



GEM4D DOCUMENTATION

BEM Stress Analysis

User Guide

PRODUCT	GEM4D
DOCUMENT	BEM Stress Analysis — User Guide
VERSION	1.9.1.4
DATE	6 October 2026

Contents

Part 1 — Getting started	4
1. What the BEM module does	4
2. Quick start: your first model	5
Step 1 — Enter the inputs	5
Step 2 — Build the model	6
Step 3 — Solve	6
Step 4 — Calculate the stresses around the excavation	6
Step 5 — Display the results	6
3. Key concepts	7
3.1 In-situ stress and induced stress	7
3.2 How the BEM models an excavation	8
3.3 Two kinds of element: FF and DD	8
3.4 Two kernels: Kelvin and Mindlin	8
3.5 Conventions	8
3.6 Words used in this guide	9
Part 2 — Building and solving a model	9
4. The BEM ribbon tab	9
5. Setup (Inputs)	10
5.1 Coordinate System	11
5.2 Rock Properties	12
5.3 In-Situ Stress	12
5.4 Kernel & solver	12
5.5 Field-point handling	13
5.6 Buttons, and saving a setup	13
6. Adding meshes (Add FF and DD objects)	14
6.1 The mesh table	14
6.2 Choosing the Type: FF or DD	14
6.3 DD rows: Width and element size	15
6.4 Mining steps	15
6.5 What GEM4D does to your triangles	15
6.6 Checks when you build	15
6.7 The completion summary	16
6.8 After you change the Setup	16
6.9 What the table remembers	17
7. Preparing meshes for BEM	17
7.1 What a good BEM mesh looks like	17
7.2 The Mesh-quality notes	17
7.3 The repair tools	18
7.4 Choosing the element size	19
7.5 Checking the result	19
8. Running, stopping and saving	19
8.1 Run model	19
8.2 Which method runs	20
8.3 Reading the status area	20
8.4 How long will it take?	20
8.5 Stop and Clear	20
8.6 Saving and reloading a solved model	21
9. Mining sequences	21
9.1 How a sequence works	21
9.2 Additive mining (the default)	21
9.3 As-mined snapshots	22

9.4 Checks in both modes	22
9.5 Solving a sequence.....	22
9.6 Mapping a sequence.....	22
9.7 Saving and reloading a sequence.....	22
Part 3 — Getting and viewing results.....	23
10. Mapping results.....	23
10.1 Choosing what to calculate	23
10.2 Map to Grid	24
10.3 Map to Octree	24
10.4 Map to datagrid	24
10.5 σ_1 arrows and critical-plane discs.....	24
10.6 Mapping a sequence.....	25
11. The BEMResult panel	25
11.1 Loading data	25
11.2 Points	26
11.3 Colours.....	26
11.4 Iso-surfaces and mesh colouring	26
11.5 Scalar bar and legend.....	27
11.6 The histogram	28
11.7 BEM filters.....	28
12. Stepping through a sequence.....	28
12.1 The controls	28
12.2 What changes at each step	29
12.3 Colouring the steps	29
12.4 Picking up a session later	29
Part 4 — Interpreting results.....	30
13. Stress, displacement and the Status column.....	30
13.1 What the columns are	30
13.2 Displacement components.....	30
13.3 The Status column.....	30
13.4 Points inside excavations.....	31
13.5 Reading stress results	31
14. Kirsch tangential stress and RCF	31
14.1 What it measures	31
14.2 How to get it.....	31
14.3 The columns	32
14.4 Reading the wall stress.....	32
14.5 Reading the RCF	32
14.6 Setting F and UCS by area	32
14.7 Points to note.....	32
15. Excess shear stress (ESS)	33
15.1 What it measures	33
15.2 Two kinds of ESS.....	33
15.3 The parameters.....	33
15.4 Checking a fault: plane-specific ESS	34
15.5 Mapping the hazard volume: Coulomb ESS	34
15.6 Limits.....	35
16. Stored energy	35
16.1 What it measures	35
16.2 Which energy output do you need?	35
16.3 On the walls: Energy ► Stored on surfaces.....	35
16.4 Through the rock: the SED checkbox	36
16.5 Reading it.....	36

16.6 Limits.....	36
17. Released energy.....	36
17.1 What it measures.....	36
17.2 How to get it.....	36
17.3 Two normalisations.....	37
17.4 Comparing with published ERR.....	37
17.5 What a sequence can and cannot show.....	37
17.6 As-mined bookkeeping.....	37
17.7 Limits.....	38
18. Tabular reefs (DD).....	38
18.1 When to use DD.....	38
18.2 Building a reef model.....	38
18.3 The results.....	38
18.4 Which area to use for ERR.....	39
18.5 Choosing the element size.....	39
18.6 The touchdown advisory.....	40
18.7 Limits.....	40
Part 5 — Reference.....	40
19. Assumptions and limitations.....	40
20. Troubleshooting.....	41
20.1 Setup and building the model.....	41
20.2 Solving.....	42
20.3 Mapping.....	42
20.4 Energy.....	43
20.5 Stepping through a sequence.....	43
20.6 Mesh-quality notes.....	43
20.7 DD preparation notes.....	43
21. Output column dictionary.....	44
21.1 Map to Grid and Map to Octree — single model.....	44
21.2 Map to Grid and Map to Octree — sequence.....	45
21.3 Map to datagrid — single model.....	45
21.4 Map to datagrid — sequence.....	46
21.5 Energy outputs.....	46
21.6 Mapping objects.....	46
22. Glossary.....	46
23. References.....	48

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.

Results changed in this edition — re-run older models. GEM4D 1.9.1.3 uses version 1.2.1.0 of the BasRock BEM library. Results computed with earlier versions are superseded. Every fictitious-force (FF) model moves: by about 1 % or less on bulky stopes, and by several percent on thin ones. The per-element energy maps, Mindlin (half-space) models and iterative solves above 6 700 elements moved more. *Theory and Verification*, Chapter 8, lists what changed and by how much.

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 σ_1 , σ_2 and σ_3 (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 distress? (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.

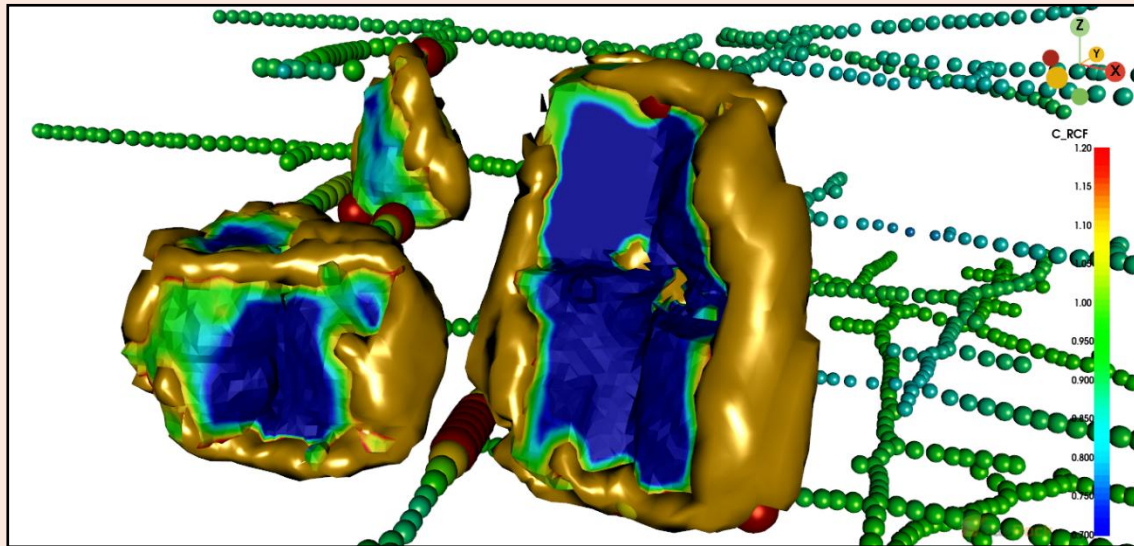


Figure 1: The Major Principal Stress (σ_1) was used to colour the stopes and create the iso-surfaces, and the development is represented by Minodes coloured and scaled on the Rockmass Condition Factor (RCF).

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, $\nu = 0.25$).
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 (k_H , k_h) 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. It opens with *"Added N FF triangles to the BEM model. Ready to solve."* Any **Mesh-quality notes** below that line are usually fine for a first run; Chapter 7 explains them.

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.

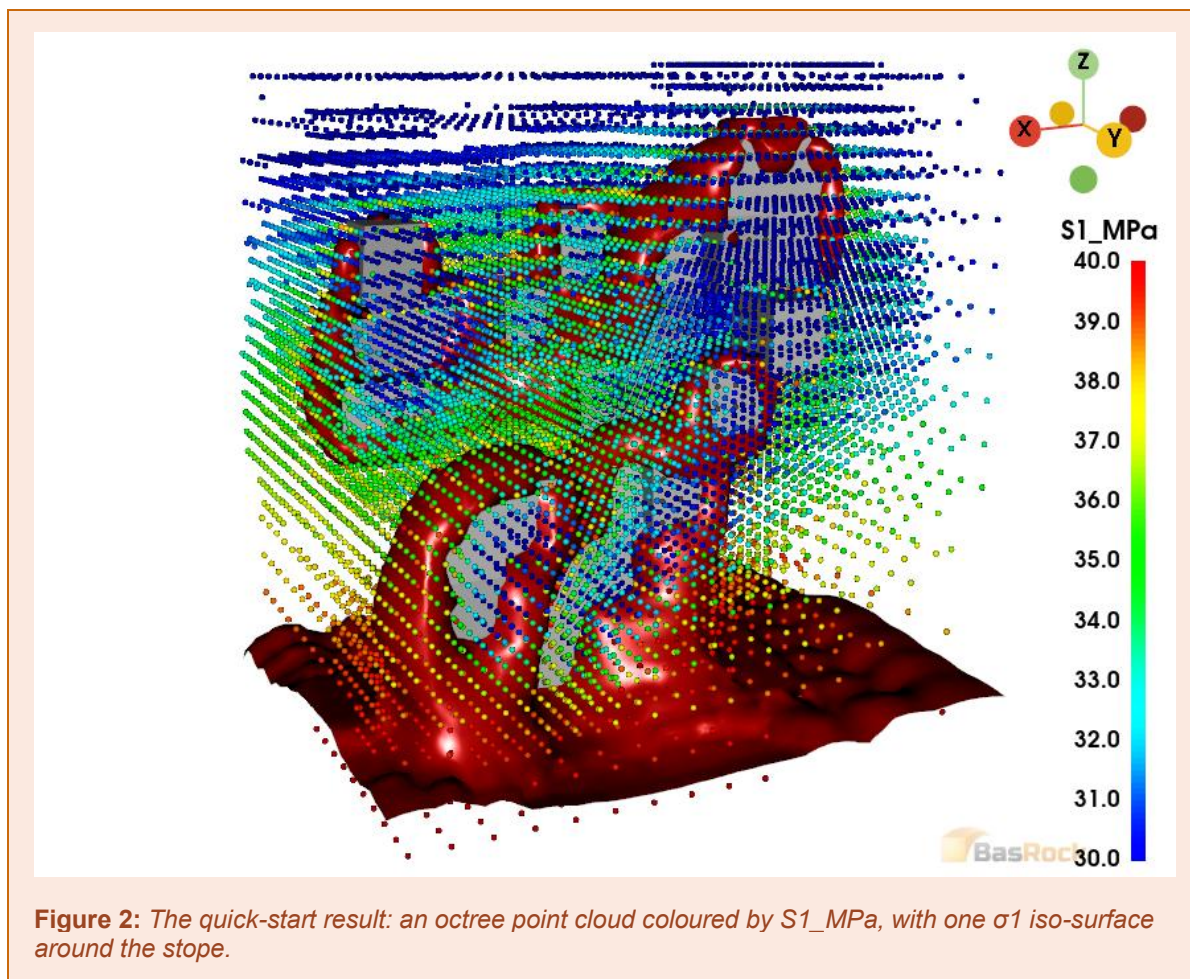
Step 4 — Calculate the stresses around the excavation

1. Click **Map to Octree**.
2. Keep the refinement depth at **5** and click **OK**.
3. The *Map BEM results* 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 σ_1 .
3. Under *Iso-surface and Colour mapping*, tick **Iso-surface** and enter a stress value. A 3D contour shell appears at that value of σ_1 .



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 9).
- 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: $kH = \sigma_H/\sigma_v$ for the major horizontal direction, and $kh = \sigma_h/\sigma_v$ 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 6 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 $\sigma_1 \geq \sigma_2 \geq \sigma_3$. So σ_1 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 <i>BEM — Model from Meshes</i>). 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 <i>datagrid</i> (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

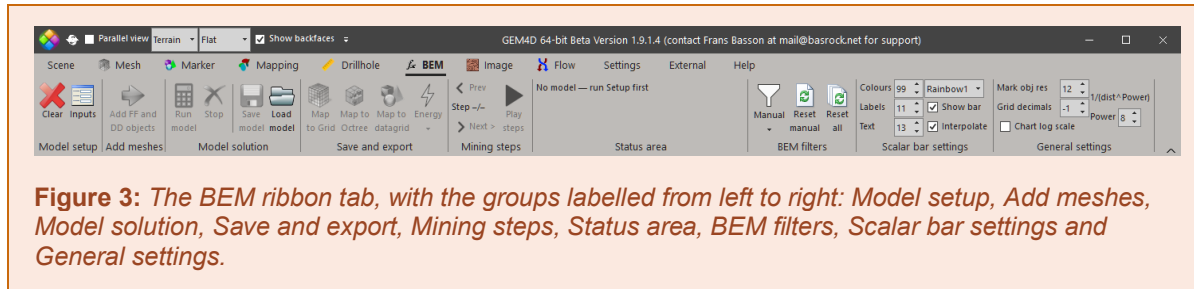
4. The BEM ribbon tab

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.	8
Add 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.	6, 9
Model solution	Run model	Solves the model in the background. A sequence is solved one step at a time.	8
Model solution	Stop	Ends the running task and keeps the model.	8
Model solution	Save model / Load model	Saves or reloads a solved model as a .bem4d file. Reloading skips the solve.	8
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	<i>(read only)</i>	Shows what is running and how far it has got.	8
BEM filters	<i>(several)</i>	Filters the rows of the BEMResult table.	11
Scalar bar settings, General settings	<i>(several)</i>	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.



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 (§6.8).

BEM Analysis — Setup

Coordinate System
Ground surface Z (mine RL, m): 1400 ☐ Show plane

Rock Properties
Young's modulus E (GPa): 70.0
Poisson's ratio v: 0.25

In-Situ Stress
☐ Uniform (specify σ_v at depth)
☒ Gravitational (self-weight, depth-varying)
Unit weight γ (kN/m³): 27.000
Horiz. stress ratio $k_H = \sigma_H/\sigma_v$: 1.50
Horiz. stress ratio $k_h = \sigma_h/\sigma_v$: 1.30
Trend of σ_H (° CW from North): 218.0

Kernel & solver
☒ Kelvin (full-space) — deep underground excavations (default)
☐ Mindlin (half-space) — shallow workings, free surface at ground Z
Iterative (GMRES) tolerance: Standard (1e-6) — recommended
Near-field threshold (elements): 71,386 ☒ Auto (RAM)
H-matrix cache (GB, 0 = no cap): 13.5 ☒ Auto (free RAM)

Field-point handling
Near-surface band (× edge): 0.0 ☒ Default (auto)
☐ Iso-surface treats interior as in-situ (else show clean hole)

Defaults Save... Load... Cancel OK

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

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 stress option measures 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; §6.6 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 (§6.6); 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 ν	Lateral strain ratio	0.01–0.49	0.25

The **Hard Rock** button fills in $E = 70$ GPa and $\nu = 0.25$; **Soft Rock** fills in $E = 20$ GPa and $\nu = 0.30$. 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 two descriptions.

Uniform (specify σ_v 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 σ_v (MPa)	The vertical stress at your mining horizon	10
Horiz. stress ratio $k_H = \sigma_H / \sigma_v$	Major horizontal $\div$ vertical	1.5
Horiz. stress ratio $k_h = \sigma_h / \sigma_v$	Minor horizontal $\div$ vertical	1.0
Trend of σ_H ($^\circ$ 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/m ³)	Overburden unit weight; $\sigma_v = \gamma \times \text{depth}$	27
k_H , k_h , Trend	As above, at every depth	1.5 / 1.0 / 0

With Gravitational stress or the Mindlin kernel, GEM4D checks that no excavation reaches above the ground surface Z when you build the model (§6.6).

The principal stresses are always one vertical and two horizontal. A tilted stress field cannot be entered.

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

Choice	Use it for
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 (§8.2). 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. Fine (1e-8) is for checking.	Standard
Near-field threshold (elements)	Above this element count, the solver recalculates part of the model at every iteration instead of keeping it in memory. Slower, but it cannot run out of RAM. Auto (RAM) sets it from your computer's memory.	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 6 GB. 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 4, explains exactly how these settings interact.

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.
- **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.

6. 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.

6.1 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 (file layer)	The mesh name.
Tris (source)	The number of triangles in the mesh.
Shape	What GEM4D measured the mesh to be (§6.2). Hover over the cell for the measurement.
Type	FF or DD (§6.2).
Width (m)	The mining width of a DD row (§6.3). Greyed on FF rows.
Mined at / Steps	The mining step(s) of the mesh (§6.4).

Below the table is the **DD element size (m)** box with its **Suggest** button (§6.3). Above it, two buttons choose how mining steps are entered (Chapter 9).

6.2 Choosing the Type: FF or DD

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

- a **closed, volumetric solid** → **FF**;
- an **open surface** → **DD**;
- a **thin closed solid** → **DD**. *Thin* means no thicker than about 15 % of its width **and** no thicker than 30 m.

The 30 m cap stops a wide, shallow excavation — an open pit, or a thick stoping block — from being treated as a reef.

The **Shape** column shows the measurement behind the choice:

Shape	Meaning
<i>Surface</i>	An open surface with a rim
<i>Thin solid 1.92 m</i>	A thin closed solid, with its measured thickness
<i>Solid</i>	A closed, volumetric solid
<i>Sheets</i>	Closed, but with no thickness at all
<i>Mixed</i>	Thin and volumetric parts in one mesh — split the mesh first

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** to show that it differs from the classification.

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 volumetric solid set to DD.** The same question in reverse.
- **Mixed normals** (§7.2). **OK** builds anyway; **Cancel** returns you to the table.

6.3 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 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 one twentieth of the largest reef's shorter span; Chapter 18 explains why. 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.

6.4 Mining steps

For a single excavation state, leave every step at **1**. For a mining sequence, see Chapter 9. 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. New rows are numbered 1, 2, 3, ... down the ticked rows.
- In **As-mined snapshots** mode the column is headed **Steps**. Give each mesh the steps it belongs to, such as 1-3 or 2+. New rows start at 1.

Switching modes rennumbers the column only if you have not edited it yet.

6.5 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.

6.6 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 **Gravitational** stress 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 **Gravitational stress and the Kelvin kernel**, warns you. The ground surface is only the depth reference here. Elements above it get tension as their in-situ stress, so results near them 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).

6.7 The completion summary

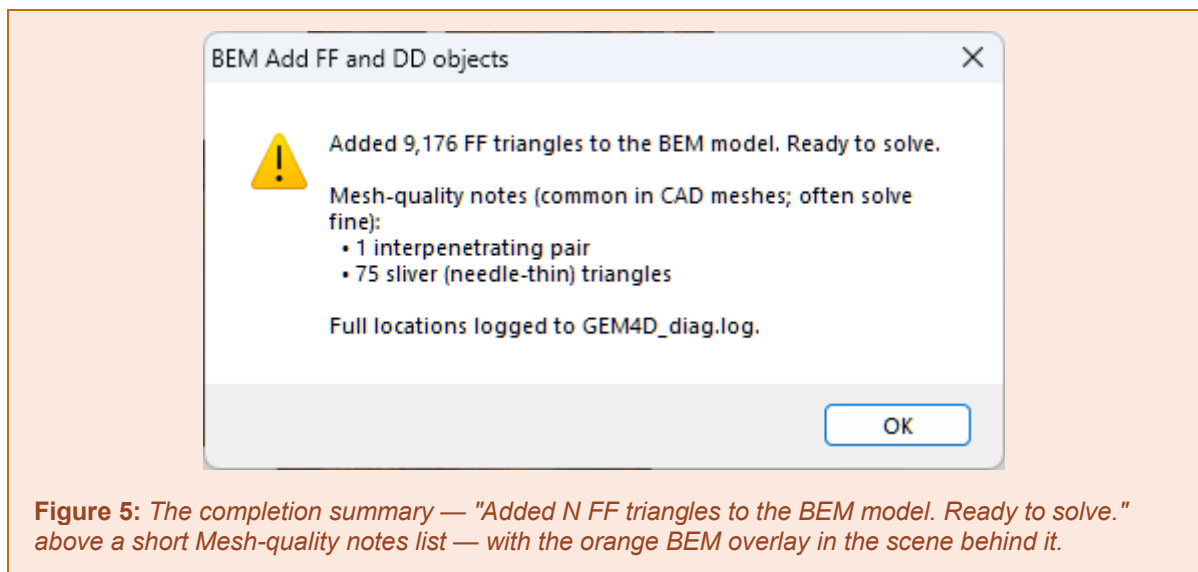
A summary opens when the model is built. It starts with the outcome, for example:

"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."*

Below that, a short **Mesh-quality notes** list appears if something is worth knowing. Each note is one line with a count. Most of these defects are common in CAD meshes and solve fine. Chapter 7 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).



6.8 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.

6.9 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.

7. Preparing meshes for BEM

A BEM model is only as good as its meshes. This chapter describes a good mesh, explains each quality note and lists the tools that repair a mesh.

7.1 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, and no more elongated than about 3 : 1 near where you will read stresses.
- **A sensible size** — a few thousand to a few tens of thousand elements is comfortable. The solver handles 250 000 and more, but such runs take hours (§8.4).

7.2 The Mesh-quality notes

These notes appear in the completion summary (§6.7). **They are advisory, not errors.** Many development meshes carry them and still solve well in minutes. Each note gives a count; the locations, in mine coordinates, go to GEM4D_diag.log.

Note	What it means	What to do
<i>"Not watertight: N open + M non-manifold edges"</i>	Real holes, or edges shared by three or more triangles. Points near them may be put on the wrong side of the wall.	Usually fine for development. If results look wrong near the gaps, repair the mesh with Remesh for BEM analysis (§7.3) or in CAD.
<i>"Mixed normals in K meshes: ..."</i>	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, and such meshes often fail to solve. GEM4D also asks about this at Build model .	Rebuild the mesh with Remesh for BEM analysis . If the seams are internal development walls, run Remove internal surfaces first.
<i>"N source edges with triangles facing both ways — re-oriented automatically (no seams)"</i>	Some triangles faced the wrong way, and GEM4D turned them round.	Nothing.
<i>"N zero-volume bodies"</i>	Closed bodies with no thickness — the front and back faces lie on top of each other. They are left-overs from CAD slicing and can stop the solve.	If the solve fails, delete them at the logged coordinates (they enclose nothing), or run Remesh for BEM analysis , which removes them.

Note	What it means	What to do
"N interpenetrating pairs"	Two closed solids inside one mesh overlap — typically stope lifts stacked without being joined.	If the solve fails, join them with Boolean union overlapping solids or Remesh for BEM analysis , or fix them in CAD.
"N sliver (needle-thin) triangles"	Triangles more than 100 times longer than they are high.	Usually fine. If the solve stalls, remesh only that mesh with Remesh and smooth at its current element size, or with Remesh for BEM analysis . Leave coarse distant meshes alone.
"body-overlap check skipped (mesh has N separate bodies)"	With more than 1 500 bodies in one mesh, the overlap check is not run.	If the solve fails, look for overlapping solids yourself.
"N open surfaces built as FF ..."	You kept an open surface as FF (§6.2).	Set it to DD, unless you meant it.
"Skipped N zero-area triangles."	Triangles with no area were dropped.	Nothing, unless the count is a large part of the mesh.

Solids that only **touch** are not reported here. On a mining sequence, a separate check warns when two meshes of one step touch or overlap (§9.4).

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

7.3 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	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. The value you enter is the largest edge length allowed. Bodies with no volume are dropped.	A mesh has mixed normals, holes, overlaps or slivers — including thin CAD stopes made of long needle triangles
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	Toolbox 1	Splits a mesh into one mesh per closed solid.	One mesh holds bodies that need different element sizes
Remove internal surfaces	Split & Boolean	Keeps only the outer skin, removing walls buried inside the excavation.	A development model has internal walls between segments
Boolean union overlapping solids	Split & Boolean	Joins overlapping solids exactly, keeping the original triangles away from the joins.	Overlapping solids, where exact dimensions matter. It cannot join solids that only share a wall — 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.

7.4 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. **Keep triangles well shaped near where you read stresses** — no more elongated than about 3 : 1. A long thin triangle is calculated less accurately at points close to it.
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**, 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.

7.5 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.

Values on or right next to the walls — the energy maps and the Kirsch stress — settle more slowly than values a few elements into the rock. Stress at sharp corners and edges keeps rising as you refine; that is the nature of a corner, not an error.

Theory and Verification, Chapter 7, gives the measurements behind these rules.

8. Running, stopping and saving

8.1 Run model

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

8.2 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. *Theory and Verification*, Chapter 4, explains how.

8.3 Reading the status area

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

Message	Meaning
Kelvin LU, Mindlin EBE, Kelvin+DD EBE	At the start: the kernel, and the method (LU = direct; EBE = iterative). +DD means the model has DD 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 blocks did not fit and will be recalculated at each iteration.
GMRES 184 · r/b 8.31E-05	Iteration 184. The second figure should fall steadily toward the tolerance.
Solved – N el · k iter	Finished. The line below shows the start and end times and the duration.

On a mining sequence each line starts with the step, for example 2/5 · GMRES 184 ·

8.4 How long will it take?

On a modern workstation, as a rough guide:

Elements	Solve time
Hundreds	Seconds
About 10 000	Tens of seconds to minutes
About 100 000	Tens of minutes
About 300 000	One to two hours

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.

8.5 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, the **Map** buttons warn you rather than interrupt it.

8.6 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 sequence is saved with all its steps (§9.7). A model with DD elements uses a newer file layout, which older GEM4D versions refuse with a clear message rather than misread.

9. 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 (§6.4): choose a mode with the two buttons above the table, then fill in the step column.

9.1 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.

9.2 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.

9.3 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 (the default)
1, 3	Steps 1 and 3
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.

9.4 Checks in both modes

GEM4D checks the bounding boxes of the meshes in each step and warns when two of them touch or overlap. Each pair is reported once. Solids that are close but separate can trigger this warning; then it can be ignored.

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

9.5 Solving a 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 (§8.2). **Stop** ends the whole run and keeps the model; the part-finished solution is discarded (§8.5).

9.6 Mapping a sequence

The **Map** and **Energy** buttons work on a sequence as on a single model, repeated for every step:

- The table or CSV gets **one column per step** for each result, named with `_s1`, `_s2`, ... (for example `S1_s3_MPa`).
- Results that go to separate files are written **once per step**, with `_s{k}` added to the file name.
- The scene shows the **current** step.

Chapter 10 describes the outputs, and Chapter 12 explains how to step through them.

9.7 Saving and reloading a 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 the *Map BEM results* 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
Sigma-1 orientation -> Mapping arrows	Arrows along σ_1 (§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** — 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**.
2. Set the **Max refinement depth**: 3 = coarse, 5 = balanced (the default), 7 = fine. Each extra level can double the resolution near the excavations. Click **OK**.
3. Choose the outputs (§10.1) and click **Map**.
4. Save the CSV. The default name is `BEM_OctreePoints.csv`.

An octree puts its points where the stress changes fastest, so it usually gives the best iso-surfaces for the number of points.

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. 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 σ_1 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.

	σ_1 arrows	Critical-plane discs
Ticked with	<i>Sigma-1 orientation -> Mapping arrows</i>	<i>Coulomb ESS critical-plane Mapping discs (separate file)</i>
One object per	Point outside the excavations	Point outside the excavations — two discs per point
Shows	The direction of σ_1 , as an arrow coloured by σ_1	The two planes most likely to slip, coloured by Coulomb ESS (Chapter 15)

	σ_1 arrows	Critical-plane discs
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 — σ_1 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 σ_1 '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 ► Number ► 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).

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).

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 $\sigma_1 = 60$ 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.

Group	What it controls
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.
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).

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.

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.

- 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**.

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** 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 (§9.7).

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 $\sigma_1 \geq \sigma_2 \geq \sigma_3$
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

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.

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 σ_1 and σ_3 with your strength criterion; a calculated column in the BEMResult table is a convenient way (right-click → **Add calculation column**).
- **Close to a wall, use the Kirsch option.** Values within about one element of a wall are less accurate than values deeper in the rock. For the stress on the wall of a drive, use Kirsch tangential stress (Chapter 14).
- **Corners keep rising.** Stress at a sharp corner or edge grows as you refine the mesh. That is the nature of a corner, not an error.
- **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.

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:

$$\text{RCF} = \text{BEM_Tang_MPa} / (\text{F_Factor} \times \text{UCS_MPa})$$

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: $3 \times \text{SigMax} - \text{SigMin}$
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 σ_1 and σ_3 : they are the extremes across the section, and always lie between them.

14.4 Reading the wall stress

A drive **at right angles to σ_1** has σ_1 in its cross-section, so SigMax is close to σ_1 and the wall stress is high. A drive **along σ_1** has σ_1 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 $F \times \text{UCS}$ 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:

$$\text{ESS} = \tau - c - \tan \varphi \cdot \sigma N$$

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	<i>Excess Shear Stress on fault (needs Dip/DipDir)</i>	<i>Coulomb ESS critical-plane Mapping discs (separate file)</i>
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 BEM results* dialog sets:

Field	Range	Default	Notes
Dynamic friction angle	0–89°	30°	Ryder's dynamic value; $\tan 30^\circ \approx 0.58$
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** (σ_N below zero) the formula would give a negative resistance, as if the opening joint helped drive the slip. With the clamp **on**, σ_N 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 σ_N is subtracted. For example, with $\tau = 10$ MPa, $c = 0$, $\phi = 30^\circ$ and $\sigma_N = -5$ MPa:

- clamp **on**: $\text{ESS} = 10 - 0.58 \times 0 = \mathbf{10.0 \text{ MPa}}$
- clamp **off**: $\text{ESS} = 10 - 0.58 \times (-5) = \mathbf{12.9 \text{ MPa}}$

Leave the clamp on unless you specifically want tension to count as driving stress. Coulomb ESS uses the critical compressive plane, where σ_N is always positive, so the clamp does not apply to it.

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
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 $\sigma_1 - \sigma_3$ 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 σ_1 . 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/m^3 . 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/m^3 . 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/m^2 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).

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

- $\Delta W/\Delta V$ (kJ/m³) — energy per cubic metre mined. Always reported.
- $\Delta W/A$ (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** $\approx 2 \times (\Delta W/A)$.

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 both in-situ stress options are supported.
- With Gravitational stress and the Kelvin kernel, elements above the ground surface get tension as their in-situ stress (§6.6), so their step-1 release is unreliable too.
- **Thin stopes** need elements no larger than their thickness (§7.4); then their released energy is reliable.
- A **negative ΔW** points to a defective mesh — check the Mesh-quality notes (§7.2).

Theory and Verification, Chapter 5, 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 6 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)

Column	Meaning
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 $1/\cos(\text{dip})$ 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 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 ($\approx$ 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 what **Suggest** fills in, 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 5, gives the formula, Chapter 7 the checks, and Appendix C works one element through by hand.

Part 5 — Reference

19. 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 ν 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 σ_1 and σ_3 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 values deeper in the rock. For the wall stress of a drive, use the Kirsch option (Chapter 14). The energy maps evaluate just inside the rock, which keeps them accurate at the wall.
- **Mesh quality matters more than thickness.** A thin stope is modelled reliably once its elements are no larger than its thickness (§7.4). Sliver triangles are the real risk on CAD stope meshes (§7.2).
- **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** is one vertical and two horizontal principal stresses. A tilted stress field cannot be entered.

20. Troubleshooting

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

20.1 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 $Z = \dots$ 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 (§6.6).
"Gravitational in-situ stress is computed from depth below the surface datum $Z = \dots$ "	A mesh reaches above the ground surface Z . Fix it as above, or click Proceed anyway if the surface is a representative average (§6.6).
"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 (§9.2–§9.3).
"Possible touching / overlapping solids within a step"	Two meshes of one step touch or overlap. If they really share walls, merge them into one shape; if they are only close, ignore it (§9.4).
"DD surfaces need the Kelvin (infinite-domain) kernel..."	Change the Setup kernel to Kelvin, or set the named rows to FF (§6.3).
"Enter a mining width (m) for each DD surface..."	Type a Width for each DD row (§6.3).
"DD surface "... has no usable triangles" / "... has no fittable plane"	The surface has no area, or all its points lie on a line.
"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.
Mesh-quality notes in the summary	See §7.2.
DD preparation notes in the summary	See §20.8.
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 (§6.8).
Results look rotated by about 90°	Check Trend of σ_H — it is in degrees clockwise from North, for the major horizontal stress — and check that kH and kh are not swapped.

20.2 Solving

Message or symptom	Cause and fix
<i>"Add at least one excavation before solving."</i>	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.
Solve seems stuck on <i>"GMRES 184 · r/b 8.31E-05"</i> , 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 (§7.2).
<i>"GMRES did not converge after N iterations"</i>	Almost always the geometry: bodies with no volume, overlapping solids or walls lying on top of each other. Rebuild the model, read the Mesh-quality notes (§7.2), fix the flagged bodies and solve again.
<i>"Solve stopped — model kept, press Run model"</i>	You clicked Stop during a solve. The meshes, steps and Setup are kept; the solution is discarded. Click Run model (§8.5).
<i>"A BEM calculation is still running."</i>	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 <i>Application Error / .NET Runtime</i> entries and the mesh to BasRock.

20.3 Mapping

Message or symptom	Cause and fix
<i>"This will evaluate N field points, which may take several minutes."</i>	More than 1 000 000 evaluations. Coarsen the grid or lower the octree depth, or filter the BEMResult table to the rows you need. On a sequence the count is points × steps (§10.1).
<i>"Load BEM datagrid data first." / "No visible BEM datagrid rows."</i>	Map to datagrid needs points in the BEMResult table, and at least one row passing the filters (§10.4).
<i>"BEM datagrid row count changed during evaluation."</i>	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).

20.4 Energy

Message or symptom	Cause and fix
Energy dropdown greyed	The energy outputs need a solved or reloaded model. Click Run model first.
<i>"Some mining steps are not solved..."</i>	Each step is measured against the one before, so every step must be solved. Solve the sequence again (§17.2).
<i>"No newly created excavation surface was found, so no energy was released."</i>	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 Mesh-quality notes for mixed normals, slivers and zero-volume bodies (§7.2). 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).

20.5 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.
<i>"Grid columns are from an older solve"</i>	The per-step columns came from an earlier solve. Run Map to datagrid again (§12.3).
<i>"Column ... not found"</i>	The per-step column was deleted. Run Map to datagrid again.
<i>"N member meshes missing from the scene"</i>	A sequence was loaded without its meshes. The overlay still steps (§9.7).
<i>"Member meshes hidden — overlay only"</i>	You have hidden all of this step's meshes. Show them in the Mesh panel to see them step (§12.2).
<i>"Mesh colours stale — press Update" / "Iso rebuilt · colours stale, press Update"</i>	Expected: Colour meshes does not follow the steps. Click Update on the BEMResult panel (§12.2).

20.6 Mesh-quality notes

See the table in §7.2.

20.7 DD preparation notes

These notes appear in the completion summary 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
<i>"... DD element placements skipped where an earlier surface already covers the reef in that step"</i>	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.

Note	What it means	What to do
"... 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.
"... 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.

21. 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.

21.1 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.

Column	Unit	Opt-in	Meaning	See
X_m, Y_m, Z_m	m		Point position, mine coordinates	

Column	Unit	Opt-in	Meaning	See
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/m ³	✓	Stored strain-energy density	16
Sxx_MPa, Syx_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
DistToSurface_m	m		Distance to the nearest wall; negative inside	13

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

21.2 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}. 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.

21.3 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, $3 \times \text{SigMax} - \text{SigMin}$	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

Column	Unit	Opt-in	Meaning	See
BEM_ESS_Band	—	✓ ESS	Stable, Low, Moderate or High	15
BEM_SED_kJm3	kJ/m ³	✓	Stored strain-energy density	16
BEM_Status	—		Far, NearSurface or Interior	13

21.4 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}. 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.

21.5 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/m ²	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

21.6 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 σ_1 '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

22. 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 (§9.2).

Term	Meaning
As-mined snapshots	The step mode in which each mesh lists the steps it belongs to (§9.3).
Back-fill	The Setup option that writes the in-situ stress, rather than blanks, at points inside excavations (§13.4).
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 <i>datagrid</i> .
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 (§8.2).
H-matrix	The compressed form in which the iterative solver stores the model's interactions (<i>Theory and Verification</i> Chapter 4).
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 (§8.2).
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 6).
Mid-surface	The surface halfway between the roof and floor of a thin solid; it becomes the DD reef (§6.5).
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 (§7.2).
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).

Term	Meaning
Sliver	A needle-thin triangle (§7.2).
Step	One stage of a mining sequence (Chapter 9).
Touchdown	A DD element that has closed by its full mining width (§18.6).
Watertight	Closed, with no holes or loose edges (§7.2).

23. References

- Beer, G., Smith, I. & Duenser, C. (2008). *The Boundary Element Method with Programming*. Springer. (Modern BEM implementation and iterative solvers.)
- Brady, B.H.G. & Brown, E.T. (2004). *Rock Mechanics for Underground Mining*, 3rd ed. Kluwer. (In-situ stress, induced stress around openings, k-ratios.)
- Crouch, S.L. & Starfield, A.M. (1983). *Boundary Element Methods in Solid Mechanics*. Allen & Unwin. (The fictitious-force and displacement-discontinuity methods; DD for tabular mining.)
- Hoek, E. & Brown, E.T. (1980). *Underground Excavations in Rock*. Institution of Mining and Metallurgy, London.
- Jaeger, J.C., Cook, N.G.W. & Zimmerman, R.W. (2007). *Fundamentals of Rock Mechanics*, 4th ed. Blackwell. (The pressurised spherical cavity used to check released energy.)
- Jager, A.J. & Ryder, J.A. (1999). *A Handbook on Rock Engineering Practice for Tabular Hard Rock Mines*. SIMRAC, Johannesburg. (RCF and ERR interpretation bands; F-factor guidance.)
- Kirsch, G. (1898). Die Theorie der Elastizität und die Bedürfnisse der Festigkeitslehre. *Zeitschrift des Vereines deutscher Ingenieure*, 42, 797–807. (The tangential wall stress around a circular opening.)
- Mindlin, R.D. (1936). Force at a point in the interior of a semi-infinite solid. *Physics*, 7, 195–202. (The half-space kernel.)
- Nikkhoo, M. & Walter, T.R. (2015). Triangular dislocation: an analytical, artefact-free solution. *Geophysical Journal International*, 201, 1119–1141. (The triangular DD element.)
- Ryder, J.A. (1988). Excess shear stress in the assessment of geologically hazardous situations. *J. S. Afr. Inst. Min. Metall.*, 88(1), 27–39. (ESS.)
- Salamon, M.D.G. (1984). Energy considerations in rock mechanics: fundamental results. *J. S. Afr. Inst. Min. Metall.*, 84(8), 233–246. (Stored and released energy.)
- Sneddon, I.N. (1946). The distribution of stress in the neighbourhood of a crack in an elastic solid. *Proc. R. Soc. Lond. A*, 187, 229–260. (The penny-shaped crack used to check DD elements.)
- Wiles, T.D. Loading system stiffness — a parameter to evaluate rockburst potential (the LERD / ESR family of energy measures). Map3D documentation.
- Wiseman, N. (1979). Factors affecting the design and condition of mine tunnels. Chamber of Mines of South Africa, Research Report. (The Rockwall Condition Factor.)