
   - **Padding around the model (m)** — how far the cells reach beyond the excavations on every side.
   - **Refinement band (cells)** — a cell is split into eight while it lies within this many of its own sizes of an element. Band 1 gives cells about as large as their distance from the wall. Band 2 keeps them finer twice as far out, for about 1.6 times the points.
2. Watch the count under the settings. It gives the number of points (on a sequence, times the number of steps) and how many there are of each cell size, and it updates a moment after each change. **Halving the finest cell gives about four times the points. OK** is available once the count is shown.
3. Click **OK**, choose the outputs (§10.1) and click **Map**.
4. Save the CSV. The default name is `BEM_OctreePoints.csv`. Its last column, `CellSize_m`, is the size of the cell each point is the centre of.

The first time you map a model, the dialog suggests settings that give about as many points as the old *refinement depth 5*. The finest cell has the same volume as that setting's cells, the coarsest is eight times the finest, the padding is 15 % of the model's largest dimension and the band is 1. **Default values** brings these back. Later in the session, the dialog opens with the last values you used on the same model.

An octree puts its points where the stress changes fastest, so it usually gives the best iso-surfaces for the number of points. On a mining sequence every step is calculated at the same points, so the cells are finest at the walls of **every** step. A finest cell smaller than the elements adds points where values are least accurate anyway (§13.5). The layout follows the *GEM4D BEM Octree* tool from IGM Geotechnical.

10.4 Map to datagrid

Map to datagrid calculates the results at the points already in the BEMResult table and adds them as new columns. Use it for your own points: instrument locations, development minodes, the facets of a fault surface, a planned drive.

1. Load your points into the BEMResult table (§11.1). The first three columns must be X, Y and Z in mine coordinates.
2. Filter the table if you only need some of the rows. **Only visible rows are calculated.**
3. Click **Map to datagrid**, choose the outputs and click **Map**.

The new columns all start with `BEM_`, for example `BEM_S1_MPa`. Rows inside an excavation get blank cells, or the in-situ values when Setup's back-fill is ticked (§13.4). Running the map again replaces the earlier `BEM_` columns. The one exception is the RCF input columns `F_Factor` and `UCS_MPa`, which keep your edits (Chapter 14).

For this map the confirmation for more than 1 000 000 evaluations comes after the options dialog, because only then is the number of visible rows known.

10.5 σ1 arrows and critical-plane discs

Two options also build a **Mapping object** — the same kind of object as your structural mapping data — so you can see orientations in the scene.

	σ1 arrows	Critical-plane discs
Ticked with	*Sigma-1 orientation -> Mapping arrows*	*Coulomb ESS critical-plane Mapping discs (separate file)*
One object per	Point outside the excavations	Point outside the excavations — **two** discs per point
Shows	The direction of σ1, as an arrow coloured by σ1	The two planes most likely to slip, coloured by Coulomb ESS (Chapter 15)
Its own CSV	`BEM_Sigma1_Arrows.csv` — `X, Y, Z, Dip, DipDir, Size, S1_MPa`	`BEM_ESS_CriticalPlanes.csv` — `X, Y, Z, Dip, DipDir, Size, ESS_MPa`
Mapping stereonet	**Ignore it** — σ1 is a line, not a plane, so the stereonet does not show it correctly	Plots the poles correctly; compare them with your mapped joint sets

Things to know:

- GEM4D has **one** Mapping object at a time. Building arrows or discs **replaces** any structural mapping you have loaded; you are asked first.
- If you tick both, both CSVs are written but only the **discs** are shown. Load `BEM_Sigma1_Arrows.csv` into the Mapping panel whenever you want to see the arrows.
- The arrow or disc CSV is offered for saving first. Cancelling it skips that file only; the scene object is still built.
- The arrows' Dip and DipDir are σ1's plunge and trend. The arrows use the **3D_Arrow** shape.
- The discs turn when you change the friction angle φ in the ESS parameters. The arrows do not.
- Above the Mapping 3D-glyph limit (Settings ▸ Max num meshes ▸ Mapping), the objects are drawn as 2D points. Filter to a section for a readable picture.
- On a sequence, one file is written per step (…`_s{k}.csv`), and the scene shows the current step.

10.6 Mapping a sequence

On a mining sequence every **Map** button calculates the same points at every step.

In the combined output — the CSV of a grid or octree map, or the BEMResult table — each result gets **one column per step**, named with `_s1`, `_s2`, …: for example `S1_s3_MPa`, or `BEM_S1_s3_MPa` in the table. Each step also gets its own Status column (`St_s{k}`), because a point inside a stope mined at step 3 is rock at steps 1 and 2 and `Interior` from step 3 on.

Per-step files. With **Write per-step full CSVs** ticked, GEM4D also writes one complete file per step, `<your name>_s{k}.csv`, laid out exactly like a single-model file. This is ticked by default for **Map to Grid** and **Map to Octree**, and off for **Map to datagrid**, whose main output is the table. Any per-step file loads into the BEMResult table on its own. GEM4D asks once before overwriting existing per-step files.

The full stress tensor has six columns per step. On the grid and octree maps it is therefore written only to the per-step files, and its checkbox is greyed while **Write per-step full CSVs** is off. On the datagrid it adds six columns per step to the table.

Chapter 22 lists every column, in both its single-model and per-step form.

11. The BEMResult panel

When the BEM tab is selected, the left panel shows *BEM result settings and data*. This is the **BEMResult panel**: a data table with display settings. It works like the Markers panel but belongs to the BEM workflow, so your survey and marker data are never touched.

11.1 Loading data

Right-click the table and choose **Load data from CSV-file**, or **Paste CSV-data from clipboard**. The first three columns must be X, Y and Z in mine coordinates. Every CSV the **Map** buttons write meets this rule.

The usual sequence is:

1. **Map to Octree** (or **Map to Grid**) and save the CSV.
2. Right-click the table → **Load data from CSV-file** → choose that file.
3. Colour the points and draw iso-surfaces (§11.3–§11.4).

Or load any set of points first and use **Map to datagrid** to add results to them (§10.4). For a Map3D model, right-click → **Load Map3D grid points (INP)** loads the points of the file's grids, finer near the excavations as Map3D refines them (*Import and Export* manual, §8.6); **Map to datagrid** then gives GEM4D's stresses where Map3D gave its own.

The same right-click menu adds and edits columns (**Add calculation column**, **Change column name**, …), hides rows, and saves the table (**Save data as CSV-file**). **Delete all BEM data** empties the table.

11.2 Points

The **BEM marker type** group sets how each point is drawn:

- **Shape** — 2D_Point, 2D_Point3D, 3D_Sphere, 3D_Cylinder, 3D_Cone or 3D_Cube;
- **Shape size**, the transparency slider and **Color**;
- **Scale on value** sizes the points by the colour column; **Reverse scale** makes small values large;
- **Text scale** shows each point's label at the size you set.

Very large tables are drawn as 2D points, because 3D shapes would be too slow.

11.3 Colours

The **Colour mode** group sets the colours:

- **Column** — the column that drives the colours, for example `S1_MPa`.
- **Mode** — **Auto** spreads the colours over the data range; **Custom** uses the **Value start** and **Value end** you type; **Remove** turns colour mapping off, so the points take the plain colour set with **Color**.
- **Reverse colour** turns the colour scale round.

The colour scheme and the scalar bar are set on the ribbon (§11.5).

A text column. When the **Column** holds text — a rock type, a zone, a joint set — every different word gets its own colour, and the scalar bar lists the words instead of numbers. A blank cell (shown as `Unknown` in the table) is drawn dark grey and listed as **Unknown**. A word keeps its colour when a filter hides other rows: the colours follow the word's place among all the words of the column. The words are coloured from a fixed set of 20 contrasting colours; beyond 20 words the set repeats, lighter and then darker. With more than 30 words every word is still coloured, but the scalar bar is not shown (one message says so); the histogram and the statistics box give the counts.

While a text column colours the points, the colour scheme, **Colours**, **Labels**, the value range, **Reverse colour**, **Chart log scale** and **Scale on value** are greyed: none of them has a meaning for words. **Remove** still turns the colours off. A column of numbers that are really codes — a material ID, say — is coloured the same way after right-clicking its header and choosing **Convert column to text**. Text columns colour the same way on the Marker, Mapping and Drillholes tabs.

11.4 Iso-surfaces and mesh colouring

The **Iso-surface and Colour mapping** group works on the colour column:

- **Iso-surface** draws a 3D contour shell at the value you set with the slider, or type in the box — for example the σ1 = 60 MPa surface.
- **Colour meshes** paints the colour scale onto the visible meshes themselves.
- **Show regular grid** shows the interpolation grid behind them, like a block model.
- **Update** rebuilds the iso-surface and the mesh colours after you change something.
- **Settings** opens the *GEM4D Shepard parameters — BEMResult* window, described below.

The Settings window. Iso-surfaces are not drawn on your points directly. The points are first interpolated onto a regular grid, and this window controls that step. It is a floating window: you can leave it open beside the scene, and the display follows your changes.

Group	What it controls
Interpolation method	**Use the data 'as-is' without interpolation** — right for a **Map to Grid** CSV, which is already regular, and by far the fastest. **Inverse distance** (Shepard's method) — the default, for scattered points such as an octree CSV or minodes. **Nearest neighbour** — used by **Colour meshes**, ignored by **Iso-surface**.
Resolution	The number of grid cells along Easting, Northing and Elevation, with a reset to square blocks at the maximum resolution. This is the main cost: an inverse-distance iso-surface takes a second or more to rebuild, a grid used as-is is instant.
Model bounds	The volume interpolated, taken from the data and extendable by a fixed distance.
Search radius	How far each grid node looks for points, with a button that estimates a sensible value from the data.
Directional (anisotropic) interpolation	**Enable directional interpolation** stretches the search along a dip and dip direction, with an along : across ratio. The direction can be taken from a mapped joint set. Use it where the stress field really is elongated along a structure.

Group	What it controls
Limit interpolation beyond data	Colours and trims grid nodes that are extrapolating rather than interpolating, so an iso-surface does not balloon into empty space.
Iso-surface options	The increment between surfaces and how many to draw.

Whether an iso-surface shows a clean hole at each excavation, or closes across it, is set in Setup before you map (§5.5).

On a mining sequence the iso-surface follows the steps by itself; **Colour meshes** does not (Chapter 12).

Both interpolate the colour column, so they need a column of numbers: with a text column (§11.3) they refuse with a message, and choosing a text column while either is on switches it off.

11.5 Scalar bar and legend

The **Scalar bar settings** group on the ribbon sets the legend:

- **Colours** — the number of colour bands (1–99);
- **Labels** — the number of labels on the bar;
- **Text** — the label size;
- the colour scheme: **Rainbow1**, **Rainbow2**, **RedBlue**, **CoralTeal** or **Custom** (below);
- **Show bar** and **Interpolate**.

The **General settings** group holds:

- **Mark obj res** — how smooth 3D shapes are drawn;
- **Grid decimals** — the decimals shown in the table;
- **Chart log scale** — a logarithmic scalar bar and histogram (below);
- **Power** — the inverse-distance power used by the interpolation, 1 to 8. The BEM tab's default is **8**: each grid node is then dominated by its nearest points, which keeps a stress field crisp rather than smeared. It is the one interpolation setting on the ribbon rather than in the Settings window.

The scalar bar belongs to the selected ribbon tab. Switching between the Marker, Mapping, Drillholes and BEM tabs shows that tab's bar, if its **Show bar** box is ticked.

Log scale. A log scale needs colour values above zero. If the range includes zero or negative values, ticking **Chart log scale** offers to start the range at the smallest positive value: **Yes** sets the colour Mode to Custom with that start; **No** leaves the box unticked. If a later change makes the range non-positive again, the box unticks itself and says so — the display is never silently linear under a ticked box. With log on, the bar labels every power of ten in the range, so **Labels** is greyed.

Custom bands. Choosing **Custom** in the colour scheme opens the *Custom Legend* dialog. Define up to 20 bands, each with its own From, To and colour, plus the colours below and above the range. The scene changes colour exactly at your band edges; a value on an edge belongs to the upper band. While Custom is on, **Colours**, **Labels**, the value range and **Reverse colour** are greyed and show what the bands imply. To edit the bands, choose Custom again.

- **OK** refuses gaps, overlaps and a From that is not below its To (and, with log on, a first edge that is not positive), naming the band.
- **Auto-distribute** spaces the bands evenly — geometrically when log is on.
- **Save…** and **Load…** keep band sets in `.clg` files.
- **Cancel** never changes the scene.

11.6 The histogram

The histogram in the bottom panel matches the scalar bar: it has one bar per legend colour, painted in that colour, and log-spaced bins when log is on. Under Custom bands it has one bar per band, labelled with the band edges. For a text column (§11.3) it has one bar per word, in the word's colour and labelled with the word, plus a grey **Unknown** bar for blank cells; the statistics box lists each word's count and share, and the clicks below that set a range do nothing.

Clicking the chart:

Click	Does
Left-click	Sets the start of the colour range
Right-click	Sets the end of the colour range
Middle-click	Resets the range to the data extremes
Ctrl + right-click	Opens the chart menu: **Save Histogram CSV…**, **Copy Histogram Data**, **Show out-of-range bins**

Under Custom bands the click gestures are off, because the bands set the range.

Show out-of-range bins adds a hatched bar beyond each end of the axis for values outside the colour range, drawn in the below- and above-range colours. Their height is capped at the tallest bar in range, with the true count printed above. The setting applies to all four histograms for the session.

11.7 BEM filters

The **BEM filters** group on the ribbon filters the rows of the BEMResult table:

- **Mesh bounds** keeps points inside the bounding boxes of the visible meshes;
- **Relative to meshes** keeps points by their position relative to the mesh surfaces;
- under **Manual**: **Pick box** and **Pick sphere** select a region you pick in the scene, and **Remove inside selection** and **Remove outside selection** use a rubber-band box;
- **Reset manual** undoes these ribbon filters but keeps any filter set in a column header of the table; **Reset all** clears both.

Rows that are filtered out disappear from the display **and are skipped by Map to datagrid**.

12. Stepping through a sequence

The **Mining steps** group on the ribbon walks a mining sequence step by step. It works as soon as a sequence with more than one step **exists** — just built, solved, or loaded from a `.bem4d` file. So you can check what each step mines before you commit to a long solve.

12.1 The controls

- **Prev** and **Next >** move one step. They wrap round: **Next** after the last step goes to step 1, and **Prev** before step 1 goes to the last step.
- **Play steps** moves on by itself, about every 1.2 seconds. While it plays, its caption reads **Stop**; click it again to stop. Once stopped, it reads **Play steps** again.
- The label between them shows the current step, for example *Step 2/5*.

After a build or a reload the scene starts on **step 1**.

The Deswik player bar. A Deswik mining sequence has a player bar of its own under the scene (*Import and Export* manual §6.10). The two take turns. **Prev**, **Next >** or **Play steps** here first gives back the stopes the bar hid, and the bar goes to its last step. Moving the bar gives back what the step-through hid.

12.2 What changes at each step

- **The meshes.** Of the sequence's meshes that you have switched on, those in the step are shown and the rest are hidden. Other scene content is untouched. **A mesh you hid stays hidden**: an unticked file or object row in the Mesh panel is never overridden. If you have hidden all of a step's meshes, the status area says *Member meshes hidden — overlay only*.
- **The orange overlay** changes to that step's elements.
- **The point colours** change to the same result at the new step, if you are colouring by a per-step column (§12.3). The histogram and scalar bar follow.
- **The iso-surface** is rebuilt for the new step, so it always matches what else is shown. A grid used as-is rebuilds instantly; an interpolated one takes a second or more per step. **Play steps** waits for it. For a quick preview, untick **Iso-surface** first.
- **The clip section**, if one is active, is re-cut for the new step.

Colour meshes does not follow the steps. Repainting the meshes rebuilds every mesh in the scene, which would also cancel a clip section at each step. The status area says *Mesh colours stale — press Update* instead. Press **Update** on the BEMResult panel when you want the mesh colours to catch up.

The skin maps of the **Energy** buttons do not follow the steps either. Each step has its own file (…`_s{k}.csv`); load another step's file to see it.

12.3 Colouring the steps

Before you map anything, stepping changes only the geometry. To watch the results change:

1. Load points into the BEMResult table and run **Map to datagrid** on the sequence (§10.4). This adds one column per step for each result.
2. Set the colour column to any per-step result — `BEM_S1_s1_MPa`, or `BEM_ESS_s1_MPa`, `BEM_SED_s1_kJm3`, `BEM_U_s1_mm`, `BEM_Tang_s1_MPa`, `BEM_RCF_s1` or a tensor component.
3. Use **Prev**, **Next >** or **Play steps**. The colours move to the same result at each step: the "4D" view of how stress, fault hazard or energy develops.

Columns from an older solve. Per-step columns belong to the solve that made them. After you rebuild, re-solve or load a different model, stepping still moves the geometry, but the status area says *Grid columns are from an older solve* and the colours stay put. Run **Map to datagrid** again to reconnect them.

12.4 Picking up a session later

To continue another day:

1. Save the model (**Save model**) and the whole BEMResult table (right-click → **Save data as CSV-file**).
2. Later, load both, in either order.

When the table's per-step columns match the steps of the loaded model, step colouring works straight away, without mapping again. The per-step `BEM_DatagridPoints_s{k}.csv` files cannot do this — each holds one step under single-model column names — so reload the whole table instead.

If the meshes of a reloaded sequence are not in the scene, the overlay still steps, and the status area says how many meshes are missing (§9.6).

Part 4 — Interpreting results

Each chapter in this part follows the same pattern: what the result measures, how to get it, how to read it, and its limits. The *Theory and Verification* companion gives the formulas and the checks behind them.

13. Stress, displacement and the Status column

13.1 What the columns are

Column	Unit	Meaning
`S1_MPa`, `S2_MPa`, `S3_MPa`	MPa	The **total** principal stresses — in-situ plus mining-induced — with compression positive and σ1 ≥ σ2 ≥ σ3
`Sxx_MPa` … `Sxz_MPa`	MPa	The six components of the total stress, in mine axes: x = East, y = North, z = up
`U_mm`	mm	The size of the **mining-induced** elastic displacement
`Status`	—	Where the point lies: `Far`, `NearSurface` or `Interior` (§13.3)
`DistToSurface_m`	m	Distance to the nearest excavation wall; negative inside an excavation
`D_over_L`	—	Distance to the nearest element over that element's longest edge, when ticked: below 1 the stresses are less certain (§13.6)

In the BEMResult table the same columns carry a `BEM_` prefix (`BEM_S1_MPa`, …). Chapter 22 lists every column.

13.2 Displacement components

`U_mm` is a size. It cannot tell you *how much a wall closed, and in which direction* — closure is movement along a chosen direction, which a size throws away.

Tick **…also Ux / Uy / Uz components** on **Map to datagrid** to add `BEM_Ux_mm`, `BEM_Uy_mm` and `BEM_Uz_mm`: the induced displacement along East, North and up. With them you can:

- calculate the **closure** between two facing wall points: the difference of their displacement vectors, projected onto the wall normal;
- take the **convergence** along any survey direction;
- plot **movement vectors**.

This option is available on the datagrid map for a single model. On a sequence, each step gets the size only (`BEM_U_s{k}_mm`).

13.3 The Status column

Every point is classified:

Status	Where	Values
`Far`	In the rock, away from the walls	As calculated
`NearSurface`	Within the near-surface band of a wall (§5.5). By default this happens with the Mindlin kernel only, within 2 element-edge lengths.	As calculated — the status is a flag only
`Interior`	Inside an excavation, or above the ground surface with the Mindlin kernel. There is no rock here.	Blank (NaN), or in-situ values — see §13.4

Use `Status` and `DistToSurface_m` to filter the table, for example to remove points close to the walls.

13.4 Points inside excavations

A point inside an excavation has no rock, so its numbers mean nothing.

- By default, every **Map** button writes blank (`NaN`) values for interior points, so an iso-surface shows a clean hole at each excavation.
- With **Iso-surface treats interior as in-situ** ticked in Setup (§5.5), the maps write the **in-situ** stress for interior points instead — with the in-situ values of any derived column, such as ESS or SED, and zero displacement. An iso-surface built from them then closes smoothly across each excavation. The `Status` column still says `Interior`.
- The setting applies when you map; changing it does not alter files or columns already written.
- **Map to datagrid** adds the blank cells without the *Empty cells in file* notice that a loaded file with blank cells raises, because they are blank on purpose. `GEM4D_diag.log` counts them.

On a sequence the status belongs to each step. A point inside a stope mined at step 3 is rock in the step 1 and step 2 columns, and `Interior` from step 3 on.

13.5 Reading stress results

- **E does not change the stresses.** In a uniform elastic model the stresses come from the geometry and the in-situ stress; E scales the displacements and energies (§5.2).
- **Compare with strength yourself.** The module gives stress, not a factor of safety. Compare σ1 and σ3 with your strength criterion; a calculated column in the BEMResult table is a convenient way (right-click → **Add calculation column**).
- **Close to a wall, read one element in** (§13.6), or, for the wall of a drive, use Kirsch tangential stress (Chapter 14).
- **Elastic means "if the rock stayed elastic".** Where the stress exceeds the rock's strength, the real rock yields and sheds load, and the elastic answer overstates the stress there.

13.6 Checking the result

Check a model the way you would check any BEM model: **refine the mesh and solve again.** Remesh the excavations near your points of interest at about half the element size. If the stresses at those points agree, you can trust them.

What to expect from a coarse mesh. On a 19 232-element mine model (typical element area about 50 m², that of an equilateral triangle with 11 m edges), halving the element size changed the results by:

Where	σ1: typical (median) / worst 10 % from	Strain-energy density: typical / worst 10 % from
At the walls (energy maps, wall values)	18 % / 72 %	37 % / 170 %
Half an element into the rock	6 % / 49 %	11 % / 120 %
One element into the rock	3 % / 25 %	7 % / 72 %
Two elements into the rock	2 % / 9 %	4 % / 23 %
Total released energy	0.5 %	

The changes gather at **sharp edges and corners** (a bend of more than 20° between neighbouring triangles); on this model nine elements in ten lay within one and a half element sizes of such an edge. On the coarse mesh the wall values read **high**: σ1 was higher on six walls in seven, and a typical

wall's energy about 35 % higher. The coarse mesh still **ranked** the walls almost exactly as the fine one did.

For a quick, approximate model:

- **Read stresses at least one element into the rock.** There a coarse mesh is within a few percent at most points.
- **Treat wall values near sharp edges as indicative.** The energy maps and wall stresses rank the walls correctly but overstate them. Compare walls within one model, or between models meshed at the same size — not against a threshold taken from a model meshed differently.
- **Totals are robust.** Released energy hardly changes with element size.
- **Stress at a sharp corner or edge keeps rising as you refine.** That is the nature of a corner, not an error; real rock yields there.

Refining costs time: halving the element size made this model's solve about seven times as long. Refine only the meshes near the points that matter.

Where you can trust the answer: the D/L column. Tick **D/L: distance over the nearest element's length** in the Map dialog (§10.1). Every map then gains a column `D_over_L`: each point's distance to the nearest element, divided by that element's longest edge. On a sequence the columns are `D_over_L_s1`, `D_over_L_s2` …, each from that step's own elements. In the BEMResult table the column is `BEM_D_over_L`.

The error of a BEM stress near a wall follows this ratio. **From D/L 1 on — one element length or more off the walls — the stresses can be trusted to a few per cent:** on the models measured, σ1 was within 2 % of a much finer mesh at 96 % of the points between D/L 1 and 2, and at 99.5 % or more beyond. Closer to the walls the error grows quickly: below D/L 0.25 it was typically 5 %, and one point in ten was off by about half or more. *Theory and Verification* §8.9 gives the method and the full table.

With the column ticked, the map's completion message says how many points in the rock lie below D/L 1 (on a sequence, at the step with the most). To trust the stresses there, refine the meshes near them — **Refine for BEM (keep shape)** (§6.5) or **Remesh for BEM analysis** at a smaller size (§6.3) — and map again. The column is geometry, so points inside an excavation carry it too; their Status says where they are. Colour the BEMResult points by `D_over_L` with a range of 0 to 2 to see at once where a later area of interest needs a finer mesh.

Theory and Verification, Chapter 8, gives the measurements behind these rules.

14. Kirsch tangential stress and RCF

14.1 What it measures

Kirsch tangential stress is the largest stress on the wall of a round drive, driven along a given direction, in the stress field the model calculates at that point. GEM4D reads each row's **Dip** and **DipDir** as the **plunge and trend of the drive's axis** — exactly what the minode generator writes.

Only use it on development minodes, or other points whose Dip and DipDir describe a drive's direction. On fault facets or ordinary points the result means nothing.

The **Rockwall Condition Factor** (RCF; Wiseman, 1979) comes with it. It compares the wall stress with the downrated rock strength:

```
RCF = BEM_Tang_MPa / (F_Factor × UCS_MPa)
```

14.2 How to get it

1. Load the minodes into the BEMResult table. They need Dip and DipDir columns; the names `Dip` / `DipDir` and `DipAngle` / `DipDirection` are both accepted.
2. Click **Map to datagrid** and tick **Kirsch tangential + RCF, tunnel section (needs Dip/DipDir)**.
3. In **RCF parameters (Kirsch)**, set the **F-factor default** (0.05–2, default 1.00) and the **UCS default** (1–500 MPa, default 100). The UCS default is only a placeholder: enter your site value before reading any RCF.
4. Click **Map**.

14.3 The columns

Column	Meaning
`BEM_SigMax_MPa`, `BEM_SigMin_MPa`	The largest and smallest stress across the drive's cross-section
`BEM_Tang_MPa`	The Kirsch wall stress: 3 × SigMax − SigMin
`F_Factor`	The rock-condition downrating: about 1.0 for massive rock, down toward 0.5 for jointed or weathered walls. An ordinary, editable column.
`UCS_MPa`	The intact-rock uniaxial compressive strength. An ordinary, editable column.
`BEM_RCF`	The RCF — a **live calculated column** that updates as soon as you edit F_Factor or UCS_MPa

SigMax and SigMin are written so you can check the arithmetic on any row (*Theory and Verification*, Appendix A, works one row by hand). They are not σ1 and σ3: they are the extremes across the section, and always lie between them.

14.4 Reading the wall stress

A drive **at right angles to σ1** has σ1 in its cross-section, so SigMax is close to σ1 and the wall stress is high. A drive **along σ1** has σ1 out of its section, so the wall stress is lower. This is the familiar rule for orienting development, and the columns show it directly.

14.5 Reading the RCF

As a broad guide (Jager & Ryder, 1999):

RCF	Conditions
Below 0.7	Good
0.7 – 1.4	Average — conventional support
Above 1.4	Poor — special support or redesign

Calibrate these bands against your own site, using your own F-factor convention.

14.6 Setting F and UCS by area

You can set different F and UCS values for different ground, without mapping again:

1. Filter the table to one geotechnical domain (§11.7, or a column-header filter).
2. Type the domain's F or UCS into one cell.
3. Right-click that cell → **Copy to visible column cells**.
4. Repeat for the other domains, then colour by `BEM_RCF`.

When you run **Map to datagrid** again and an `F_Factor` or `UCS_MPa` column already exists, GEM4D compares it with the dialog values. If any visible cell differs, it asks once: **Yes** overwrites all visible rows with the dialog values; **No** keeps yours.

14.7 Points to note

- On a sequence each step gets `BEM_Tang_s{k}_MPa` and `BEM_RCF_s{k}`. **One** F_Factor / UCS_MPa pair serves every step, so a change to one cell updates the RCF at every step.
- Rows inside an excavation have no Tang, so their RCF is blank. An F × UCS of zero or less also gives a blank RCF.
- `BEM_RCF` is calculated, so you cannot type over it. Deleting F_Factor, UCS_MPa or the Tang column is refused while an RCF column uses it — delete the RCF column first.
- A CSV export writes the RCF **values**. After re-importing, they are plain numbers until the next Kirsch map recreates the live column. The per-step `BEM_DatagridPoints_s{k}.csv` files likewise hold fixed values.

15. Excess shear stress (ESS)

15.1 What it measures

Excess shear stress (Ryder, 1988) measures how far a plane of weakness is from slipping. It is the driving shear stress on the plane minus the friction that resists it:

ESS = τ − c − tan φ · σN

where τ is the shear stress on the plane, σN the normal (clamping) stress, φ the friction angle and c the cohesion. It is a standard screen for fault-slip rockbursts in deep mines.

Read the sign first:

ESS	Meaning
Above 0	**Over-stressed.** The plane can slip; the value is the excess shear stress available to drive the event. Larger is more hazardous.
0	On the point of slipping
Below 0	**Stable.** The size of the value is the reserve: how much more shear stress the plane could carry before it slips. This is the normal state away from the excavations.

15.2 Two kinds of ESS

	Plane-specific ESS	Coulomb ESS
Map	**Map to datagrid**	**Map to Grid**, **Map to Octree**
Checkbox	*Excess Shear Stress on fault (needs Dip/DipDir)*	*Coulomb ESS critical-plane Mapping discs (separate file)*
Plane	Each row's own plane, from its Dip and DipDir	The worst plane at each point, whatever its orientation
Use it for	A known fault or dyke	Where **any** plane could slip — the hazard volume around the excavations
Columns	`BEM_ESS_MPa`, `BEM_SigN_MPa`, `BEM_Tau_MPa`, `BEM_SlipPl_deg`, `BEM_SlipAz_deg`, `BEM_ESS_Band`	`ESS_Coulomb_MPa`, plus the critical-plane discs (§10.5)

Coulomb ESS is always at least as large as the plane-specific ESS at the same point, because it takes the worst orientation.

> **Kirsch and plane-specific ESS read Dip and DipDir differently.** Kirsch reads them as a drive's **axis**; ESS reads them as a **plane**. A dataset therefore feeds one or the other, not both. If you tick either without Dip and DipDir columns, GEM4D says so and leaves those columns out.

15.3 The parameters

The **Excess Shear Stress parameters** group of the Map dialog (*Coulomb ESS parameters* on Grid and Octree) sets:

Field	Range	Default	Notes
Dynamic friction angle	0–89°	30°	Ryder's dynamic value; tan 30° ≈ 0.58
Cohesion c	0–50 MPa	0	Zero under dynamic slip
Tensile normal stress -> zero frictional resistance	—	On	Plane-specific ESS only

The tensile clamp. Friction resists slip only while a plane is clamped shut. On a plane in **tension** (σN below zero) the formula would give a negative resistance, as if the opening joint helped drive the slip. With the clamp **on**, σN is treated as zero in the friction term, so an opening plane simply offers no resistance.

Unticking the clamp **raises** ESS on a tensile plane, because σN is subtracted. For example, with τ = 10 MPa, c = 0, φ = 30° and σN = −5 MPa:

- clamp **on**: ESS = 10 − 0.58 × 0 = **10.0 MPa**
- clamp **off**: ESS = 10 − 0.58 × (−5) = **12.9 MPa**

Leave the clamp on unless you specifically want tension to count as driving stress. Coulomb ESS has no clamp. On its critical plane σN = (σ1 + σ3)/2 − (σ1 − σ3)/2 · sin φ, which is compressive unless σ3 is tensile by more than σ1 (1 − sin φ)/(1 + sin φ) — a third of σ1 at φ = 30°. In such a zone Coulomb ESS, like plane-specific ESS with the clamp off, counts the tension as driving stress.

15.4 Checking a fault: plane-specific ESS

1. Make the fault surface visible, then export its facets: **Mesh** tab → **Save other formats** → **Save info as CSV** → **Poly faces information**. This writes one row per triangle, with `Easting`, `Northing`, `Elevation`, `DipAngle` and `DipDirection`.
2. Load that CSV into the BEMResult table.
3. **Map to datagrid** with **Excess Shear Stress on fault** ticked.
4. Colour by `BEM_ESS_MPa`.

Column	Meaning
`BEM_ESS_MPa`	The excess shear stress
`BEM_SigN_MPa`, `BEM_Tau_MPa`	The normal and shear stress on the plane
`BEM_SlipPl_deg`, `BEM_SlipAz_deg`	The plunge (downward) and azimuth of the shear direction on the plane — the direction it would slip
`BEM_ESS_Band`	The band below

ESS (MPa)	`BEM_ESS_Band`	Meaning
Below 0	`Stable`	The plane holds

ESS (MPa)	BEM_ESS_Band	Meaning
0 – 5	Low	Slip possible, but a burst is unlikely
5 – 15	Moderate	Hazardous — a shear event is credible
15 and above	High	Implausibly high for a real fault: an earlier event should already have relieved it. Check the mining scenario.

15.5 Mapping the hazard volume: Coulomb ESS

Tick **Coulomb ESS critical-plane Mapping discs (separate file)** on **Map to Grid** or **Map to Octree**. This adds `ESS_Coulomb_MPa` to the CSV and builds the critical-plane discs (§10.5).

- **Iso-surface `ESS_Coulomb_MPa` at 0** (or at your design ESS). The positive lobes, usually hugging the excavations where σ1 − σ3 is large, are where a plane of the right orientation could slip. A negative value means **no** plane through that point can slip, for your c and φ.
- **Compare the discs with your mapped joints.** Each point gets two discs — the two planes most likely to slip, mirror images about σ1. A joint set close to either is critically oriented. Their poles plot correctly on the Mapping stereonet.
- Raising c or φ pushes more of the field below zero. The discs turn when you change φ.

15.6 Limits

ESS here assumes dry conditions, with the clamping taken from the modelled stress and no dynamic overshoot. It uses the modelled total stress, so points inside excavations follow the usual Status rules (§13.4).

16. Stored energy

16.1 What it measures

Stored strain-energy density (SED) is the elastic energy packed into each cubic metre of rock, in kJ/m³. As mining proceeds, energy that is not released concentrates in the remaining rock — abutments, pillars, the skins of highly stressed drives — and that is where **strainbursts** start. Where ESS asks *"can a plane slip?"*, SED asks *"how much energy is stored here?"*

GEM4D calculates SED from the principal stresses and the Setup E and v. Typical skins in deep hard rock run from tens to a few hundred kJ/m³. Calibrate any threshold against your own site.

16.2 Which energy output do you need?

GEM4D reports elastic energy in three ways. Two are the same quantity in different places; the third is a different quantity.

You want	Use	You get
Energy stored **at the excavation walls** — the strainburst screen	**Energy ▸ Stored on surfaces** (§16.3)	One SED value per wall element, for the whole model
Energy stored **through the rock** — contours, iso-surfaces, values at your points	**Strain energy density at these points** on any Map dialog (§16.4)	An SED column at your points
Energy **released by a mining step** — the ERR design criterion	**Energy ▸ Released on surfaces** (Chapter 17)	ΔW in MJ per step, and a kJ/m² map

The first two share one formula, but neither replaces the other. A field point placed on a wall does not give the wall value, and the wall map never leaves the wall. Released energy is not a sample of stored energy at all: stored energy is a **state**, released energy an **increment** between two states.

16.3 On the walls: Energy ▸ Stored on surfaces

Click **Energy ▸ Stored on surfaces**. GEM4D calculates SED at every FF element of the solved model, just inside the rock (*Theory and Verification* §2.4 explains why), and reports it at the wall.

- The results are saved as `BEM_StoredEnergy_kJm3.csv` (`X_m, Y_m, Z_m, SED_kJm3`) and loaded into the BEMResult table, one point per element, coloured by `SED_kJm3`.
- A summary reports the **largest** and the **area-weighted mean** wall SED.
- DD reef elements are left out: a reef has rock on both faces, so it has no wall.

On a sequence there is one file per step (`…_s{k}.csv`), the summary gives a table by step, and the current step is shown. The displayed points do not follow **Prev** / **Next** — load another step's file to see it.

16.4 Through the rock: the SED checkbox

Tick **Strain energy density at these points** on any **Map** dialog. It adds `SED_kJm3` to a grid or octree CSV — iso-surface it to see the energy concentrating in abutments and pillars — or `BEM_SED_kJm3` to the BEMResult table.

On a sequence each step gets its own column (`SED_s{k}_kJm3`, or `BEM_SED_s{k}_kJm3` in the table). To **animate** the build-up of stored energy, use **Map to datagrid** and step through the `BEM_SED_s1_kJm3` column (§12.3).

16.5 Reading it

SED follows the stress **level** (not the difference between the principal stresses), weighted by the rock's stiffness.

- **High SED on a wall** flags development prone to strainbursts.
- **High SED next to critically oriented structure** (positive ESS) is the fault-slip burst case.
- **High SED without such structure** is the classic pillar or skin strainburst case.
- Watching the high-SED lobes move from step to step shows where mining is loading the abutments.

16.6 Limits

SED comes from the same elastic stress as every other output, with one E and v for the whole model. It is the energy stored **now**, not the energy released by a step (Chapter 17). Interior points follow the Status rules (§13.4).

Wall SED carries the element-size error of every wall value (§13.6). On a coarse mesh it reads high near sharp edges — on a test mine model a typical wall element read about 35 % high and the area-weighted mean about 50 % high — while still ranking the walls correctly. Compare walls within one model, or between models meshed at the same size.

17. Released energy

17.1 What it measures

Released energy is the elastic energy a mining step lets go: ΔW, in MJ. Spread over the new excavation surface it gives a release density, w, in kJ/m². This is the classic design criterion for sizing

regional and closure pillars in burst-prone ground: ore locked in pillars on one side of the trade-off, seismic hazard on the other.

If stored energy (Chapter 16) asks where energy concentrates, released energy asks *how hard does this cut hit?*

17.2 How to get it

Click **Energy ▸ Released on surfaces**. It needs a solved (or reloaded) model. On a sequence **every step must be solved**: each step is measured against the one before, so a missing step is refused rather than leaving a term silently out.

Single model — one result, for the whole excavation against the in-situ state. The summary reports W (MJ), the surface area A (m²), the excavated volume V (m³), and W/V (kJ/m³) and W/A (kJ/m²). The per-element map is saved as `BEM_ReleasedEnergy_kJm2.csv` (`X_m, Y_m, Z_m, w_kJm2`) and loaded into the BEMResult table, coloured by `w_kJm2`.

Sequence — one increment per step, in one pass. Each step gets its own map file (`…_s{k}.csv`) and the current step is shown. The summary table is offered as `BEM_ReleasedEnergy_Summary.csv`:

Column	Meaning
`Step`	The step
`NewElements`	Elements on the surface newly created by this step
`ExcludedInterior`, `NearZeroTraction`	As-mined bookkeeping (§17.6)
`A_new_m2`, `dV_m3`	New surface area; volume mined in this step
`dW_MJ`, `cumW_MJ`	Energy released in this step; running total
`dW_per_V_kJm3`, `dW_per_A_kJm2`	The two normalisations (§17.3)

The displayed map does not follow **Prev** / **Next** — load another step's file to see it.

17.3 Two normalisations

- **ΔW/ΔV** (kJ/m³) — energy per cubic metre mined. Always reported.
- **ΔW/A** (kJ/m²) — energy per square metre of new surface. Reported in **Additive** mode, where every element of a step's new mesh is new surface. In **As-mined** mode a step's shape can re-cover wall that already existed, so "new area" has no clean meaning, and the column is left blank rather than misleading.

17.4 Comparing with published ERR

Published ERR for tabular mining is quoted per square metre of **reef mined**, and the Jager & Ryder bands are built on that. A thin slab has about **twice** its plan area in surface (a hangingwall and a footwall), so for a thin slab **classic ERR ≈ 2 × (ΔW/A)**.

For bulky 3D excavations the factor is not 2, and the plan-area idea does not carry over at all. There, **ΔW in MJ** is the robust figure. For reef-scale ERR, model the reef as DD (Chapter 18): its energy per unit area *is* classic ERR.

17.5 What a sequence can and cannot show

In an elastic model the **total** energy released depends only on the final shape. Summed over any mining order, the steps add up to the single-step total of the final excavation (to about 0.4 % on the test models). What the order **does** change is how the energy is spread over the steps — and so when the hazard peaks.

An elastic sequence study is therefore a sound way to compare **when** energy comes out, and to find the steps that release the most. It cannot show an order that releases less energy overall; a result that seems to is a modelling artefact.

The energy of removing a pillar. Add an extra step that mines the pillar, solve, and read that step's ΔW. That is the energy its removal releases — the figure a burst-severity argument needs.

17.6 As-mined bookkeeping

In As-mined mode a step's shape is not all new, so the summary and `GEM4D_diag.log` give two counts:

- **ExcludedInterior** — elements lying inside the previous step's void. That ground was already mined, so they are left out.
- **NearZeroTraction** — elements whose load had already been at least half relieved: old wall that this step's shape merely re-covered. They stay in the sum, where they contribute almost nothing. A large count with a small ΔW is the normal sign of a step that mostly re-meshed existing geometry.

17.7 Limits

- The model is linear-elastic, dry and static, with one material. The release is the **elastic** release: no seismic efficiency is assumed and no magnitude is estimated.
- Both kernels and all three in-situ stress descriptions are supported.
- With Gravitational stress and the Kelvin kernel, elements above the ground surface get no in-situ stress (§7.6), so their step-1 release is unreliable too.
- **Thin stopes** need elements no larger than their thickness (§6.6); then their released energy is reliable.
- A **negative ΔW** points to a defective mesh — check the quality grade and notes (§7.8).

Theory and Verification, Chapter 6, gives the formula, and Appendix B works one element through by hand.

18. Tabular reefs (DD)

18.1 When to use DD

A reef or seam can be modelled in two ways:

- as a **thin FF void**, with a hangingwall, a footwall and a rim; or
- as a **DD surface**: a single surface that the rock on either side can close across.

On a thin tabular opening both give the same released energy to within a few percent. DD is the formulation the tabular mining industry has used for ERR since Crouch and Starfield: one element per unit of reef instead of two walls and a rim, and its energy per unit area **is** classic ERR, with no factor of 2 to explain.

A DD element is a flat triangle with three results: the **closure** across the reef and two **ride** components along it. Mining an element means making the load across it zero, just as mining a stope wall does.

18.2 Building a reef model

Chapter 7 covers the steps: add the reef as a mesh (a surface, or the thin closed solid your mine planning already has), set its **Type** to **DD**, give it a **Width**, choose the **DD element size**, and assign its **Steps**.

- A reef needs no excavation solids — a model of DD rows only is complete.
- When FF and DD rows are mixed, they are solved together in **one coupled system**: the stope feels the reef and the reef feels the stope. The status area shows `Kelvin+DD ….`
- **A hole in the surface is a pillar** — nothing is mined there.
- DD needs the **Kelvin** kernel. For a shallow reef where the ground surface matters, model it as a thin FF solid instead.

18.3 The results

Click **Energy ▸ Released on surfaces**. On a model with FF and DD rows, both parts are reported together.

Panel map — `BEM_TabularPanels.csv` (or `…_s{k}.csv` per step), loaded into the BEMResult table with one point per element:

Column	Meaning
`Closure_mm`	Closure across the reef — positive when it closes
`RideS_mm`, `RideT_mm`	Movement along the reef: along strike (S) and along dip (T)
`tN_MPa`	The normal stress that acted across the reef before this step (compression positive)
`w_kJm2`	The energy released per square metre
`Width_m`	The element's mining width — measured on a thin solid, entered for a surface

Colour by `w_kJm2` for energy, or by `Closure_mm` for convergence.

Summary — `BEM_TabularPanels_Summary.csv`:

Column	Meaning
`Step`, `Panels`	The step, and the number of elements mined in it
`CarriedOver`	Elements mined at an earlier step — already free of load, so left out
`Touchdown`	Elements that closed by their full width (§18.6)
`A_reef_m2`, `A_plan_m2`	Area mined, in the plane of the reef and in plan
`V_mined_m3`	Volume mined: area × width
`dW_MJ`, `cumW_MJ`	Energy released in this step; running total
`ERR_MJm2`, `ERR_plan_MJm2`	Energy release rate per reef area, and per plan area

On DD elements the total over a sequence matches the single-step total **exactly**, so a reef sequence study is a clean comparison of when energy comes out.

18.4 Which area to use for ERR

GEM4D's headline is **ERR per reef-plane area** (`ERR_MJm2`), with the plan-area figure beside it (`ERR_plan_MJm2`). The ERR literature grew up on largely **flat** South African reefs, where the two are the same. On a **steep** reef they differ: the plan-area figure grows as 1/cos(dip) and runs away toward a vertical reef.

On a flat reef the columns are equal and any published band applies to either. On a dipping reef, use the reef-plane column and say so when you quote it. The Jager & Ryder bands apply to the reef-plane column directly.

18.5 Choosing the DD element size

Accuracy at the mined edge depends on the element size against the mined span. Measured against the exact solution for a circular reef:

Element edge	Elements	Error in crack volume (≈ released energy)
span / 12	216	+8.6 %
span / 20	600	+5.4 %

The error falls steadily as you refine. **Span / 20 is the working default** — it is roughly what **Suggest** fills in (§7.3), it costs a few hundred elements, and about 5 % is fine for comparing layouts. Refine further for a number you intend to quote.

The error is always **positive**: a coarse reef **over**-estimates ERR. That is on the safe side, but it means two layouts must be compared **at the same element size** — otherwise part of the difference is the mesh, not the mining.

18.6 The touchdown advisory

The model has **no contact**: the hangingwall and footwall are free to pass through each other. Where the calculated closure reaches an element's mining width, the real stope has closed onto itself. Further closure would be resisted, so the released energy there is **overstated**.

Those elements are counted (`Touchdown`) and flagged in the summary. Nothing is adjusted. Treat a run with many touchdowns as an upper bound — reduce the span, check the mining width, or use a code with contact.

A model reloaded from an early file that holds no widths reports the touchdown count and mined volume as unavailable.

18.7 Limits

- **Any shape.** The reef's own triangles are the elements, so an undulating, folded or steeply dipping reef is modelled as drawn. Several reefs in one model are fine.
- **No contact, no backfill** (§18.6).
- **Kelvin only** — there is no free surface for DD elements.
- **Stored energy on the walls** (Chapter 16) covers FF walls only.
- **Do not let a reef cut through an excavation solid.** A seam running through a void means nothing, and neither do the numbers it produces.
- Linear-elastic, dry and static, with one material (Chapter 20).

Theory and Verification, Chapter 6, gives the formula, Chapter 8 the checks, and Appendix C works one element through by hand.

Part 5 — Reference

19. Automating a run (macros)

A **macro** records a sequence of GEM4D operations and replays it later. A BEM analysis you run by hand can be captured once and re-run with one click, on the same inputs or on different ones.

- Macros are **deterministic**: a replay reproduces the original result exactly.
- They run entirely **offline**, with no network or AI calls.
- They are stored as **readable JSON** files that you can open and edit in a text editor.

19.1 What is recorded

Recording covers the analysis steps of the BEM and Flow modules — the expensive, repeatable work where automation pays.

Recorded step	Captured from	Replays as
Load geometry	Any mesh or CAD file you load	Re-imports that file. A Deswik `.duf` also records the grouping and attribute you chose.
Set material	BEM **Inputs → OK**	The same E and v
Set field stress	BEM **Inputs → OK**	The same in-situ stress, kernel and ground surface Z. Measured principal stresses record as *SetMeasuredFieldStress*, which GEM4D versions from before them refuse as an unknown step. Directions that cannot be squared up stop the replay with the dialog's message.
Run BEM	**Run model**	Builds a single model from the visible meshes and solves it (§19.4)
Export results	**Save model**	Writes the `.bem4d` to the recorded path
Run Flow	Flow **Run flow model**	Re-runs the flow model; mesh roles are matched to the visible meshes by name
Save Flow / **Load Flow**	Flow **Save flow** / **Load flow**	Writes or reads the `.flow4d` at the recorded path
Export Flow dilution	Flow **Dilution CSV**	Writes the dilution CSV to the recorded path
Flow cells to Markers	Flow **Cells to Markers**	Rebuilds the Marker object from the flow cells

Camera moves, picking and display changes are **not** recorded: a macro captures the analysis, not the navigation.

19.2 The Macros tab

Group	Button	What it does
Record	**Record**	Starts recording. The status shows ● *Recording — N step(s)* and counts up as you work.
Record	**Stop**	Stops recording and keeps the macro in memory.
Macro	**Play…**	Runs the current macro — the one just recorded, or one you loaded.
Macro	**Save…**	Saves the macro as a `*.gem4dmacro.json` file.
Macro	**Load…**	Loads a macro file, asking for any parameters (§19.5).

19.3 Recording and replaying a BEM run

To record:

1. Click **Record**.
2. Run the analysis as usual: load the meshes, set the inputs (**Inputs → OK**), **Add FF and DD objects**, **Run model**, **Save model**.
3. Click **Stop**.
4. Click **Save…** and name the macro. Macros are saved by default in `%AppData%\BasRock\GEM4D\Macros`.

To replay:

1. Click **Load…** and choose the macro (or use the one you just recorded).
2. Click **Play…**. GEM4D asks how to handle errors: **Yes** stops at the first error; **No** carries on and lists the failures at the end; **Cancel** aborts.
3. A progress dialog shows the current step. Its **Cancel** button stops the run cleanly, even part-way through a solve.
4. At the end GEM4D reports success, or lists which steps failed and why.

Because the solve is deterministic, a replay reproduces the original solution. You can check this by comparing the re-saved `.bem4d` with the original.

19.4 What Run BEM reproduces

A recorded **Run BEM** step builds a **single** model from **all visible meshes**, then solves it.

- It does **not** reproduce a subset you ticked in the mesh table, or a mining sequence. For sequences, run the steps by hand.
- It does reproduce **DD rows**: it records each DD mesh's name and mining width, and the DD element size. A DD mesh must be visible when the macro is replayed. A Mindlin kernel with DD rows is refused.
- A macro without DD information replays every mesh as FF.

19.5 Parameters

A macro can carry **named parameters**, so that one file drives many runs — for example on a different mesh or stress value each time.

In the JSON, a parameter is written as `${name}`; for example a Load step's path might read `"${meshPath}"`. Parameters are added by editing the JSON by hand: a `Parameters` list, plus `${…}` tokens in the steps.

When you **Load…** a macro with parameters, GEM4D asks for each value, offering any default. A parameter left without a value is reported before the run starts.

19.6 What a macro file holds

- The **GEM4D version** that recorded it and a **schema version**, for traceability.
- Plain, indented JSON — easy to read and to compare.

20. Assumptions and limitations

The BEM module calculates where stress **would** concentrate if the rock stayed elastic. Interpreting over-stress, yield and support is the engineer's job. Be aware of what the module does **not** model:

- **One elastic material.** The rock is linear-elastic, homogeneous and isotropic: one E and one v everywhere. There is no plasticity, no softer or stiffer zones, and no backfill stiffness.
- **No discontinuities.** Joints and faults are not modelled as surfaces that can slip. ESS (Chapter 15) tells you where a plane *would* slip; it does not let it slip.
- **Independent steps.** Each mining step is an elastic snapshot. This is exact for an elastic model, but nothing carries over between steps — no fault slip, no fill, no damage. As a result the **total** released energy is fixed by the final shape (§17.5).
- **No yield criterion or factor of safety.** The only strength-based output is the RCF screen (Chapter 14). Compare σ1 and σ3 with your strength criterion yourself.
- **Dry and static.** No pore pressure, and no dynamic or seismic loading.
- **Constant-strength elements.** Values within about one element of a wall are less accurate than deeper in the rock, most of all near sharp edges (§13.6), and a thin stope needs elements no

larger than its thickness (§6.6). For the wall stress of a drive, use the Kirsch option (Chapter 14). Element size matters more than triangle shape: elongated triangles add a smaller error, and extreme slivers can stall the solve (§7.8; *Theory and Verification* §8.2).

- **DD reefs** need the Kelvin kernel and have **no contact**: where closure reaches the mining width, the released energy is overstated. This is reported (the touchdown count), never clamped (Chapter 18).
- **In-situ stress** changes with depth only, and linearly — not across the model and not along a curve with depth. Measured principal stresses may have any orientation, each with its own constant and gradient (§5.3), but their directions do not change with depth, and a full stress tensor cannot be typed in yet.

21. Troubleshooting

Find the stage where the problem appears, then the message or symptom.

21.1 Setup and building the model

Message or symptom	Cause and fix
Status shows *"No model — run Setup first"*; buttons greyed	The buttons enable in order: **Inputs** → **Add FF and DD objects** → **Run model** → **Map**.
"The half-space (Mindlin) kernel treats Z = … as the traction-free ground surface. N selected meshes extend above it and cannot be loaded"	A mesh reaches above the ground surface Z. Move, untick or trim it, or raise the ground surface Z. On uneven ground, use Kelvin with Gravitational stress instead (§7.6).
"The in-situ stress is computed from depth below the surface datum Z = …"	A mesh reaches above the ground surface Z. Fix it as above, or click **Proceed anyway** if the surface is a representative average (§7.6).
"Invalid input: Rows 1 and 3 are … from perpendicular" at **OK**	Two measured directions are more than 10° from perpendicular. Check the trends and plunges against the report — a typing slip or a dip/dip-direction pair read as trend/plunge is the usual cause (§5.3).
"Invalid input: 'Proportional to depth' needs the measurement below the ground-surface RL"	The measurement RL lies above the ground surface Z. Correct the RL or the ground surface Z, or choose another **Change with depth** (§5.3).
An older GEM4D cannot open a `.bemset` or `.bem4d`	It was saved with measured principal stresses, which that version does not have (§5.6). Open it in the current version.
"BEM already contains N elements… Replace…?"	Normal. **Add FF and DD objects** always builds a new model with the current Setup.
"No triangles found in the selected mesh objects."	No ticked mesh contains triangles. Tick the excavation meshes.
"Invalid step entry: …", *"Fix the Mined-at column for: …"*, *"Step assignment problem: …"*	A step cell cannot be read, or the steps are not continuous from 1. Fix the named rows; the table stays open (§8.2, §8.4).
"Model quality: too many defects (red)", or a step line ending *"quality: too many defects"*	Walls that cross, or a surface that is in the model twice. Read the notes, fix the meshes they name, and build again (§7.8, §8.6).
"DD surfaces need the Kelvin (infinite-domain) kernel…"	Change the Setup kernel to Kelvin, or set the named rows to FF (§7.3).
"Enter a mining width (m) for each DD surface…"	Type a Width for each DD row (§7.3).
"DD surface "…" has no usable triangles" / *"… has no fittable plane"*	The surface has no area, or all its points lie on a line.

Message or symptom	Cause and fix
"no roof sheet …" / "no floor sheet …"	A "thin solid" without a roof or floor — usually an open sheet flagged as closed. Check its **Shape**.
"Every DD element was covered by an earlier surface in every step — nothing new to mine."	An earlier surface already covers this one in all its steps.
The quality grade and notes in the summary	See §7.8.
DD preparation notes in the summary	See §21.7.
After the build only **one** object shows in orange	You built a sequence, and the scene shows step 1. Use **Next** to see the later steps (Chapter 12).
Out-of-date Setup warning at **Run model** or a **Map** button	Setup changed after the build. Click **Add FF and DD objects** again (§7.9).
Results look rotated by about 90°	Check **Trend of σH** — it is in degrees clockwise from North, for the **major** horizontal stress — and check that kH and kh are not swapped.

21.2 Solving

Message or symptom	Cause and fix
"Add at least one excavation before solving."	The model is empty. Click **Add FF and DD objects**.
A solve takes **far** longer than expected — tens of minutes on a few thousand elements	The Intel MKL files may be missing from the installation; GEM4D warns about this at the first solve of a session. The direct method then runs about 100 times slower. Reinstall, or contact BasRock. The `BEM linear algebra:` line in `GEM4D_diag.log` should read **Intel MKL**; if not, it names the missing file.
The **same** model solves much more slowly than before	The iterative method's speed depends on the RAM free when you click **Run model**. Other programs, a large scene or an earlier solution all reduce it. Each step writes one line to `GEM4D_diag.log` with its memory settings and the free RAM it saw — compare a fast run with a slow one. Closing other programs, or a fresh GEM4D session, is the quickest test.
The status shows *"GPU not used · CPU"* or *"GPU failed · CPU"*	The GPU could not be used for this solve, so it ran on the processor — correctly, but more slowly. The `BEM GPU:` line and the step's `GPU not used (…)` / `GPU failed (…)` line in `GEM4D_diag.log` give the reason; an out-of-date graphics driver is the usual one. Update the driver, or clear **Use the GPU of this computer** in Setup (§5.4). *self-check failed* means the GPU's sums disagreed with the processor's the first time it was used; GEM4D then keeps that kind of calculation on the processor until it is restarted — everything when the check of full-space (Kelvin) sums failed, only half-space or DD solves when the check of their sums did, and only their maps and energy when the check of their field sums did — so update the driver. *not enough RAM for its near pairs* means the computer ran short of memory; close other programs and solve again.

Message or symptom	Cause and fix
A warning *"BEM — GPU not used (ran on the processor)"* after a solve, a map or an energy calculation	The GPU was allowed (§5.4) but could not be used, so that part ran on the processor. The results are correct; it only took longer. The warning names the reason and what usually helps: an out-of-date graphics driver (*self-check failed*, *GPU failed*), too little free RAM, a model too large for the GPU's memory, or a model too thin for the GPU's single precision (*did not reach the tolerance*). It appears once per session for each kind of reason; every case is in `GEM4D_diag.log`. A computer without a GPU, or the box cleared in Setup, gives no warning: the processor is then the normal path.
The status shows *"GPU tolerance not met · CPU"*	The GPU calculates in single precision. On openings much thinner than their elements it can fail to reach even the **Standard** tolerance. Each such step is solved again on the processor. The results are correct, but the time spent on the GPU is lost. For such a model, try the **Coarse** tolerance, which may stay on the GPU; or clear **Use the GPU of this computer** in Setup so that no GPU time is lost.
A model solves **more slowly** after it worked on the GPU before	Check the box in Setup (§5.4): a box cleared earlier in this session stays clear until GEM4D is closed. After each step solved by the iterative method, `GEM4D_diag.log` has a line ending in *"solved: far field on the GPU (…)"* when the GPU was used, or *"solved: far field on the processor (H-matrix)"* and the reason when it was not — *GPU off (BEM Setup)* when the box is cleared. The step's line before the solve names only what the step will try.
The status after a solve ends in *"· low RAM"*	At least one step had less free RAM than it needs outside the solver's cache plus the 2 GB minimum cache, so Windows may have moved memory to disk and the solve ran slowly. Its line in `GEM4D_diag.log` says **LOW RAM**. The results are still correct. Close other programs and solve again, or use a computer with more RAM for a model this size.
Solve seems stuck on *"GMRES 184 · r/b 8.31E-05"*, with the second figure falling slowly	Normal for large models. If it barely moves for a long time, try the **Coarse** tolerance for scoping, or check the mesh for slivers (§7.8).
"GMRES did not converge after N iterations"	Almost always the geometry: walls that cross, or surfaces that are in the model twice. Read the quality notes (§7.8), fix the flagged meshes and solve again.
"Stopped — model kept, press Run model"	You clicked **Stop** during a solve. The meshes, steps and Setup are kept; the solution is discarded. Click **Run model** (§9.5).
"A BEM calculation is still running."	Wait for it, or end it with **Stop** (keeps the model) or **Clear** (deletes it).
GEM4D **disappears**, with no error, during **Remesh for BEM analysis**, **Remesh and smooth** or **Reduce polygon count**	A fault inside a library, which `GEM4D_crash.log` cannot catch. These tools write their progress to `%LOCALAPPDATA%\GEM4D\GEM4D_diag.log`, so the last line shows where it stopped. Send that file, the Windows Event Viewer *Application Error* / *.NET Runtime* entries and the mesh to BasRock.

21.3 Mapping

Message or symptom	Cause and fix
"This will evaluate N field points, which may take several minutes."	More than 1 000 000 evaluations. Coarsen the grid, use a larger finest cell or a smaller band for the octree, or filter the BEMResult table to the rows you need. On a sequence the count is points × steps (§10.1).
"More than 5,000,000 points …" in the octree dialog	The settings would give more points than GEM4D maps at once. Use a larger finest or coarsest cell, less padding or a smaller band (§10.3).
"Load BEM datagrid data first." / *"No visible BEM datagrid rows."*	**Map to datagrid** needs points in the BEMResult table, and at least one row passing the filters (§10.4).
"BEM datagrid row count changed during evaluation."	The table was edited during the run. Map again.
Kirsch or ESS columns missing	The table has no Dip and DipDir columns. GEM4D says so and leaves those columns out (§15.2).
Iso-surface has a ragged hole at the excavation	That is the default for points inside excavations. For a closed surface, tick **Iso-surface treats interior as in-situ** in Setup and map again (§13.4).
The progress of a map drops back, then climbs more slowly	The GPU failed partway through the map, so GEM4D calculates it again on the processor from the start — to 0, or on a mining sequence back to the start of the step it was on. The results are correct. The reason is in `GEM4D_diag.log`, and in a warning the first time it happens in a session (§21.2).

21.4 Energy

Message or symptom	Cause and fix
Energy dropdown greyed	The energy outputs need a solved or reloaded model. Click **Run model** first.
"Some mining steps are not solved…"	Each step is measured against the one before, so every step must be solved. Solve the sequence again (§17.2).
"No newly created excavation surface was found, so no energy was released."	This step's shape is the same as the step before. Normal for a repeated as-mined snapshot; check the Steps column.
A large **NearZeroTraction** count	Not an error. The step mostly re-covered existing wall (§17.6).
ΔW negative, or implausibly small	A negative ΔW points to a defective mesh: check the quality notes for mixed normals, crossing walls and duplicated surfaces (§7.8). A small ΔW is often correct, for a step that mostly re-meshes existing wall.
A non-zero **Touchdown** count	Those DD elements closed by their full width; the released energy there is overstated. Treat the run as an upper bound (§18.6).

21.5 Stepping through a sequence

Message or symptom	Cause and fix
Mining steps group greyed	It needs a sequence with more than one step. If every mesh is at step 1, the model is a single state.

Message or symptom	Cause and fix
"Grid columns are from an older solve"	The per-step columns came from an earlier solve. Run **Map to datagrid** again (§12.3).
"Column … not found"	The per-step column was deleted. Run **Map to datagrid** again.
"N member meshes missing from the scene"	A sequence was loaded without its meshes. The overlay still steps (§9.6).
"Member meshes hidden — overlay only"	You have hidden all of this step's meshes. Show them in the Mesh panel to see them step (§12.2).
"Mesh colours stale — press Update" / *"Iso rebuilt · colours stale, press Update"*	Expected: **Colour meshes** does not follow the steps. Click **Update** on the BEMResult panel (§12.2).

21.6 Macros

Message or symptom	Cause and fix
"No macro loaded — use Load… (or Record then Stop) first."	Record a run and click **Stop**, or **Load…** a macro file.
A replayed result differs from the original	**Run BEM** rebuilds one model from **all visible meshes**. Load the same meshes and make them visible. A ticked subset or a sequence is not reproduced (§19.4).
"Missing value for macro parameter(s): …"	Give a value when asked, or add a default in the file (§19.5).

21.7 DD preparation notes

These notes appear in the completion summary, under **For information**, when the model has DD rows. They are advisories with counts only; the detail for each row is in `GEM4D_diag.log`.

Note	What it means	What to do
"… DD element placements skipped where an earlier surface already covers the reef in that step"	Ground already mined in that step was drawn again. Each element is mined once; an element counts as covered only when the earlier surface passes through it.	Nothing.
"… coincident DD triangles dropped (a surface's second sheet)"	A two-sided export: the second copy of each triangle was removed.	Nothing.
"… DD triangles could not join the surface mesh (a third face on an edge) — kept as loose elements"	A third triangle on one edge. It is kept as its own element.	Nothing, unless the count is large — then clean the surface.
"… faces shared by two glued blocks removed before the mid-surface"	Two closed blocks share a wall, which lies inside the reef.	Nothing.
"… mid-surface DD elements dropped where a surface's own sheets overlap"	Blocks drawn over the same ground. The smaller sheet's elements there were dropped.	Check the blocks if the count is large.

Note	What it means	What to do
"… mid-surface rim vertices moved to close gaps under 1 m between its pieces"	Sub-blocks at slightly different levels. Gaps under 1 m were closed so the reef is covered; wider gaps (real pillars) stay. A trailing *"… left where the move would fold an element"* counts refused moves.	Nothing.
"… zero-area DD triangles dropped"	Triangles with no area.	Nothing.
"… sliver DD triangles dropped (thinner than 1 % of the element size …)"	Needle-thin triangles left by the refinement, which would make the solve fail. A few dozen per few thousand elements is normal.	Nothing.
"… mid-surface DD elements took the row width (roof/floor cast missed)"	The roof-to-floor gap could not be measured there, so the row's Width was used.	Check the row's Width.
"… DD surfaces used as-is with more than 200,000 triangles — decimate with Toolbox 1 → Reduce polygon count if unintended"	A very fine surface is used as it is; GEM4D never coarsens a surface for you.	Reduce it if you meant it to be coarser.
"DD edges up to X m remain (target Y m) — a rim the remesher could not refine"	Part of the outline stayed coarser than the DD element size.	Usually fine. Refine the source if the coarse edge is in your area of interest.
"… DD rows skipped — no mesh data on the actor: …"	The named mesh has no geometry.	Reload the mesh.

22. Output column dictionary

Every column the BEM module writes. *Opt-in* columns appear only when their checkbox is ticked (§10.1). In the BEMResult table each header is shown with a number in front (for example `7_BEM_S1_MPa`): its position in the colour-column list.

22.1 Map to Grid and Map to Octree — single model

Order as written: `X_m, Y_m, Z_m, S1_MPa, S2_MPa, S3_MPa [, U_mm] [, ESS_Coulomb_MPa] [, SED_kJm3] [, Sxx_MPa … Sxz_MPa], Status, DistToSurface_m [, CellSize_m] [, D_over_L]`.

Column	Unit	Opt-in	Meaning	See
`X_m`, `Y_m`, `Z_m`	m		Point position, mine coordinates	
`S1_MPa`, `S2_MPa`, `S3_MPa`	MPa		Total principal stresses, compression positive	13
`U_mm`	mm	ticked by default	Size of the induced displacement	13
`ESS_Coulomb_MPa`	MPa	✓	Orientation-free excess shear stress	15
`SED_kJm3`	kJ/m³	✓	Stored strain-energy density	16
`Sxx_MPa`, `Syy_MPa`, `Szz_MPa`, `Sxy_MPa`, `Syz_MPa`, `Sxz_MPa`	MPa	✓	Total stress tensor; x = East, y = North, z = up	13
`Status`	—		`Far`, `NearSurface` or `Interior`	13

Column	Unit	Opt-in	Meaning	See
DistToSurface_m	m		Distance to the nearest wall; negative inside	13
CellSize_m	m	octree only	Size of the octree cell the point is the centre of	10.3
D_over_L	—	✓	Distance to the nearest element over that element's longest edge	13.6

Default file names: BEM_FieldPoints.csv (grid), BEM_OctreePoints.csv (octree).

22.2 Map to Grid and Map to Octree — sequence

Combined file: X_m, Y_m, Z_m, then for each step k: S1_s{k}_MPa, S2_s{k}_MPa, S3_s{k}_MPa [, U_s{k}_mm] [, ESS_Coul_s{k}_MPa] [, SED_s{k}_kJm3], St_s{k} [, D_over_L_s{k}], and for an octree one CellSize_m column after the last step. St_s{k} is that step's Status. The tensor is not in this file.

Per-step files (<name>_s{k}.csv, when *Write per-step full CSVs* is ticked): the single-model layout of §22.1, for one step each, including the tensor if ticked.

22.3 Map to datagrid — single model

Added to the BEMResult table in this order:

Column	Unit	Opt-in	Meaning	See
BEM_S1_MPa, BEM_S2_MPa, BEM_S3_MPa	MPa		Total principal stresses	13
BEM_U_mm	mm	ticked by default	Size of the induced displacement	13
BEM_Ux_mm, BEM_Uy_mm, BEM_Uz_mm	mm	✓	Induced displacement along East, North, up	13.2
BEM_Sxx_MPa … BEM_Sxz_MPa	MPa	✓	Total stress tensor	13
BEM_SigMax_MPa, BEM_SigMin_MPa	MPa	✓ Kirsch	Largest and smallest stress across the drive's section	14
BEM_Tang_MPa	MPa	✓ Kirsch	Kirsch wall stress, 3 × SigMax − SigMin	14
BEM_RCF	—	✓ Kirsch	Rockwall Condition Factor — a live calculated column	14
F_Factor, UCS_MPa	—, MPa	✓ Kirsch	Editable RCF inputs; kept when you map again	14
BEM_ESS_MPa	MPa	✓ ESS	Plane-specific excess shear stress	15
BEM_SigN_MPa, BEM_Tau_MPa	MPa	✓ ESS	Normal and shear stress on the plane	15
BEM_SlipPl_deg, BEM_SlipAz_deg	°	✓ ESS	Plunge and azimuth of the slip direction	15
BEM_ESS_Band	—	✓ ESS	Stable, Low, Moderate or High	15
BEM_SED_kJm3	kJ/m³	✓	Stored strain-energy density	16
BEM_Status	—		Far, NearSurface or Interior	13
BEM_D_over_L	—	✓	Distance to the nearest element over that element's longest edge	13.6

22.4 Map to datagrid — sequence

For each step k: `BEM_S1_s{k}_MPa, BEM_S2_s{k}_MPa, BEM_S3_s{k}_MPa [, BEM_U_s{k}_mm] [, BEM_Sxx_s{k}_MPa … BEM_Sxz_s{k}_MPa] [, BEM_Tang_s{k}_MPa, BEM_RCF_s{k}] [, BEM_ESS_s{k}_MPa] [, BEM_SED_s{k}_kJm3], BEM_St_s{k} [, BEM_D_over_L_s{k}]`. One `F_Factor` / `UCS_MPa` pair, after the step blocks, serves every step. Displacement components are not available on a sequence.

Per-step files (`BEM_DatagridPoints_s{k}.csv`, when *Write per-step full CSVs* is ticked): `X_m, Y_m, Z_m` and the single-model block of §22.3 for one step — with `BEM_RCF, F_Factor, UCS_MPa` as fixed values, not live columns.

22.5 Energy outputs

File	Columns	See
`BEM_StoredEnergy_kJm3.csv` (`…_s{k}.csv` per step)	`X_m, Y_m, Z_m, SED_kJm3` — one row per FF wall element	16
`BEM_ReleasedEnergy_kJm2.csv` (`…_s{k}.csv` per step)	`X_m, Y_m, Z_m, w_kJm2` — one row per new wall element; w = release density, kJ/m²	17
`BEM_ReleasedEnergy_Summary.csv`	`Step, NewElements, ExcludedInterior, NearZeroTraction, A_new_m2, dV_m3, dW_MJ, cumW_MJ, dW_per_V_kJm3, dW_per_A_kJm2`	17.2
`BEM_TabularPanels.csv` (`…_s{k}.csv` per step)	`X_m, Y_m, Z_m, Closure_mm, RideS_mm, RideT_mm, tN_MPa, w_kJm2, Width_m` — one row per DD element	18.3
`BEM_TabularPanels_Summary.csv`	`Step, Panels, CarriedOver, Touchdown, A_reef_m2, A_plan_m2, V_mined_m3, dW_MJ, cumW_MJ, ERR_MJm2, ERR_plan_MJm2`	18.3

22.6 Mapping objects

File	Columns	See
`BEM_Sigma1_Arrows.csv` (`…_s{k}.csv` per step)	`X, Y, Z, Dip, DipDir, Size, S1_MPa` — Dip and DipDir are σ1's plunge and trend	10.5
`BEM_ESS_CriticalPlanes.csv` (`…_s{k}.csv` per step)	`X, Y, Z, Dip, DipDir, Size, ESS_MPa` — two rows per point, one per critical plane	10.5

23. Glossary

Term	Meaning
ACA	Adaptive cross approximation — the compression the iterative solver applies to the interactions between distant groups of elements.
Additive mining	The step mode in which each mesh has one step, the step at which it is mined (§8.2).
As-mined snapshots	The step mode in which each mesh lists the steps it belongs to (§8.4).
Back-fill	The Setup option that writes the in-situ stress, rather than blanks, at points inside excavations (§13.4).

Term	Meaning
BEM	Boundary Element Method: a stress analysis that divides only the excavation surfaces into elements (§3.2).
BEMResult table	The data table in the left panel when the BEM tab is selected; the ribbon calls it the *datagrid*.
Closure	How far the two sides of a reef move towards each other (Chapter 18).
Collocation point	The point on each element where the solver makes the boundary condition hold.
Coulomb ESS	The largest excess shear stress over all plane orientations at a point (Chapter 15).
DD	Displacement discontinuity: an element type for a reef or seam, a surface the rock on either side can close across (§3.3).
Element	One triangle of the BEM model.
ERR	Energy release rate: released energy per unit area of reef mined (Chapters 17–18).
ESS	Excess shear stress: the shear stress on a plane minus the friction resisting it (Chapter 15).
FF	Fictitious force: the element type for closed excavation solids (§3.3).
GMRES	The iterative method used for models above 6 700 elements (§9.2).
H-matrix	The compressed form in which the iterative solver stores the model's interactions (*Theory and Verification* Chapter 5).
In-situ stress	The stress in the ground before mining (§3.1).
Induced	Caused by mining — the change from the in-situ state. Displacements are always induced.
Interior	A point inside an excavation, where there is no rock (§13.3).
Iso-surface	A 3D contour surface through all points with a given value (§11.4).
Kelvin	The kernel for rock that extends to infinity in all directions — deep workings (§3.4).
Kernel	The elasticity solution the elements are built from: Kelvin or Mindlin (§3.4).
kH, kh	The major and minor horizontal stresses as ratios of the vertical stress (§5.3).
LU	The direct method used for models up to 6 700 elements (§9.2).
Matrix-free	Recalculated at every iteration instead of stored — slower, but uses no memory (§5.4).
Mesh table	The table that **Add FF and DD objects** opens (Chapter 7).
Mid-surface	The surface halfway between the roof and floor of a thin solid; it becomes the DD reef (§7.5).
Mindlin	The kernel for rock with a load-free ground surface — shallow workings (§3.4).
Minode	A point generated along development, whose Dip and DipDir give the drive's direction (Chapter 14).
Non-manifold edge	An edge shared by three or more triangles, as at an internal wall (§7.8).
Octree	An adaptive grid: dense near the excavations, coarse far away (§10.3).
RCF	Rockwall Condition Factor: wall stress over downrated rock strength (Chapter 14).
Ride	Movement along a reef, as opposed to closure across it (Chapter 18).
SED	Stored strain-energy density: elastic energy per cubic metre of rock (Chapter 16).
Sliver	A needle-thin triangle (§7.8).
Step	One stage of a mining sequence (Chapter 8).
Touchdown	A DD element that has closed by its full mining width (§18.6).

Term	Meaning
Watertight	Closed, with no holes or loose edges (§7.8).

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