GEM4D DOCUMENTATION

Wedge Stability at Minodes

User Manual

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This manual shows you how to screen a development network for roof wedges with GEM4D, how to read the results, and how the calculation works.

> **Scope and engineering responsibility.** *Wedge stability at Minodes* is a **screening** tool. It assumes every joint set can occur anywhere, that each wedge is the largest that fits the opening, and that the rock is dry and loaded by gravity alone. It shows *where* wedge risk concentrates and how sensitive it is to joint scatter. It does not design support. The design factors of safety, κ values and Pfail readings quoted here are common starting points from the literature, not acceptance criteria: use your site's standards. Check critical locations with a detailed single-location analysis, and have the results reviewed by a competent geotechnical engineer before they inform a design.

How to use this manual

If you want to…	Read
Know what the tool does	Chapter 1
Get a first result quickly	Chapter 2
Prepare the inputs and set up a run	Chapters 3 and 4
Read and act on the results	Chapters 5 and 6
Understand the calculation	Part 2 (Chapters 7–10)
Fix a problem or look up a term	Part 3 (Chapters 11–13)
Check a result by hand	Appendix A

Part 1 — Using the tool

1. What the tool does

Wedge stability at Minodes screens a whole underground development network for roof wedges in one run. It works at the **minodes**: Marker points along the drives, each carrying the local direction of its drive.

At every minode, GEM4D:

1. **Measures the opening** with 48 horizontal rays fired out to the tunnel walls.
2. **Forms every possible roof wedge** from the joint sets you supply. Each wedge is bounded by three joints and the back, and is the largest that fits the measured opening.
3. **Solves each wedge** for its failure mode (fall, plane slide, edge slide or stable) and its **factor of safety (FoS)**. The method is classic gravity limit equilibrium (Hoek & Brown 1980; Goodman 1989), the same family of methods as UNWEDGE.
4. **Optionally runs a Monte-Carlo simulation** that varies the joint orientations, to estimate a **probability of failure**.
5. **Writes fourteen result columns** to the Marker table and, if you ask, builds the wedges as colour-coded meshes in the scene.

The results are ordinary Marker data. You can colour the minodes by them, filter them and export them.

Use the tool to find **where** along kilometres of development the wedge risk concentrates. Then check those few locations with a detailed analysis, for example in UNWEDGE.

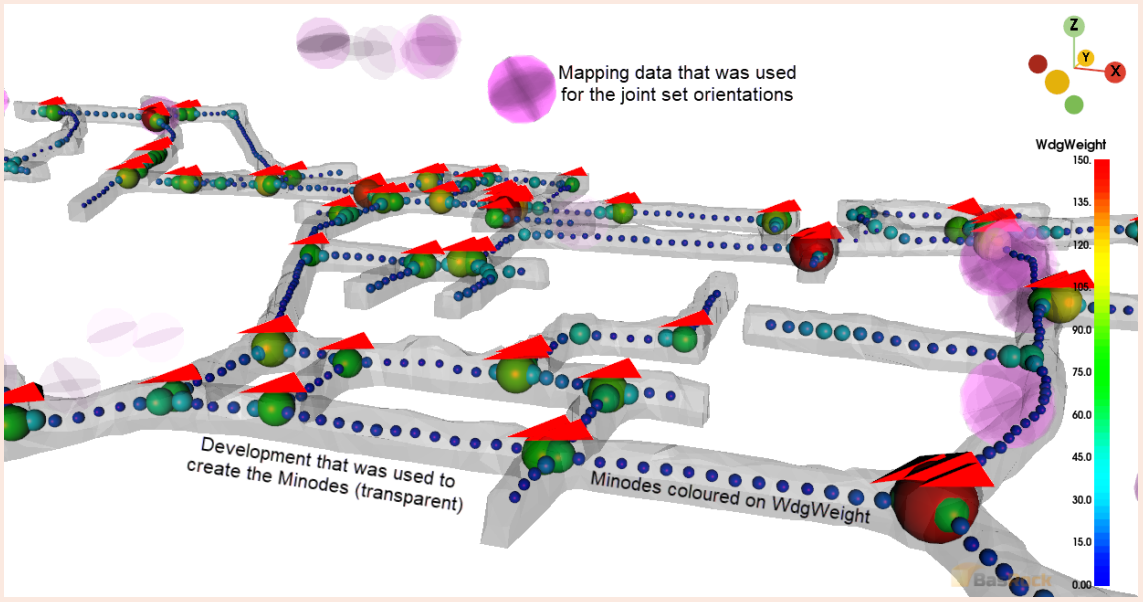


Figure 1 — A case where the wedge persistence for all sets was increased to 90m. When the actual joint persistence is used, this mine shows only small wedges. The Minode Markers were coloured and sized by WdgWeight, showing that the risk largely concentrates at intersections.

2. Quick start

These steps take you from development meshes to a coloured result.

1. **Create the minodes.** Load the development meshes. Open **Toolbox 2 ▸ Minodes from development meshes**. In the *Generate Minodes* dialog, under *Output columns*, tick **Coordinates + Dip, DipDir, ERF, CirRad, EstHR, VertZ, numPnts** and **Centre coordinates in the tunnel for accurate calculations**. Press **Generate**, and save the minodes as a CSV file when asked. GEM4D loads them into the Marker table and hides the meshes.
2. **Show the tunnel meshes again** (tick them in the Objects list). GEM4D measures the openings against every visible mesh, so leave other meshes hidden (§3).
3. **Load structural mapping (optional).** Load your Mapping data. The stereonet (on the Mapping tab of the bottom panel) groups the poles into joint sets, and these fill the wedge dialog's joint-set table. Its right-click *Cluster Membership* menu tightens or loosens which poles belong to each set, and with them each set's mean orientation, κ, *n* and persistence. Without mapping, you type the sets in yourself.
4. **Choose the minodes (optional).** Filter the Marker table to the area you want. Only visible rows are analysed.
5. **Open the tool.** Click **Calc ▸ Wedge stability at Minodes**. Calc is the Σ button on the scene toolbar; its tooltip starts *Calc:*.
6. **Check the settings** (Chapter 4). Set the **Design FoS** to your site's value. The other defaults suit a first run.
7. **Press Analyse.** GEM4D shows a busy cursor while it works, and the bar in the status bar cycles to show that it is busy; it does not show progress. A run cannot be cancelled. A few thousand minodes with 1 000 trials each take from seconds to a couple of minutes.
8. **Save the wedge meshes (if you asked for them).** GEM4D asks where to save them as a DXF file.
9. **Read the summary**, then colour the Markers by `WdgFoS` and `WdgHeavyWeight` (Chapter 5).

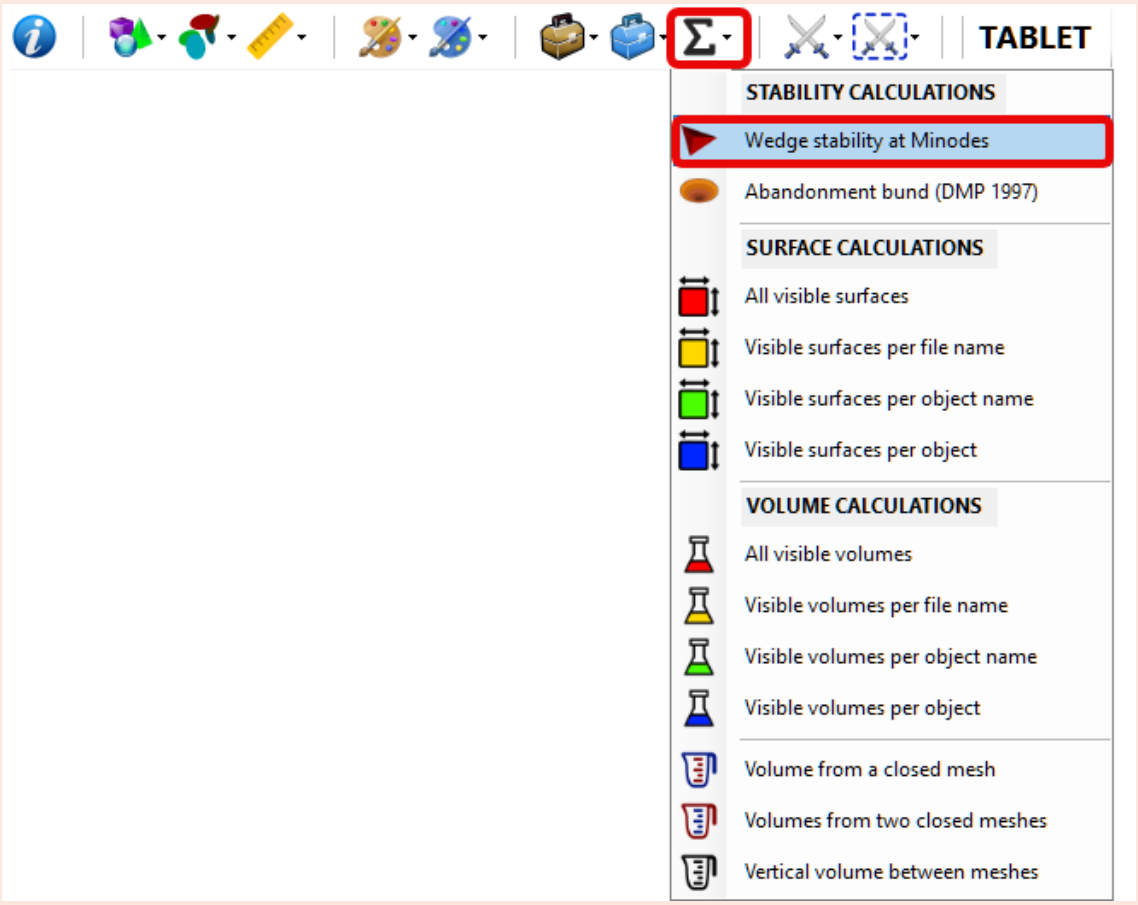


Figure 2 — The Calc (Σ) dropdown with "Wedge stability at Minodes" highlighted.

What the summary tells you. The summary dialog reports, in order:

- how many visible rows were analysed, and how many were skipped for *no Dip/DipDir value* or *no mesh within* the search distance;
- the number of joint sets, the number of set combinations solved at each location, and the number of trials;
- a Monte-Carlo note, when the trials could not vary anything (§11.3);
- the reminder that each wedge is fitted inside the outline traced by 48 rays, a missed ray counting as the search distance (Chapter 8);
- the worst deterministic FoS;
- how many locations hold a wedge below the design FoS, and the heaviest such wedge in tonnes;
- what happened to the wedge meshes (Chapter 6);
- the columns written.

3. Before you run: the inputs

Input	How to get it	Needed?
Minode Markers with Dip and DipDir columns	**Toolbox 2 ▸ Minodes from development meshes**, with both *Output columns* boxes ticked (Chapter 2, step 1). Dip and DipDir give the direction of the drive at each minode.	**Yes**

Input	How to get it	Needed?
Visible tunnel meshes	Load the development triangulations and show them: *Minodes from development meshes* hides them, so tick them again in the Objects list. Hide every other mesh, such as faults, orebody or stope solids and topography: each visible mesh stops the rays and makes the measured opening smaller, without a warning. In clipping mode, GEM4D uses the visible clipped pieces.	**Yes**
Mapping data	Load structural Mapping data. The stereonet's joint sets fill the table with each set's mean orientation, κ, pole count and mean trace length.	No: you can type the sets in

Centre the minodes. GEM4D sizes each wedge around its minode. A minode close to one wall meets that wall first and gets a smaller wedge. *Centre coordinates in the tunnel for accurate calculations* moves each minode onto the drive centre-line. It is off by default, so tick it.

Only visible rows are analysed. Filter the Marker table to restrict a run to one area. Any Marker filter works: a ribbon filter, a column filter, *Hide selected rows* or a rubber band. The filter stays on after the run, and the results are kept when you reset it. Each run first clears the result columns on **every** row, then writes the visible ones. Results from an earlier run on other rows are therefore not kept. To keep two areas together, run them with one filter that shows both.

Marker files from elsewhere work too, provided they have columns named exactly **Dip** and **DipDir** (capitals as shown; a load prefix such as `4_Dip` is fine) giving the drive direction.

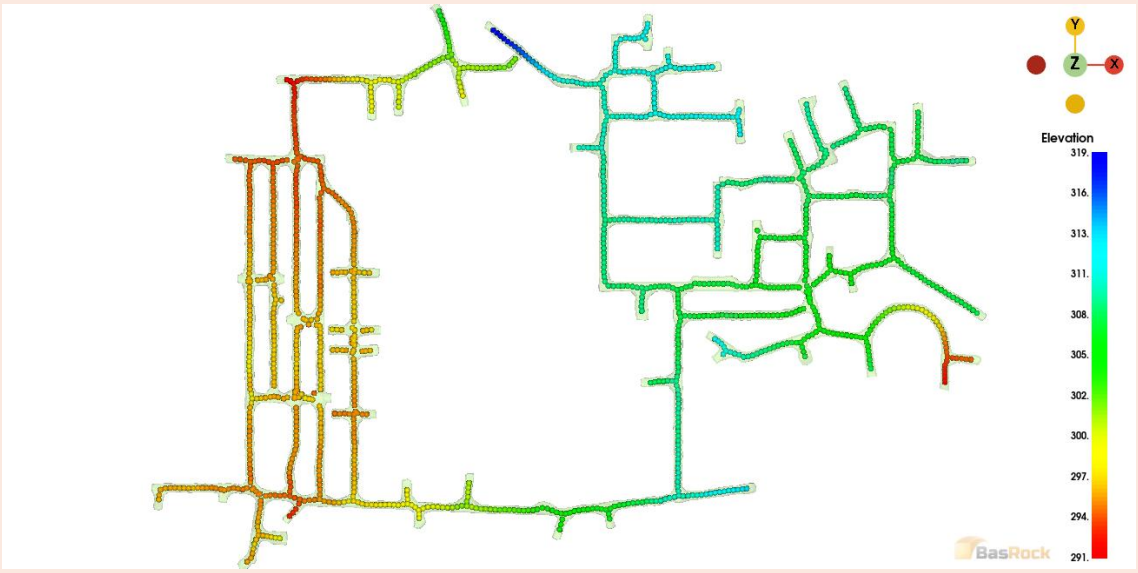


Figure 3 — Minode Markers coloured on elevation strung along a development mesh, as created by "Minodes from development meshes".

4. The settings dialog

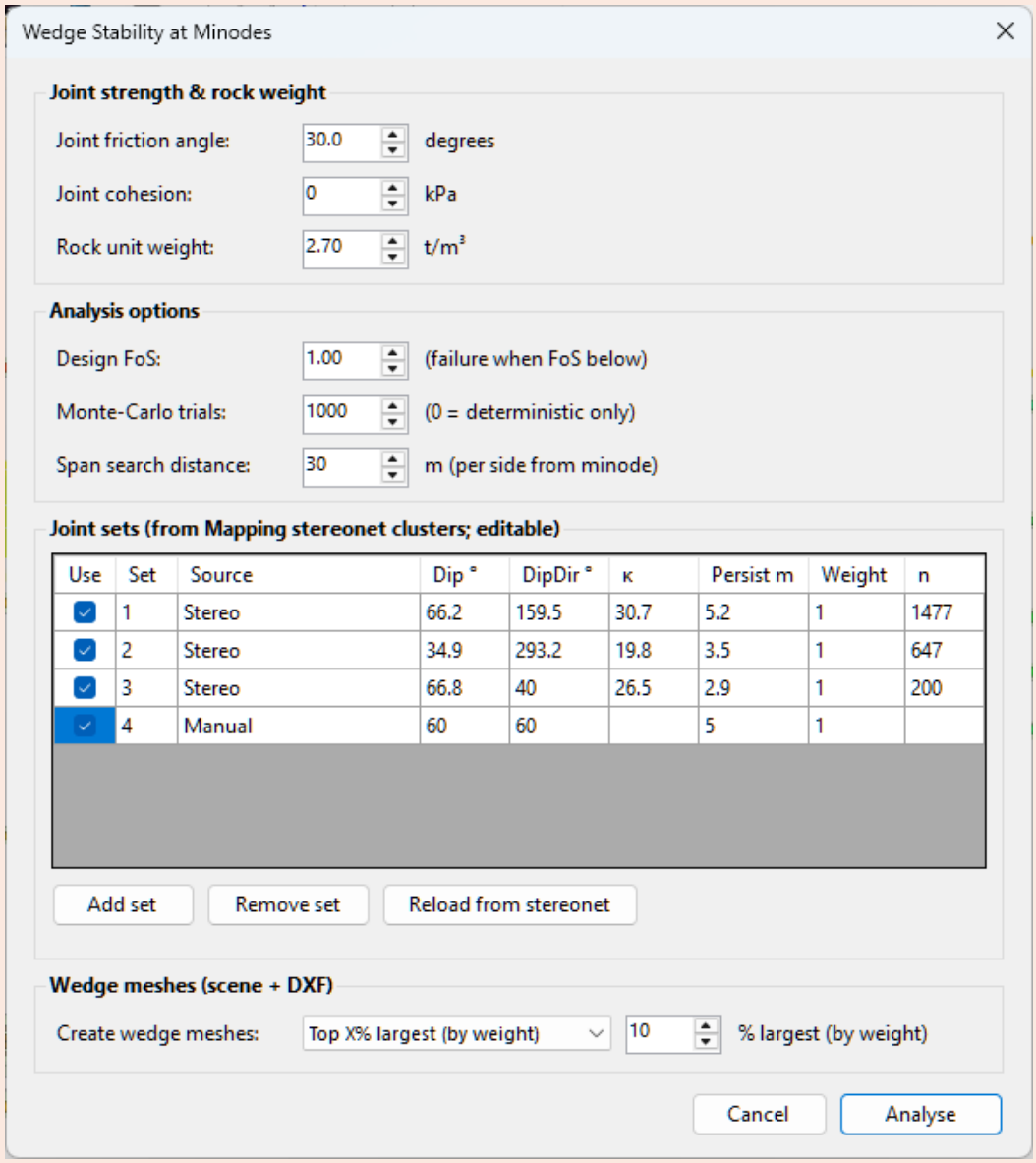


Figure 4 — The Wedge Stability at Minodes dialog, with three Mapping stereonet-sourced rows and one manual row in the joint-set table.

The dialog remembers your settings for the rest of the session: every value, the whole joint-set table, your manual rows and your edits. It forgets them when GEM4D closes.

> **Changed the mapping or the clusters since the last run?** The remembered table does not follow them. Press **Reload from stereonet** to bring in the current sets.

4.1 Joint strength & rock weight

Field	Default	Range	Notes
Joint friction angle	30°	5–89°	One value for all sets.
Joint cohesion	0 kPa	0–1 000	One value for all sets. Zero is the usual conservative choice; it makes the FoS independent of wedge size (§7.5).
Rock unit weight	2.7 t/m³	1–5	Turns wedge volume into tonnes.

4.2 Analysis options

Field	Default	Range	Notes
Design FoS	1.0	0.1–10	The failure threshold (*failure when FoS below*). It chooses the heavy wedge (§5.1), decides whether a Monte-Carlo trial fails, and drives the *FoS < design FoS* mesh option and the summary count. The default of 1.0 is bare limit equilibrium: set your site's value. Screening often uses 1.3–2.0.
Monte-Carlo trials	1 000	0–100 000	0 gives the deterministic columns only. The trials need something to vary: a κ or a Weight below 1 on at least one set (Chapter 9).
Span search distance	30 m	5–200	How far each ray looks for a wall, on each side of the minode. Make it comfortably larger than your widest opening, but not so large that rays reach other excavations.

4.3 The joint-set table

The table fills from the stereonet's joint sets, largest first, up to eight rows. You can edit every row and add your own.

Column	Meaning
Use	Tick to include the set. At least **three** ticked sets are needed.
Set	The set's number. The `WdgSets` columns report wedges by these numbers. Removing a row, or pressing **Reload from stereonet** (which puts the *Manual* rows after the stereonet sets), renumbers the rows; `WdgSets` values from an earlier run then refer to the old numbers.
Source	*Stereo* (from a stereonet set), *Stereo (girdle)* (a girdle-shaped set, whose κ is unreliable) or *Manual*.
Dip ° / DipDir °	The set's mean orientation: dip 0–90°, dip direction 0–360°.
κ	The Fisher concentration, which sets how much the orientation scatters in the Monte-Carlo trials. Blank means no scatter. Stereonet rows carry their set's κ; manual rows start blank.
Persist m	Persistence: the longest trace this set can leave on the back, in metres. Blank means unlimited. Stereonet rows start with the mean trace length (the Mapping *Size* column) of their set. Check these values before you run: a short persistence keeps that set's wedges small (§7.3). If your *Size* column is not a trace length, clear the cells.
Weight	How often the set is present, from just above 0 to 1. A set seen in 30 % of mapped windows can take 0.3. Blank means 1, always present. Only the Monte-Carlo trials use it.
n	The number of poles in the stereonet set. Trust a set of 8 poles less than one of 300.

Buttons

- **Add set** adds a *Manual* row at 45°/000°.
- **Remove set** removes the selected row. The Delete key does the same when you are not editing a cell.
- **Reload from stereonet** replaces the *Stereo* rows with the current stereonet sets and keeps the *Manual* rows. Edits you made to *Stereo* rows are lost.

The table holds eight sets at most. Every combination of three sets is solved at every minode, and eight sets already give 56 combinations. A note under the table says when smaller stereonet sets were left out, and warns about girdle-shaped sets.

Typed values are checked. An out-of-range value opens an *Invalid joint-set value* message that names the allowed range, and the cell stays open until you fix it. Press Esc to restore the old value.

4.4 Wedge meshes (scene + DXF)

Create wedge meshes chooses which wedges are also built in the scene:

Option	What is built
None *(default)*	No meshes, columns only.
FoS < design FoS	The heavy wedge (§5.1) of every minode whose FoS is below the design FoS: the wedges that need support.
Top X% largest (by weight)	The heaviest X % of the analysed minodes (default 10 %). Each minode is ranked by its heavy wedge, or by its governing wedge when nothing fails there.
All analysed	The governing wedge of every analysed minode. Clear on small runs, crowded on large ones.

Chapter 6 describes the meshes.

5. Reading the results

5.1 Two wedges at every location

With five joint sets there are ten possible wedges at each minode. Several usually fall, and others slide. GEM4D reports two of them, because one wedge cannot answer both questions an engineer asks.

- **The governing wedge** is the least stable one: the lowest FoS. When several tie, for example several falling wedges at FoS 0, the heaviest of them governs. It answers *how unstable is this location?* Its columns are `WdgFoS`, `WdgMode`, `WdgSets`, `WdgDepth` and `WdgWeight`.
- **The heavy wedge** is the heaviest wedge whose FoS is below your design FoS, whatever its mode. It answers *how much support does this location need?* Its columns start `WdgHeavy`.

A 24 t edge slide at FoS 0.6 beside a 2 t falling wedge is the support-design case, and the governing wedge alone would hide it. **Read `WdgFoS` for how unstable, and `WdgHeavyWeight` for how much support.**

5.2 The result columns

GEM4D adds fourteen numeric columns to the Marker table. A re-run overwrites them in place, and they survive a CSV save and reload. A column that was blank on every row (for example `WdgPfail` after a run with 0 trials) comes back from the CSV as text; the next run turns it back into numbers, unless a calculated column uses it (§11.3). Values are rounded to two decimals (`WdgPfail` to one).

A **blank** cell means *not applicable*. The row was hidden, or had no Dip/DipDir, or found no mesh within the search distance, or the value does not exist (for example `WdgHeavy*` where nothing fails).

Column	Units	Meaning
`WdgSpan`	m	The narrowest full crossing of the opening at the minode: the drive width in a straight drive, the diagonal at an intersection (§8.4). A check on the measurement.
`WdgFoS`	–	FoS of the governing wedge. 0 means a free fall without cohesion; 99 means stable, or an FoS of 99 or more (`WdgMode` tells them apart).

Column	Units	Meaning
`WdgMode`	code	Failure mode of the governing wedge: 1 fall, 2 plane slide, 3 edge slide, 4 stable, 0 no wedge could form from any set combination (§7.4).
`WdgSets`	code	The three sets forming the governing wedge, as their Set numbers in ascending order: **125** means sets 1, 2 and 5. It is a number so that you can colour and filter by it.
`WdgDepth`	m	Apex depth of the governing wedge: its height into the back.
`WdgWeight`	t	Weight of the governing wedge.
`WdgPfail`	%	Percentage of Monte-Carlo trials in which any wedge had an FoS below the design FoS. Blank when trials = 0.
`WdgDepth95`	m	95th-percentile apex depth of the heaviest failing wedge of each failing trial, over the failing trials only. Blank when no trial failed.
`WdgWeight95`	t	The same for weight.
`WdgHeavyFoS`	–	FoS of the heavy wedge. Blank when no wedge fails.
`WdgHeavyMode`	code	Failure mode of the heavy wedge (codes as for `WdgMode`).
`WdgHeavySets`	code	The three sets forming the heavy wedge (as for `WdgSets`).
`WdgHeavyDepth`	m	Apex depth of the heavy wedge: the bolt-length check.
`WdgHeavyWeight`	t	Weight of the heavy wedge: the support-capacity check. Never less than `WdgWeight` where both exist.

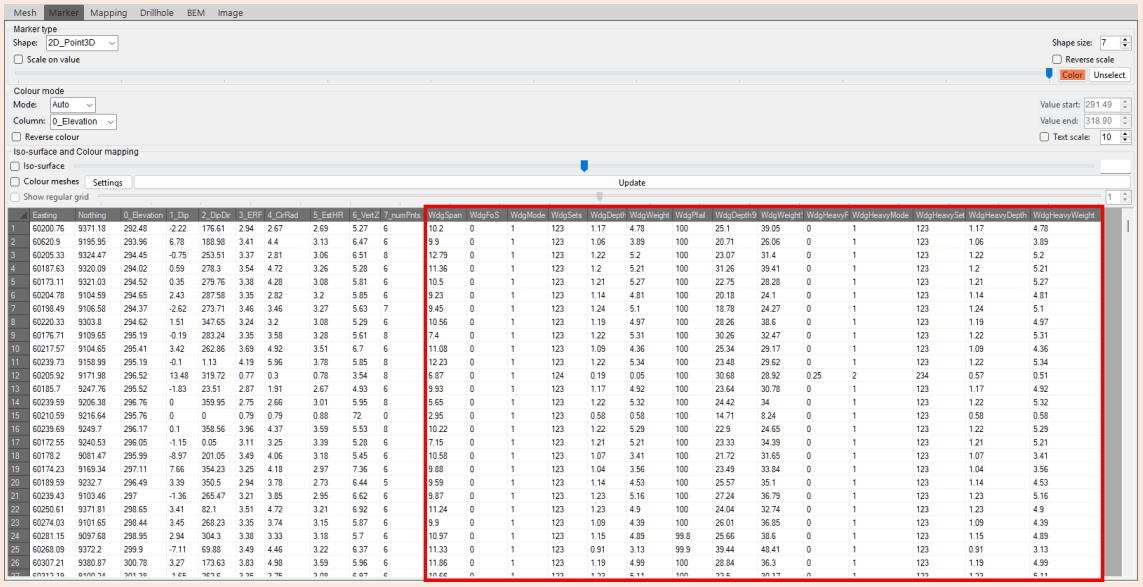


Figure 5 — The Marker grid showing the fourteen `Wdg*` columns after a run.

5.3 Screening by FoS and mode

The deterministic columns use each set's **mean** orientation and assume **every** ticked set is present. Read them together.

- **`WdgFoS` against your design FoS is the main screen.** Colour by `WdgFoS` with a legend band at your design value.
- **`WdgMode` tells you why.** A falling wedge (mode 1) has no frictional resistance at all: only support holds it, and its weight governs the bolt design. Sliding wedges (modes 2 and 3) keep some friction, so their FoS depends on the friction angle you chose. Run a sensitivity check on it.

- **`WdgHeavyDepth` and `WdgHeavyWeight` size the support.** Bolts must pass the apex depth with anchorage to spare, and the plates and strands must carry the weight. A 0.4 m, 2 t faller and a 4 m, 300 t edge slide at the same minode both fail, but only `WdgHeavy*` names the 300 t one.
- **`WdgSets` and `WdgHeavySets` tell you which sets to blame.** A set that appears in nearly every wedge across an area deserves the most mapping attention. Check its *n* and κ in the dialog before trusting it.

Remember the built-in conservatism. Each wedge is assumed to exist at every point, at its largest size, fully formed and dry. An FoS below design over a large area is a reason to look closer, not proof of imminent failure.

5.4 Probability of failure: WdgPfail

`WdgPfail` answers a different question from `WdgFoS`. It asks: *given how much the mapped orientations scatter (κ), and how often each set occurs (Weight), in what share of plausible cases does a wedge here fail the design FoS?*

FoS	Pfail	Reading
High	Low	Comfortably fine.
Low	High	The mean wedge fails and so do most variations of it. A genuine, robust problem area.
Above design	Noticeable (say 5–20 %)	The mean geometry is fine, but the scatter reaches failing wedges. Common with diffuse sets (low κ). The FoS alone would miss these locations.
Below design	Moderate (say 30–60 %)	The mean is unfavourable, but many variations escape. Often a marginal geometry near a mode boundary.

A low Pfail where the FoS is poor can mean the offending set is rare. The FoS assumes every set is present, while the trials drop sets with a Weight below 1. That is what the Weight column is for.

Pfail is a ranking tool, not a calibrated probability. Within one run with consistent inputs, ranking locations by Pfail is meaningful. Comparing its value with another mine's criteria is not.

5.5 How big when it fails: WdgDepth95 and WdgWeight95

These give the 95th-percentile apex depth and weight of the **heaviest failing wedge in each failing trial**, taken over the failing trials only. `WdgPfail` says how often a location fails; these say **how bad the bad cases are**.

- **They pair with `WdgHeavyDepth` and `WdgHeavyWeight`,** which describe the same "heaviest failing wedge" at the mean orientations. With tightly clustered sets the two pairs agree.
- **They can exceed the heavy wedge,** because a varied orientation can form a deeper wedge than the mean one. Use `WdgDepth95` as well as `WdgHeavyDepth` when you check bolt lengths.
- **They are blank when no trial failed,** which is good news.
- **Read them with Pfail.** A 50 t `WdgWeight95` at Pfail 0.4 % is a rare tail case; the same value at Pfail 45 % drives the design.
- **Small samples are unreliable.** The percentile comes from the failing trials only, so from Pfail × trials values. With 1 000 trials and Pfail 1 % there are 10 values, and the "95th percentile" of 10 values is simply the largest of them. It will jump between runs. To design from these columns at low-Pfail locations, raise the trials to 10 000 or more until the values settle.

5.6 A suggested screening workflow

1. Run with cohesion 0, your site's design FoS and 1 000 trials.
2. Colour by `WdgFoS` to find the problem areas, their modes and their sets.

3. Colour by `WdgPfail` to find scatter-driven locations the FoS missed, and to set aside FoS-only hits caused by rare sets.
4. Filter to the worst locations. Compare `WdgHeavyDepth` and `WdgDepth95` with your standard bolt length, and `WdgHeavyWeight` and `WdgWeight95` with your support capacity.
5. Check the few critical locations in a single-location tool such as UNWEDGE, with site strength data, water and support, before you change any design. Expect the mode and FoS to agree, and the sizes to agree in a straight drive. Sizes differ where the opening is more than two walls, such as an intersection, a brow or an irregular back. They also differ where the search distance caps a wedge running along a drive.

6. Wedge meshes

When you choose a mesh option (§4.4), GEM4D builds one wedge for each selected minode. *FoS < design FoS* draws the heavy wedge. *Top X%* draws the heavy wedge, or the governing wedge where nothing fails, so green stable wedges can appear. *All analysed* draws the governing wedge. Each wedge sits with its face on the back above its minode, exactly where it was sized.

The wedges are grouped into **one mesh object per failure mode**:

Object	Mode	Colour
`WedgesFall`	1 — fall	**Red**
`WedgesPlaneSlide`	2 — plane slide	**Orange**
`WedgesEdgeSlide`	3 — edge slide	**Yellow**
`WedgesStable`	4 — stable	**Green**

GEM4D asks once where to save them as a DXF file, binary if the Mesh tab's **Binary files** box is ticked. They are then normal mesh objects: they appear in the Objects list, you can show, hide and colour them, and you can reload the DXF later. Cancelling the save shows *Saving was cancelled and the created objects deleted*; no meshes are built, and the result columns are kept.

The summary's mesh line reads one of:

Line	Meaning
Wedge meshes: N wedge(s) in K failure-mode actor(s)	The meshes were built.
…; M skipped (no back found above the minode)	M selected minodes found no back to place their wedge on (§8.5). They are analysed, but not drawn.
Wedge meshes: none built — the N selected wedge(s) had no back found above the minode.	None of the selected wedges could be placed.
Wedge meshes: no wedges matched the selection.	The option selected nothing, for example *FoS < design FoS* when every wedge passes.
Wedge meshes: cancelled at the save dialog.	You cancelled the DXF save.

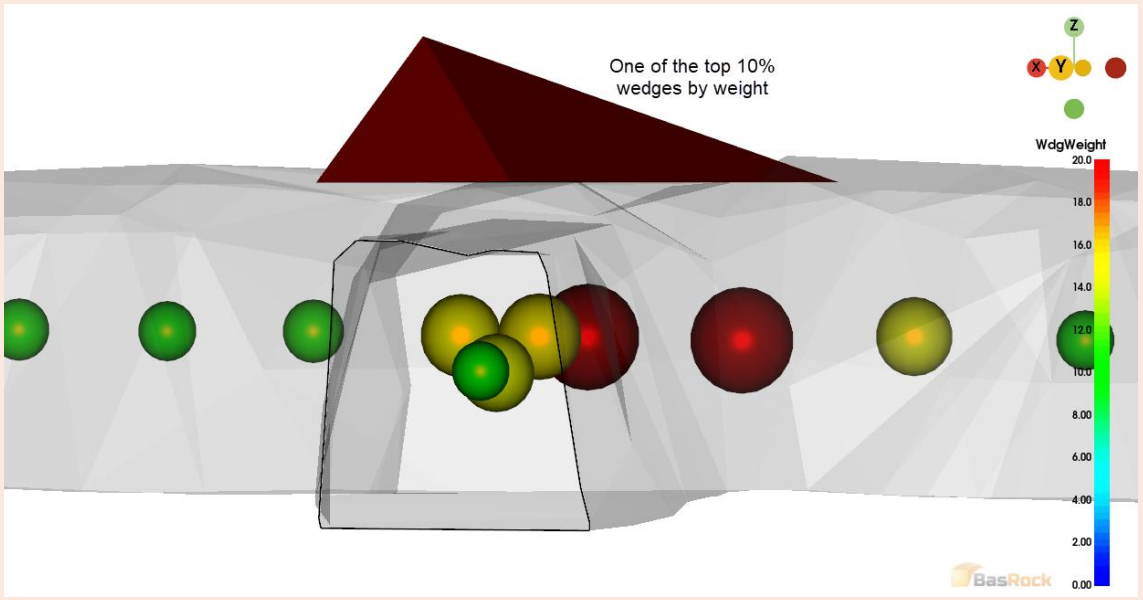


Figure 6 — A single intersection wedge viewed from the side, with the tunnel semi-transparent, and the Minodes coloured and scaled on WdgWeight.

Part 2 — How it works

7. Wedges in jointed rock

7.1 Why roof wedges matter

Three joints meeting above the back can cut out a four-sided block: three joint faces and the back. If gravity can move it into the opening, by falling or by sliding on one or two joints, it is a potential **roof wedge**.

7.2 Joints are assumed to be everywhere

GEM4D does not know where each joint actually is. It makes the standard conservative screening assumption that joints of every set can occur **anywhere** ("ubiquitous joints"). Every combination of three sets then forms the largest wedge that fits at every location.

So the tool does not answer "*is* there a wedge here?". It answers "**if** the worst-placed wedge formed here, how big would it be, and would it stand?". UNWEDGE takes the same view. It overstates how often wedges occur, in exchange for never missing one that could form.

7.3 Wedge geometry: three joints and the back

For each combination of three sets, the three joint planes cut lines (traces) across the back. The traces bound a triangle on the back, the **face**, and the three planes meet at a point above it, the **apex**. The block between them is the wedge.

Two rules size the wedge:

- **It fits the opening.** The face is scaled to the largest triangle of its shape that fits inside the opening measured around the minode (Chapter 8). In a straight drive the walls limit it, and it can run along the drive. At an intersection the pillar corners limit it. This is the largest wedge the excavation exposes: the design case for support.

- **Persistence can cap it.** Real joints have a finite size. If a set has a persistence (§4.3), none of its traces on the face may be longer than that. The wedge may then be smaller than the opening allows. UNWEDGE scales wedges by joint length in the same way.

7.4 Failure modes and the factor of safety

Gravity limit equilibrium puts each wedge into one of these modes:

Code	Mode	Meaning
1	**Fall**	The block drops straight down without touching any joint, so friction cannot act. FoS is 0 without cohesion. With cohesion, FoS = cohesion × (total area of the three joint faces) ÷ weight (Hoek & Brown). A wedge falls when the vertical line down from its apex passes through its face.
2	**Plane slide**	The block slides down one joint. FoS = (friction + cohesion on that joint) ÷ the driving force.
3	**Edge slide**	The block slides along the line where two joints meet, pressing on both.
4	**Stable**	No gravity-driven mode exists: every way out of the opening would carry the block uphill. That needs an inclined back. On a level back it never happens, and on a 1-in-7 decline about one combination of randomly oriented joints in 700 is stable. FoS is shown as 99, a placeholder for "stable", not a calculated value; a calculated FoS above 99 is also shown as 99.
0	**None**	The three joints cannot form a wedge with this back, for example when a joint is almost parallel to the back.

The factor of safety is the shear resistance available divided by the gravity force driving the wedge. Below 1, the wedge cannot hold itself up without support. Just above 1, it stands with little margin.

A flat joint does not always mean sliding. A wedge formed by one shallow joint and two steep ones falls, rather than slides, whenever the vertical line from its apex passes through its face. Sliding needs a wedge skewed enough for the apex to overhang an edge of the face.

Which wedge is reported is explained in §5.1: the lowest FoS (heaviest at a tie), and the heaviest below the design FoS.

7.5 Strength model

Shear resistance on each joint follows **Mohr–Coulomb**:

```
resistance = cohesion × contact area + normal force × tan(friction angle)
```

- **Friction angle** and **cohesion** are single values for all sets.
- **With zero cohesion, the FoS does not depend on wedge size.** Only the angles matter. Persistence and opening size then change the depth and weight, but not the FoS.
- **With cohesion, smaller wedges gain more.** Cohesion acts on area while weight grows with volume, so the FoS rises as the wedge shrinks.
- **Rock unit weight** turns volume into weight.

The analysis is **dry and gravity-only**: no water pressure, no clamping by the ground stress, no blasting or seismic load (Chapter 10).

8. Measuring the opening and sizing the wedge

8.1 The ray fan

At each minode GEM4D fires **24 pairs of opposite horizontal rays**, one pair every 7.5°, starting across the drive, each ray out to the span search distance. Each ray stops at the first wall it meets.

8.2 The outline

Joined up in angular order, the 48 ray ends trace the **outline** of the excavation as seen from the minode.

- **A ray that meets no wall** ends at the search distance: the opening is at least that long in that direction. Along a straight drive the outline therefore runs out to the search distance. The rays 7.5° either side of the drive axis still meet the walls, about four drive widths from the minode when that is within the search distance (drives up to about 7.8 m wide at the default 30 m), and in practice they bound a wedge running along the drive.
- **Between two ray ends, the outline is a straight line.** Where a pillar corner falls midway between two rays, that line passes outside the corner, by up to about a tenth of the drive half-width: roughly 0.25 m at a 5 m crossing. A wedge can reach that far into the corner.

8.3 Fitting the wedge

GEM4D centres the wedge's face on the minode: the middle of its extent across the drive and along it sits on the minode. It then scales the face up until its edge first touches the outline. The fit happens in plan.

Because the outline is measured from the minode, a minode near one wall meets that wall first and gets a smaller wedge. Centred minodes (§3) avoid this.

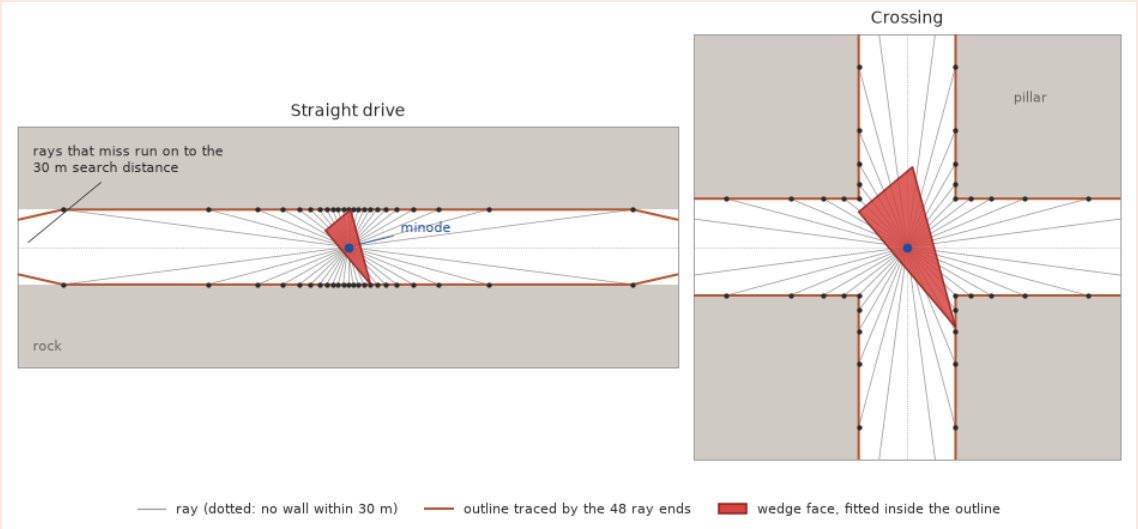


Figure 7 — The ray fan and the fitted wedge, in plan. The same three joint sets in a 5 m straight drive (left) and at a crossing of two 5 m drives (right). Grey lines are the 48 rays; dotted ones met no wall within 30 m. The terracotta line is the outline traced by the ray ends. In the straight drive the walls limit the wedge's face to 5.2 m long; at the crossing it reaches into the cross-cut, to 8.6 m, until the pillar corners stop it.

8.4 WdgSpan

`WdgSpan` is the shortest of the ray pairs whose two rays both met a wall. It approximates the diameter of the largest circle that fits in the opening. In a straight drive it is the drive width, even when the minode is off-centre. At an intersection it is the diagonal, not the length of a cross-cut.

`WdgSpan` is a check on the measurement. The wedge is fitted to the whole outline, not to this number. If no pair met walls on both sides, GEM4D uses the pair across the drive, counting a missed ray as the search distance.

8.5 The back probe

A further ray runs from the minode up through the back, perpendicular to it. It finds the back above the minode, and the wedge mesh is placed there (Chapter 6). It is **not** a test: a minode whose side rays meet walls is analysed even when this ray finds no back, though its wedge cannot be drawn. A row is skipped only when no ray at all meets a mesh.

8.6 What this means in practice

- **Wedges are largest at intersections,** which matches experience. That is where the red wedges usually appear.
- **In a straight drive, wedges grow along the drive** when the joint traces run with it.
- **Check `WdgSpan` when a result looks odd** (§11.4).

9. Orientation scatter: the Monte-Carlo simulation

Mapped orientations scatter. The poles of a joint set spread around the set's mean. The standard model for that spread is the **Fisher distribution**. Its concentration **κ (kappa)** acts like an inverse variance: above about 100 the poles are tightly clustered; below about 20 the set is diffuse.

Each trial redraws every orientation. With *Monte-Carlo trials* above 0, GEM4D repeats the whole wedge analysis at each minode many times. In each trial it draws a random orientation for every set from its Fisher distribution. A trial **fails** if any of its wedges has an FoS below the design FoS. From the trials it reports `WdgPfail` and the percentile columns (§5.4, §5.5).

Persistence and Weight apply in every trial. Persistence caps the traces exactly as in the deterministic solve. A set with a Weight below 1 is present in only that share of trials. A trial with fewer than three sets present forms no wedge; it counts as a trial that did not fail.

With nothing to vary, GEM4D skips the trials. If no ticked set has a κ and none has a Weight below 1, every trial would repeat the mean wedges. GEM4D then writes the exact result directly: `WdgPfail` is 100 where a wedge is below the design FoS and 0 elsewhere, and the percentiles equal the heavy wedge. The summary says so. Enter κ per set to get a scatter-based Pfail; mapped sets are typically κ 20–100.

Each run draws a fresh random seed, so `WdgPfail` changes slightly between identical runs. More trials make it steadier. For the percentiles, see the small-sample note in §5.5.

10. Assumptions and limitations

Keep these in mind whenever the results feed a decision.

1. **Roof wedges only.** The analysed face is the back, following the drive's grade. Sidewall wedges are not analysed.
2. **Four-sided wedges only.** Each wedge is three joints plus the back. Blocks bounded by four or more joints are not modelled; the four-sided wedge is the largest, most conservative case.
3. **Dry and gravity-only.** There is no water pressure and no blasting or seismic load. Ground stress is ignored: it often clamps a wedge in place, but near a de-stressed back that help may be absent.
4. **Joints everywhere.** Wedges are assumed possible at every point (§7.2), so occurrence is overstated by design. The Weight column is the only control on occurrence, and it is statistical, not spatial.
5. **One strength for all joints.** One friction angle and one cohesion apply to every set.

6. **Mean-orientation sets.** Each set enters as one mean plane, plus Fisher scatter in the trials. Local orientation changes that the mapping missed are invisible to the analysis.
7. **Persistence caps the traces on the back,** not the wedge edges running up to the apex. UNWEDGE uses the same convention.
8. **The opening is measured horizontally,** at the minode's elevation. An arched back is wider at mid-height than at the crown, so the fitted wedge errs large there. Check `WdgSpan` at very irregular profiles such as tall stope brows.

Part 3 — Reference

11. Messages and troubleshooting

11.1 Before the dialog opens

Message	Cause and fix
"First load meshes to the scene" (title *Missing information*)	No mesh is loaded. Load the development meshes.
"Every mesh is hidden. Show the meshes to use: tick them in the Objects list." (title *Missing information*)	Meshes are loaded but none is visible. Right after *Minodes from development meshes* this is expected: that tool hides the meshes when it loads the minodes, so tick them again in the Objects list. In clipping mode, the visible clipped pieces count.
"Load minode Markers first…"	The Marker table is empty. Create minodes with **Toolbox 2 ▸ Minodes from development meshes**, ticking both *Output columns* boxes.
"The Marker table has no Dip / DipDir columns…"	The Markers lack the drive-direction columns. Re-create the minodes with **Coordinates + Dip, DipDir, ERF, …** ticked, or load a Marker CSV that has Dip and DipDir columns.

11.2 In the dialog

Message	Cause and fix
"Invalid joint-set value" (window title)	A typed value is out of range: dip 0–90, dip direction 0–360, κ and persistence above 0, Weight above 0 and at most 1. The message names the value and its range. Correct it, or press Esc to restore the old value.
"The joint-set table is limited to 8 sets (3-set combinations grow combinatorially)."	**Add set** was refused because the table is full. Remove a set first, or merge two that describe the same structure.
"N row(s) could not be kept — the table is limited to 8 sets."	**Reload from stereonet** found more sets than fit. It kept the stereonet sets first, then your manual rows, up to eight.
"No stereonet clusters are available to reload…"	No Mapping data is loaded, or the stereonet found no sets. Load Mapping data and check the stereonet, or type the sets in.
"Wedge analysis needs at least 3 enabled joint sets…"	Fewer than three rows are ticked. Tick more rows, add manual sets, or reload from the stereonet. The dialog stays open.

11.3 After you press Analyse

Message or summary line	Cause and fix
"No visible Marker rows to analyse."	Your filter hides every Marker. Relax it.
"No visible mesh geometry to measure the tunnel spans against…"	The visible objects contain no triangles (only lines or points). Make the triangulated tunnel meshes visible.
"Cannot write the wedge columns: an existing non-numeric column named '…' is in the way."	A text column holding values already uses one of the `Wdg*` names, usually from a hand-edited CSV. (A `Wdg*` column with no value in any row is turned back into numbers, §5.2, unless a calculated column uses it.) Rename or delete it and run again; a column that a calculated column uses can be renamed, or deleted once that calculated column is gone.
A large *"Skipped — no mesh within X m"* count	Those minodes met no mesh within the search distance in any direction. They are often left over from a deleted mesh, or the search distance is too short.
"Monte-Carlo: no enabled set has a Fisher κ (and none a partial Weight)…"	The trials could vary nothing, so `WdgPfail` is only 0 or 100 and the percentiles equal the heavy wedge (Chapter 9). Enter κ per set.
"Monte-Carlo: no enabled set has a Fisher κ — WdgPfail reflects set presence (Weight) only."	Some sets have a Weight below 1, but none has a κ, so Pfail measures only how often sets are absent. Enter κ per set to include orientation scatter.
The *Wedge meshes* line	See Chapter 6.

11.4 Results that look wrong

Symptom	Cause and fix
Wedges absurdly large at one spot	Check `WdgSpan` there. The rays probably escaped through a hole in the mesh or into an unmeshed void. Repair or hide that geometry.
Wedge meshes reach past the drive walls	They stay inside the traced outline, apart from up to about 0.25 m at a pillar corner (§8.2). Anything more means the rays escaped there: check `WdgSpan` and the mesh for holes.
`WdgHeavy*` blank where `WdgFoS` is below your design FoS	The run used a lower design FoS than the one you are comparing with. Run again with your current value.
`WdgPfail` differs slightly between identical runs	Normal sampling noise: each run draws a fresh seed. Raise the trial count for steadier values.
`WdgPfail` only ever 0 or 100	No set has a κ (Chapter 9). Enter κ per set; stereonet rows carry it, manual rows start blank.
A *Stereo (girdle)* set dominates the results	Girdle-shaped sets have unreliable Fisher statistics. Consider replacing it with manual sets that describe the structure properly.
Wedge weights differ from GEM4D 1.9.0	Expected: since 1.9.1 wedges are fitted to the measured outline (Chapter 8) and the heaviest wins a tie. They are the same or larger in straight drives, and can be smaller at T-junctions.
The table ignores new mapping	The dialog remembers its table. Press **Reload from stereonet**.

12. Glossary

Term	Meaning
Apex	The point where the three joints of a wedge meet, inside the rock above the back.
Apex depth	The height of the apex above the back, measured perpendicular to the back.
Back	The roof of a drive. GEM4D takes it as the plane that follows the drive's grade and is level across the drive.
Design FoS	Your failure threshold. Wedges below it fail.
Face	The triangle a wedge exposes on the back.
Fisher κ (kappa)	How tightly a joint set's poles cluster: larger means tighter.
Governing wedge	The least stable wedge at a minode: the lowest FoS, the heaviest at a tie.
Heavy wedge	The heaviest wedge at a minode with an FoS below the design FoS.
Minode	A Marker point along a drive, carrying the drive direction (Dip, DipDir). Made by *Toolbox 2 ▸ Minodes from development meshes*, which can centre it in the drive.
Outline	The excavation outline traced by the 48 ray ends around a minode.
Persistence	The longest trace a joint set can leave on the back.
Pfail	The percentage of Monte-Carlo trials in which a wedge failed the design FoS.
Trace	The line a joint plane cuts across the back.
Ubiquitous joints	The assumption that every joint set can occur anywhere.

13. References

- Hoek, E. & Brown, E.T. (1980). *Underground Excavations in Rock.* IMM, London. (Wedge limit-equilibrium procedure.)
- Goodman, R.E. (1989). *Introduction to Rock Mechanics*, 2nd ed. Wiley. (Block kinematics and limit equilibrium.)
- Goodman, R.E. & Shi, G. (1985). *Block Theory and its Application to Rock Engineering.* Prentice-Hall. (Removable-block theory behind the mode classification.)
- Fisher, R.A. (1953). Dispersion on a sphere. *Proc. Royal Society A*, 217, 295–305. (Orientation statistics used in the Monte-Carlo trials.)
- Rocscience UNWEDGE documentation. (The joint-length and opening-size scaling conventions GEM4D follows.)

Appendix A — One wedge by hand

This appendix works one wedge through by hand so that you can check GEM4D's arithmetic. GEM4D's own tests check these numbers against the program's calculation.

Sizing the face to a real opening is a geometric step (Chapter 8). To keep the hand calculation short, the example starts from a face of known size.

A.1 A symmetric falling wedge

Inputs. Three joint sets, each dipping 60°, at dip directions 000°, 120° and 240°. A level back. The face is an equilateral triangle with its corners on a 10 m circle. Friction 35°, no cohesion, unit weight 2.7 t/m³.

Step	Working	Result
Face side	10 m circle, radius R = 5 m: side = R√3	**8.660 m**
Distance from face centre to each edge	r = R / 2	2.500 m
Apex depth	Each joint rises from its edge at 60°: h = r × tan 60°	**4.330 m**
Face area	(3√3 / 4) × R²	**32.48 m²**
Volume	face area × h / 3	**46.875 m³**
Weight	46.875 × 2.7	**126.56 t**

Mode. The wedge is symmetric, so the vertical line from its apex passes through the centre of its face. It falls (mode 1). Without cohesion, **FoS = 0**.

A.2 The same wedge with cohesion

Add 50 kPa of cohesion. A falling wedge's only resistance is cohesion on its three joint faces.

Step	Working	Result
Height of each joint face	√(r² + h²) = √(2.5² + 4.330²)	5.000 m
Area of each joint face	½ × 8.660 × 5.000	21.65 m²
Total joint-face area	3 × 21.65	64.95 m²
Weight as a force	126.56 t × 9.80665 kN/t	1 241.15 kN
FoS	50 × 64.95 / 1 241.15	**2.62**

A.3 A single-plane slide

Inputs. A sliding joint dipping 40° toward 180°, with two steep release joints (80°/095° and 75°/265°). Level back, friction 35°, no cohesion.

The wedge slides down the 40° joint (mode 2). Without cohesion, the classic result is **FoS = tan φ / tan ψ**, where ψ is the dip of the sliding joint:

FoS = tan 35° / tan 40° = 0.7002 / 0.8391 = **0.834**

The wedge's size does not enter this result. Doubling the opening gives the same FoS (§7.5).

A.4 The 95th percentile

GEM4D uses the **nearest-rank** rule. Sort the *n* values from smallest to largest and take value number ⌈0.95 × *n*⌉.

- *n* = 10: ⌈9.5⌉ = 10, the **largest** value.
- *n* = 20: ⌈19⌉ = 19, the second largest.
- *n* = 100: value number 95.

This is why `WdgDepth95` and `WdgWeight95` jump between runs when only a few trials fail (§5.5).