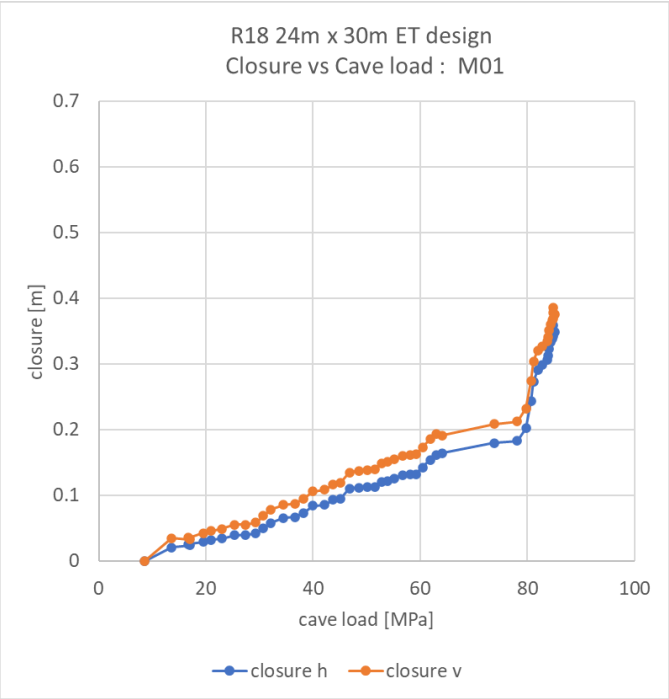
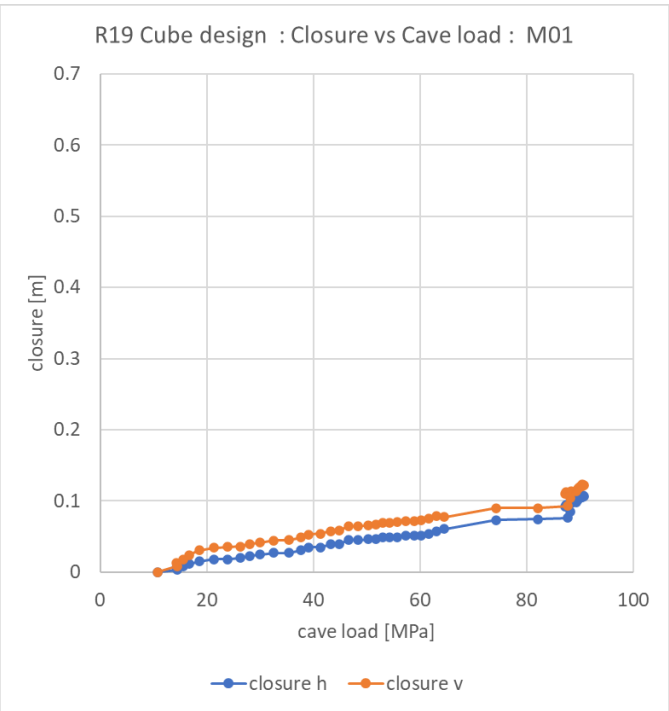
Stability analysis of the Cube drawbell design

Main findings

- Two different designs were investigated and subjected to similar load histories from a large block cave operation
- The two deigns were 24m x 30m El Teniente layout (R18) and the 50m x 50m cube drawbell design (R19)
- R18 was taken from the 24m x 30m ET design footprint stability assessment and was selected as it was the largest 'contemporary' footprint design that was assessed the maximise stability
- For both designs the rock mass performance for two different rock types (M01 and M02) was analysed.
- Both rock types have the same DFN in the model
- M01 = diorite (stronger rockmass)
- M02 = endoskarn (moderate strength rockmass)
- The rock mass performance was measured by observation of damage and deformation and the drive closure during increasing cave load





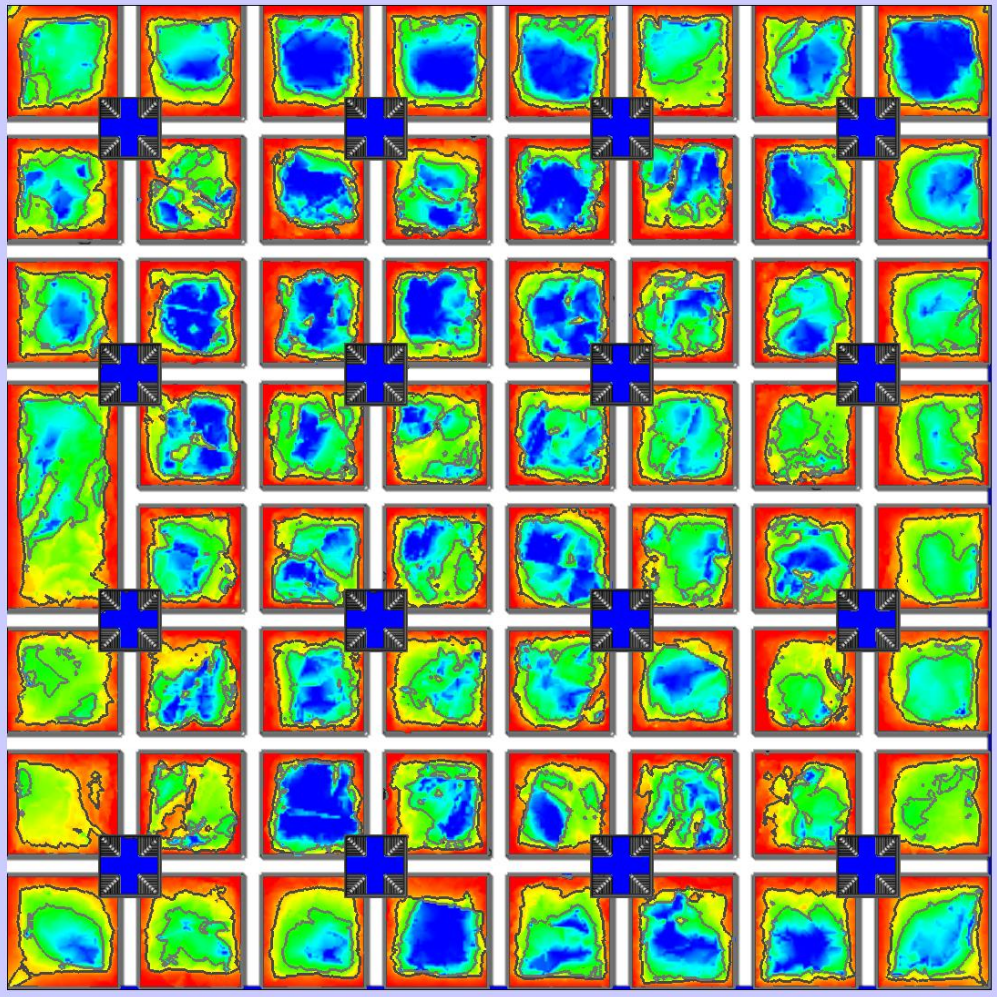
Main findings

- Results summary – the cube design is forecast to experience significant less closure and deformation in the drives. Drive closure forecasts for the 24m x 30m ET design is approximately double the closure forecast in the cube design.
- In the model simulations:
  - Development in the cube design is subject to high levels of stress resulting in significant rockmass damage in the perimeter of excavation that would require heavy ground support. Only minor levels of rockmass damage are forecast in the pillar cores
  - In the 24m x 30m El Teniente design, significant levels of rockmass damage extend through large portions of the pillars. The onset of rockmass yielding begins to occur in pillar cores as the cave loads are artificially increased to test footprint stability.
- Closure increases significantly as the cave loads are artificially increased at the end of mining to test for stability affects. This effect is somewhat similar to a strength test in a lab where a rock sample is continuously loaded to test for (potential) failure. The increase in loads has a marginal impact on the Cube footprint when compared to the contemporary El Tenitente design, noting that a 24m x 30m drawbell spacing has pillars larger than typical 18m x 30m or 20m x 30m layouts.
- It must be noted that the damage and closure induced by the blasting of the DBs and undercut is similar, if not more significant, for the very large draw bells of the Cube design. However, when the two footprint designs are compared by drive closure performance only, the Cube DB design is superior.
- The Cube footprint design is a post undercut type design. This means that much of the extraction level development is not 'protected' or shadowed by an advanced undercut ahead of the majority of development. This means that development in the cube design will be subject to potentially high levels of stress, depending on the mining depth
- The main vulnerability of the cube design is the 4 way intersections and potential for deformation and damage to the drives during development in extreme operating environments (high stress, low rockmass strength etc)
- The main vulnerability of the El Teniente design, in terms of stability, is also the 4 way intersections, as well as the elongated pillar noses and smaller pillar dimensions. The pillar geometry in a El Teniente layout is more susceptible to pillar instability in adverse conditions compared to the cube design with larger and more regular shaped pillars

Comparison of rockmass damage

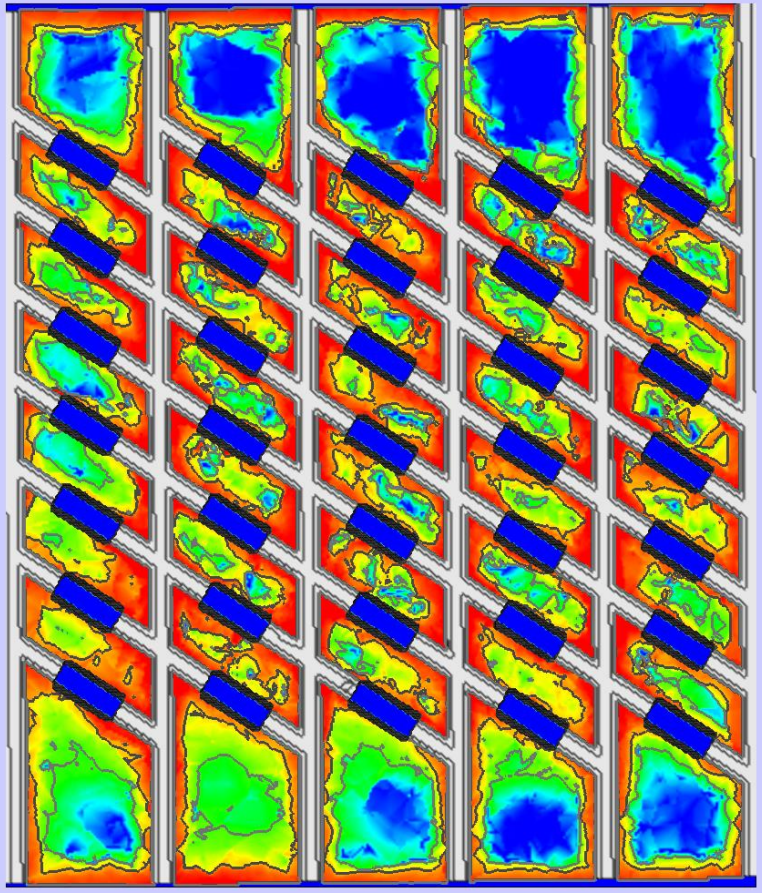
Cube design

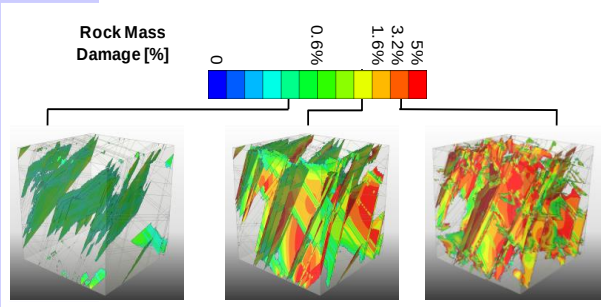
Moderate to significant damage around drives due to high stress conditions. Minor rockmass damage in pillar cores. Rockmass damage forecasts are sufficiently high to require heavy support and rehabilitation of drives, but not sufficiently high to cause drawbells to be abandoned due to pillar instability



24m x 30m El Teniente layout

Significant damage through the pillar noses. Moderate to significant damage extends through the pillars, including pillar cores. Deformation is sufficiently high that LOM production would be impacted due to stability issues as well as delays caused by ongoing rehabilitation of damaged pillars and drawpoints





Recommendations (stability)

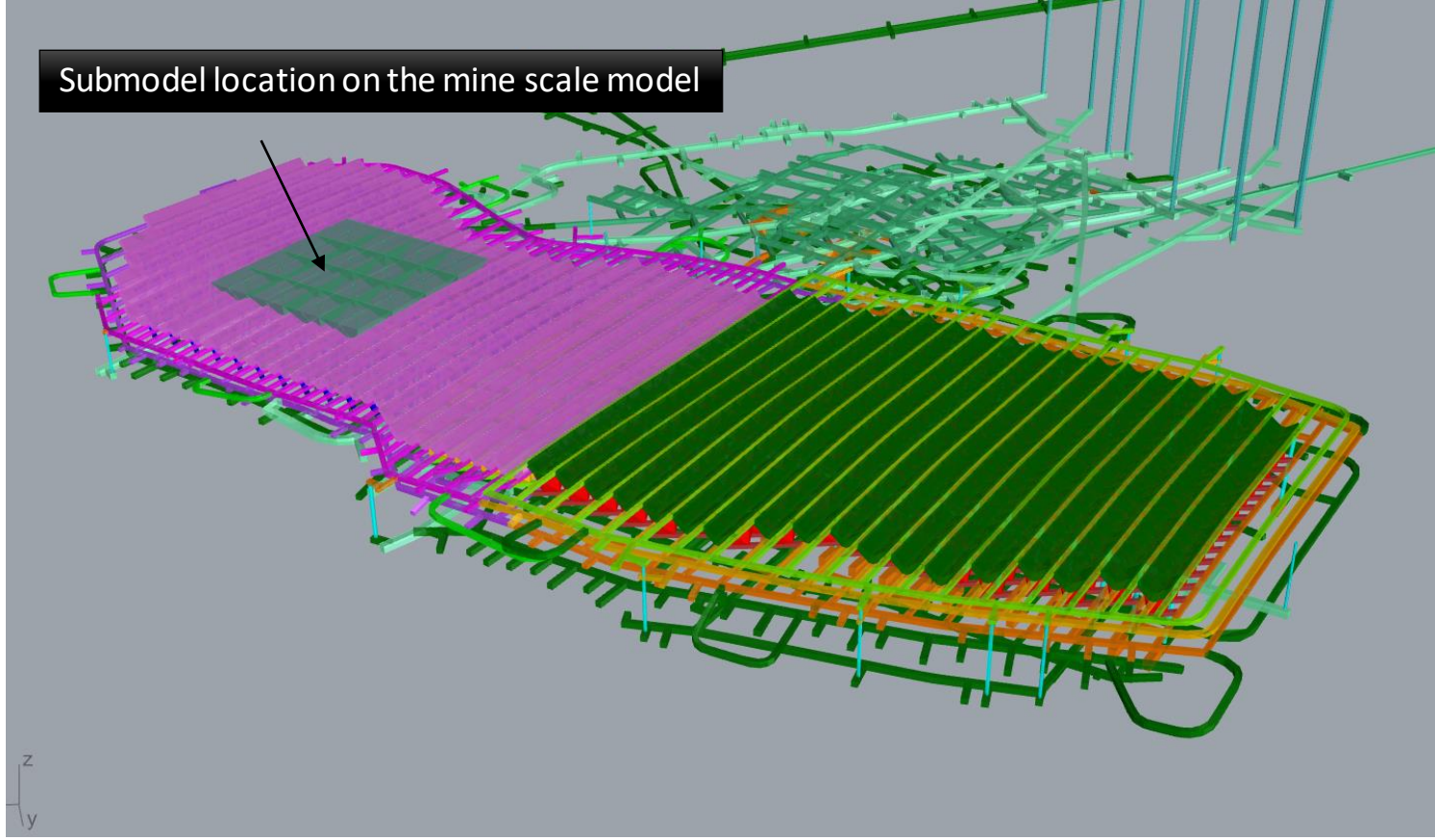
- Consider offsetting the access drives to avoid 4 way intersections. This could be done by mining the drawpoint drives at an angle to the main access drive and offsetting the 3 way intersections. A similar principal is used for an offset herringbone layout. This would improve stability for the intersections, but is likely to have some operational ramifications for drawpoint loading, tramming routes or the use of conveyors / continuous loading equipment. It is uncertain if a fit-for-purpose layout could be achieved with offset drives, however such a design is worth consideration.
- The cube design is essentially a post undercut design and the extraction level is subject to significant stress change and (potential) rockmass damage during mining of the large drawbells. The extraction level drives must be supported sufficiently to manage anticipated levels of deformation. Mining a horse-shoe drive profile is a means to improve drive stability. This may be a requirement for mine development on the extraction in extreme environments.

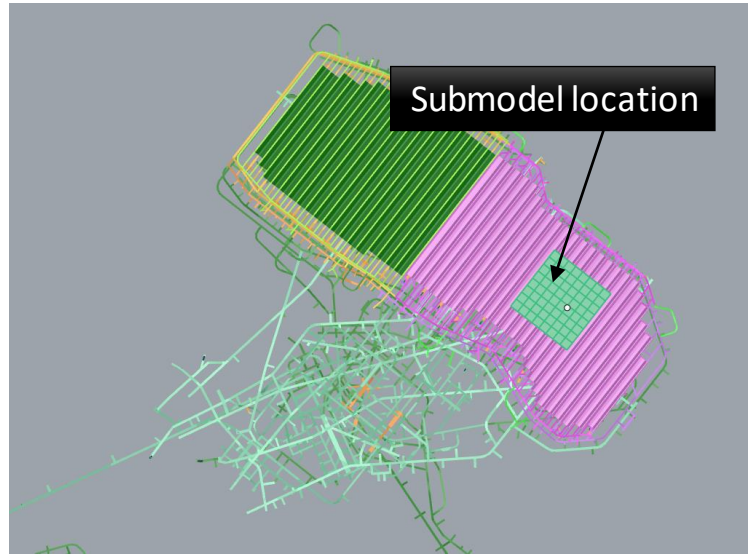
Work flow

1. Create submodels with different designs 24m x 30m ET design & Cube DB design to match the selected locations of the mine scale model footprint
2. Impose a DFN into each of the submodels
3. Adjust global mine scale model to host the submodels for the two drawbell layouts and run global simulations
4. Sequence the submodels according to the mine scale model sequence
5. Extract mine scale deformation pattern at the boundary location of the submodels
6. Run the submodels with different material properties and load histories taken directly from the global mine scale model
7. Evaluate cave loads and drive closure for each of the runs. Results evaluation is limited to the center region of the submodels.

Submodel locations

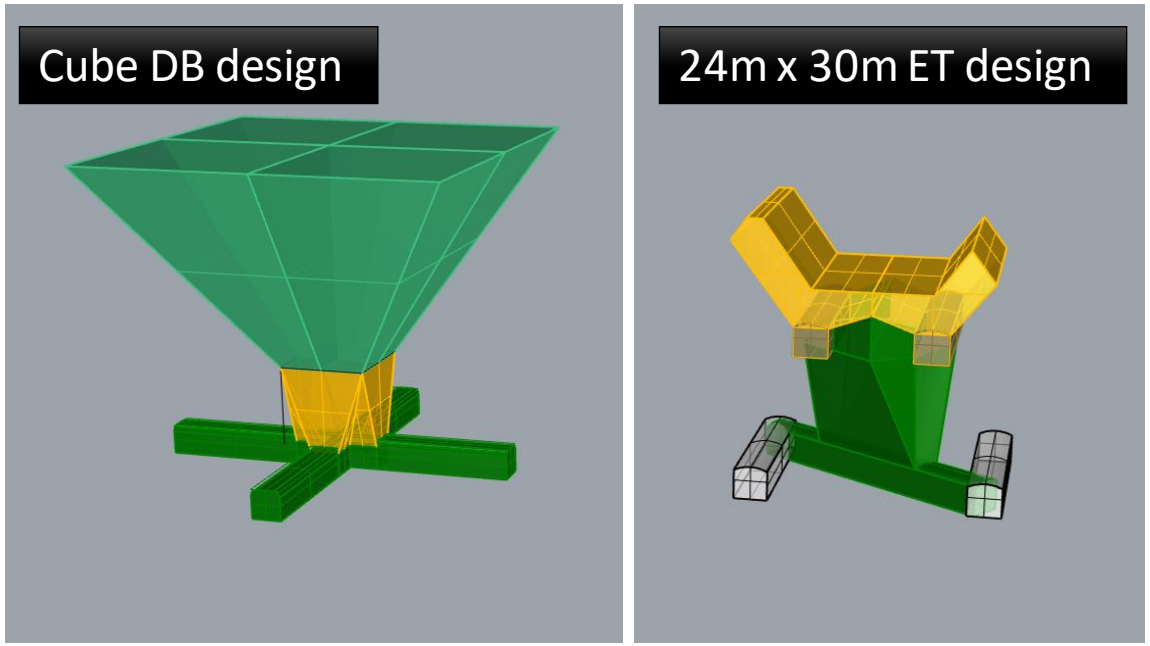
- For the submodel analysis runs 1 locations at the DMLZ footprint was selected
- Depth of the DMLZ extraction level is ~1350m and below the exhausted DOZ
- The location was selected to allow an easy placement of the submodel on the footprint and to avoid boundary effects from the outer regions of the footprint
- To cover a larger area of the footprint different submodel designs would have been required (alignment of draw point access with the global model must be given)

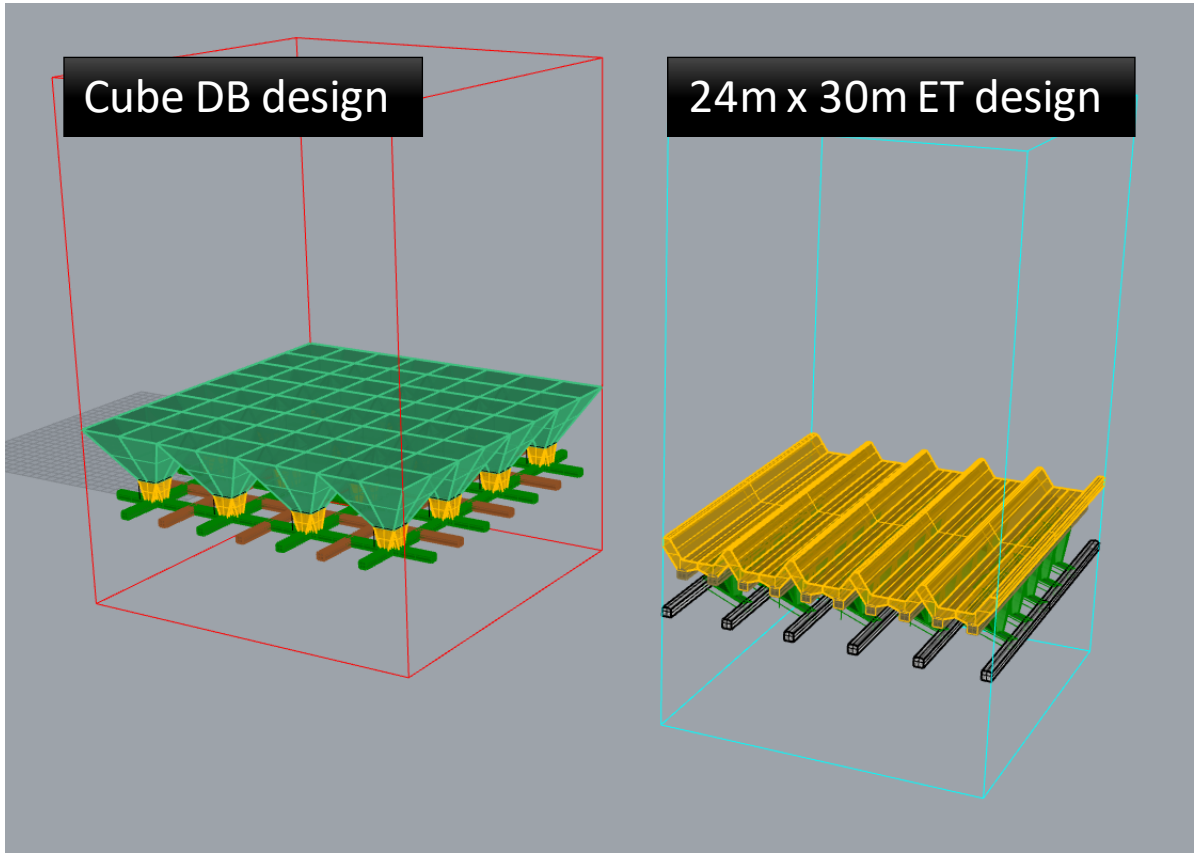




Footprint model geometry

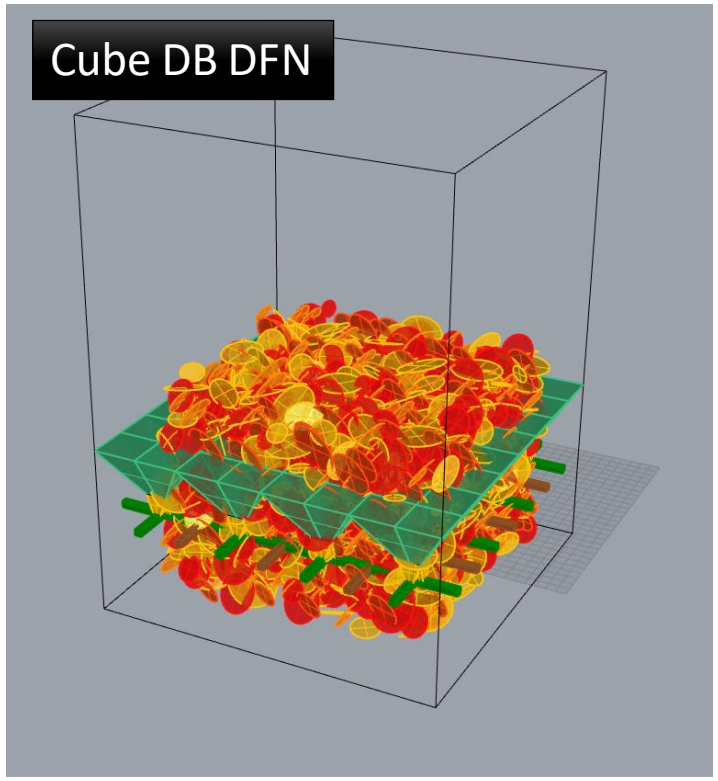
- Model design 24m x 30m ET design consists of 20 (5x4) draw-bell-ring cells and model design of 16 (4x4) cells. Both designs cover the approximately same area to allows the placement of the submodels at the same location in the global model

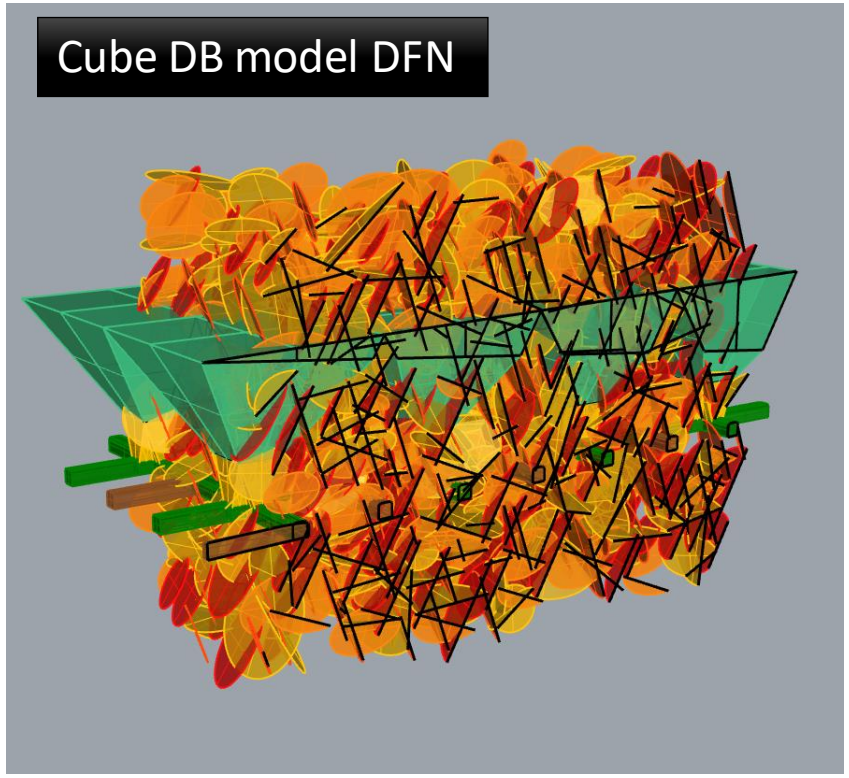




DFN

- Both models use the same embedded explicitly build DFN to establish the assumption that both models perform in the same rock type.
- However, due to the different orientation of the extraction level drives and the draw bells and rings the intersection of cracks with excavations may leads to different typical effects in pillar damage and drive deformation





Material properties

- For simplicity both submodels were assumed to host a single rock mass type
- The rock mass properties taken from corresponding calibrated material property sets determined during the simulations of the global mine-scale model.

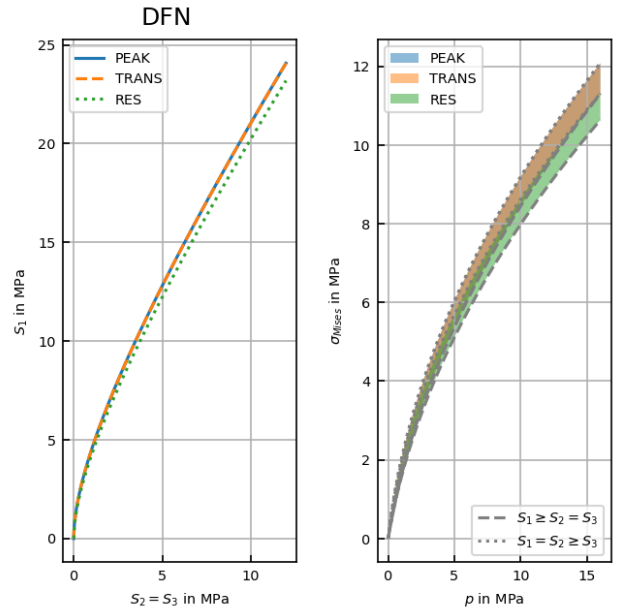
General Properties

Type	Computator V13 PLR
ρ [kg/m³]	2700.00
UCS_i [MPa]	30.00
GSI	30.00
n_{aniso}	1.00
s_{aniso}	1.00

LR2 Parameters

	PEAK	TRANS	RES
ϵ_{plast} [%]	0.00	3.34	5.85
E [GPa]	6.27	6.27	6.27
ν	0.22	0.22	0.22
s	1.93e-04	1.93e-04	8.43e-05
m_b	0.40	0.40	0.35
a	0.50	0.50	0.50
e	0.60	0.60	0.60
d	0.07	0.07	0.03

DFN



DFN

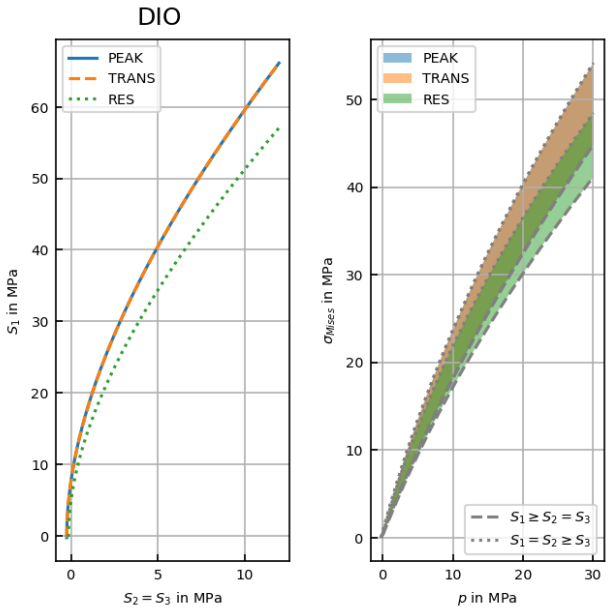
... for M01 and M02 host rock

General Properties

Type	Computator V13 PLR
ρ [kg/m³]	2700.00
UCS_i [MPa]	120.00
GSI	60.00
n_{aniso}	1.00
s_{aniso}	1.00

LR2 Parameters

	PEAK	TRANS	RES
ϵ_{plast} [%]	0.00	1.95	3.41
E [GPa]	25.08	25.08	25.08
ν	0.27	0.27	0.27
s	4.38e-03	4.38e-03	1.91e-03
m_b	1.99	1.99	1.39
a	0.50	0.50	0.50
e	0.60	0.60	0.60
d	0.30	0.30	0.11



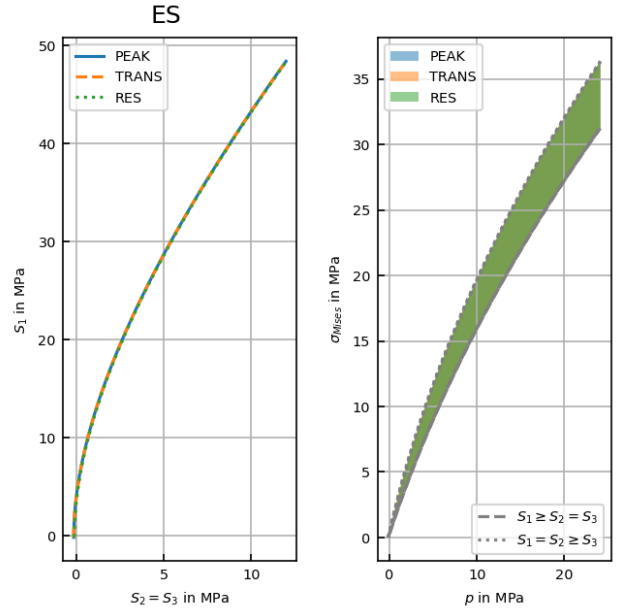
M01 : DIO

General Properties

Type	Computator V13 PLR
ρ [kg/m³]	2700.00
UCS_i [MPa]	100.00
GSI	40.00
n_{aniso}	1.00
s_{aniso}	1.00

LR2 Parameters

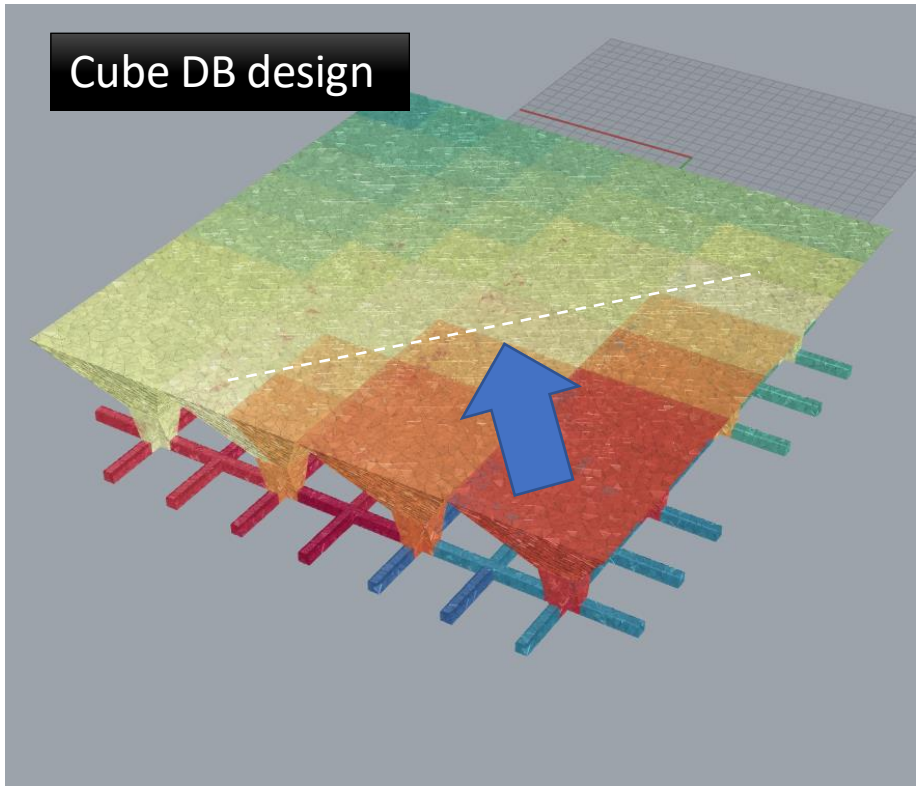
	PEAK	TRANS	RES
ϵ_{plast} [%]	0.00	2.20	3.84
E [GPa]	20.90	20.90	20.90
ν	0.26	0.26	0.26
s	1.70e-03	1.70e-03	1.26e-03
m_b	1.09	1.09	1.09
a	0.50	0.50	0.50
e	0.60	0.60	0.60
d	0.25	0.25	0.09

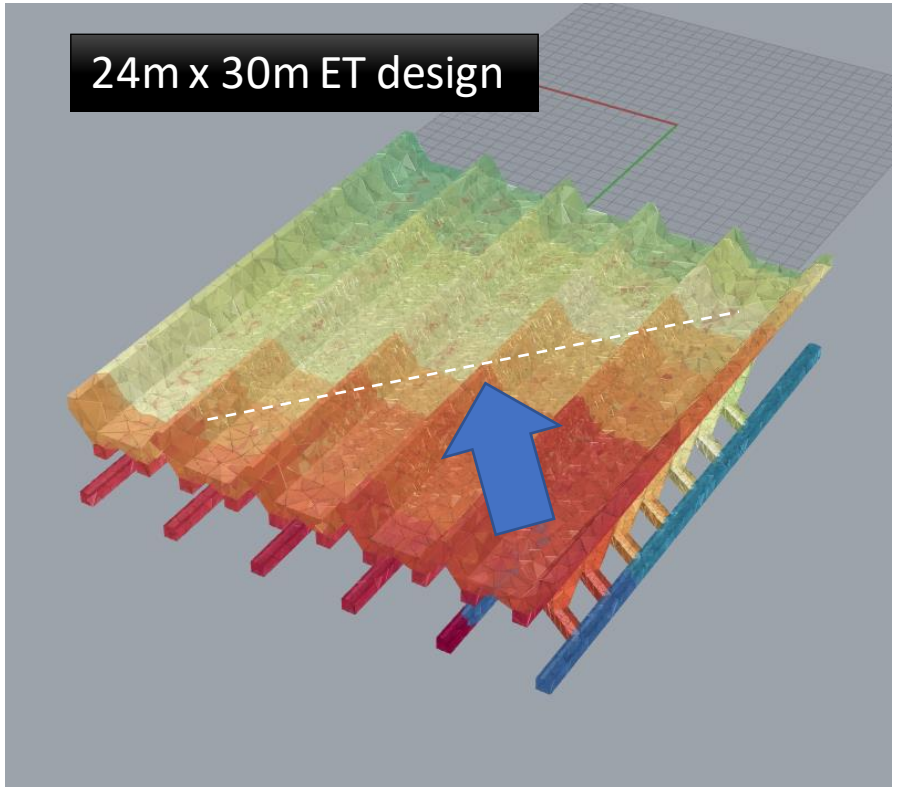


M02 : ES

Sequence

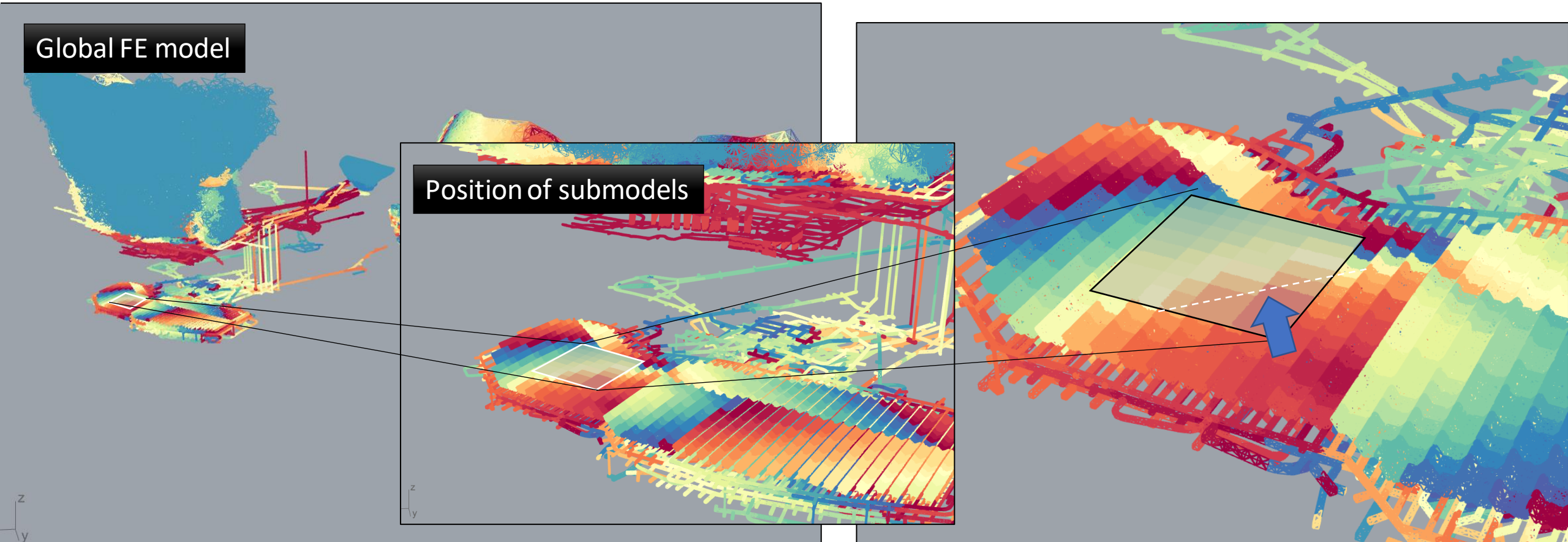
- The sequence for both models is derived from the original sequence of the global model.
- The time span from initial blasting and full production is similar in both models





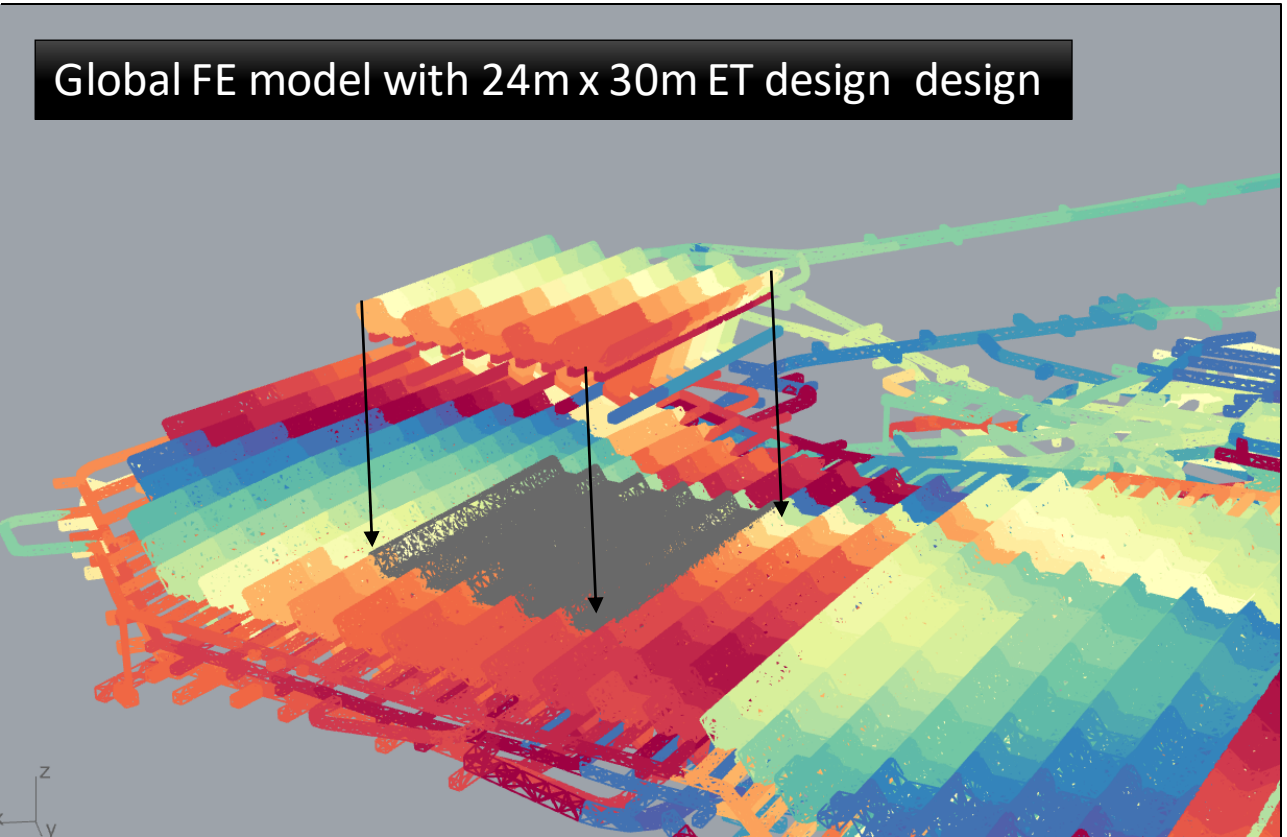
Global block cave model to provide a realistic load scenario

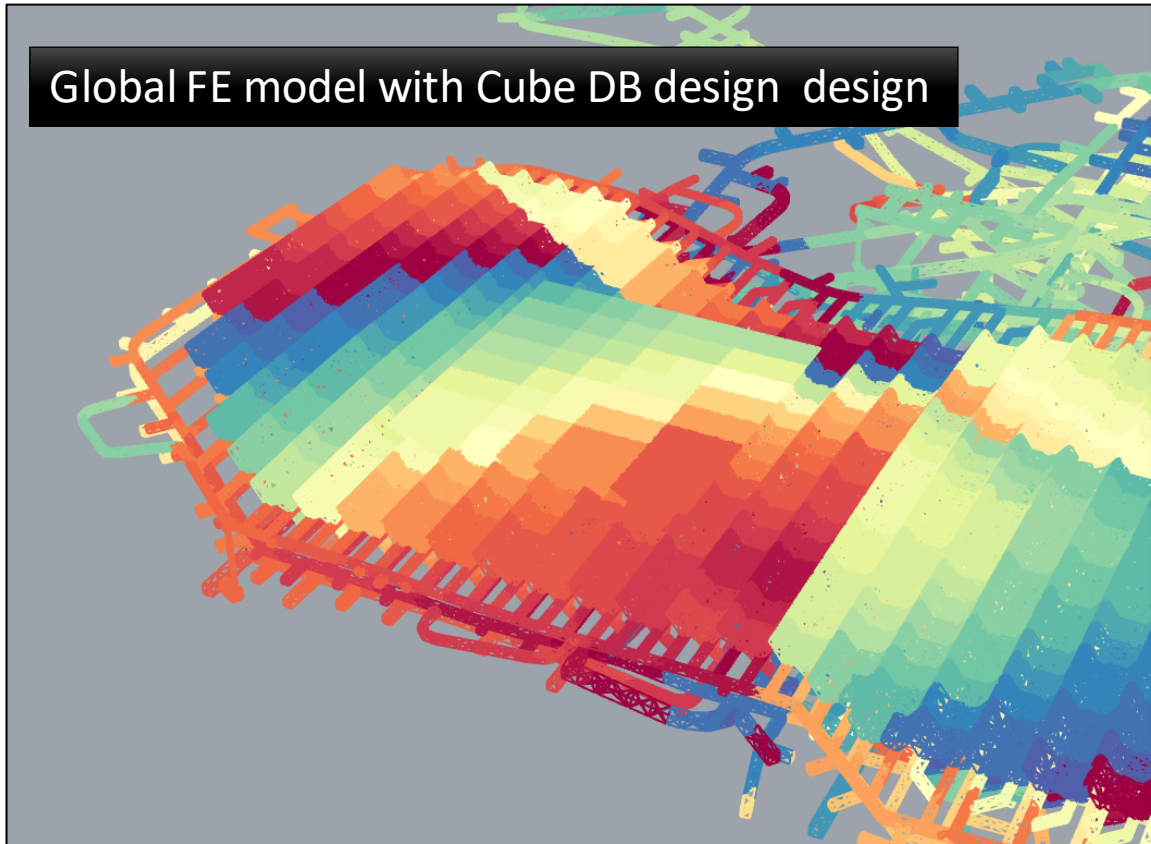
- In order to apply a realistic load path, a global mine-scale block cave model was modified to provide external load conditions. The mine-scale model was running separately for each of the different designs



Global block cave model to provide a realistic load scenario

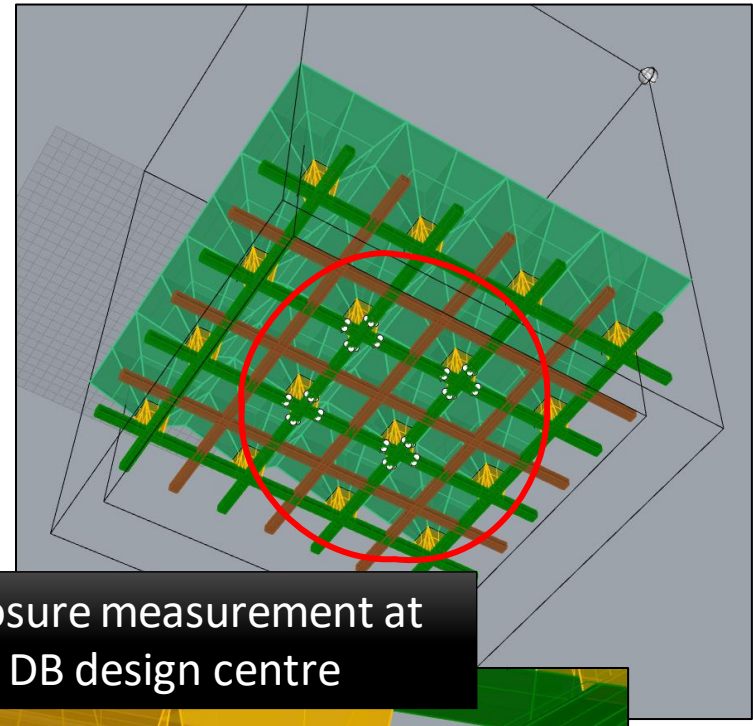
- The original global model used for the simulation used a design almost identical to the 24m x 30m ET model design. Therefore the integration of the sequence and the alignment of the drive connectivity was more seamless than for the Cube DB design .
- However, the draw point drive performance and the pillar performance in the centre of the submodel is not affected



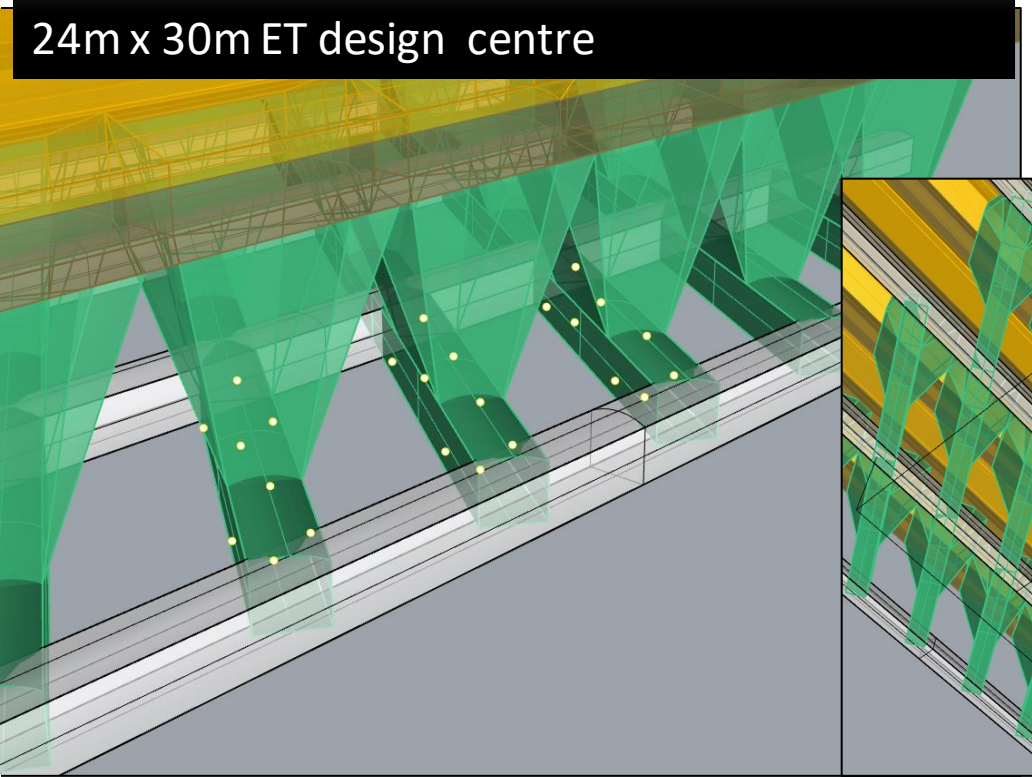


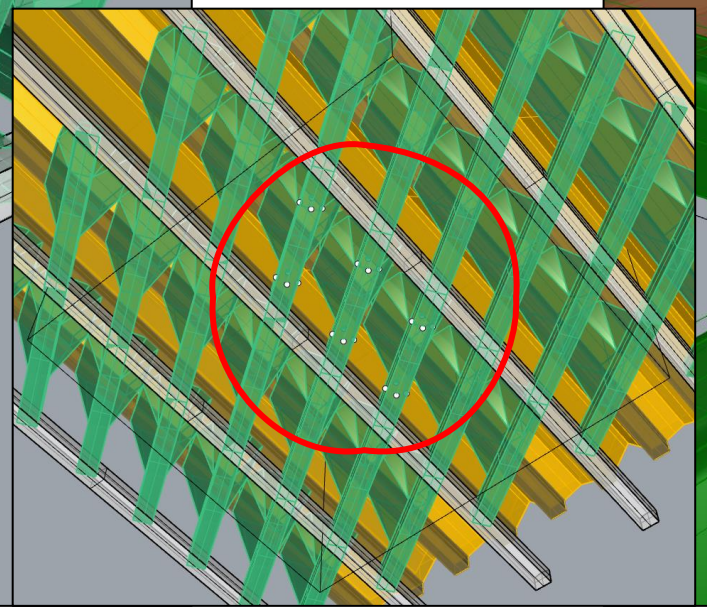
Measurement of drive closure

- The drive closure was measured at adjacent point of the drive walls and back and floor close to the draw points (2m distance). Vertically aligned points provide vertical drive closure and laterally aligned points provide horizontal closure.

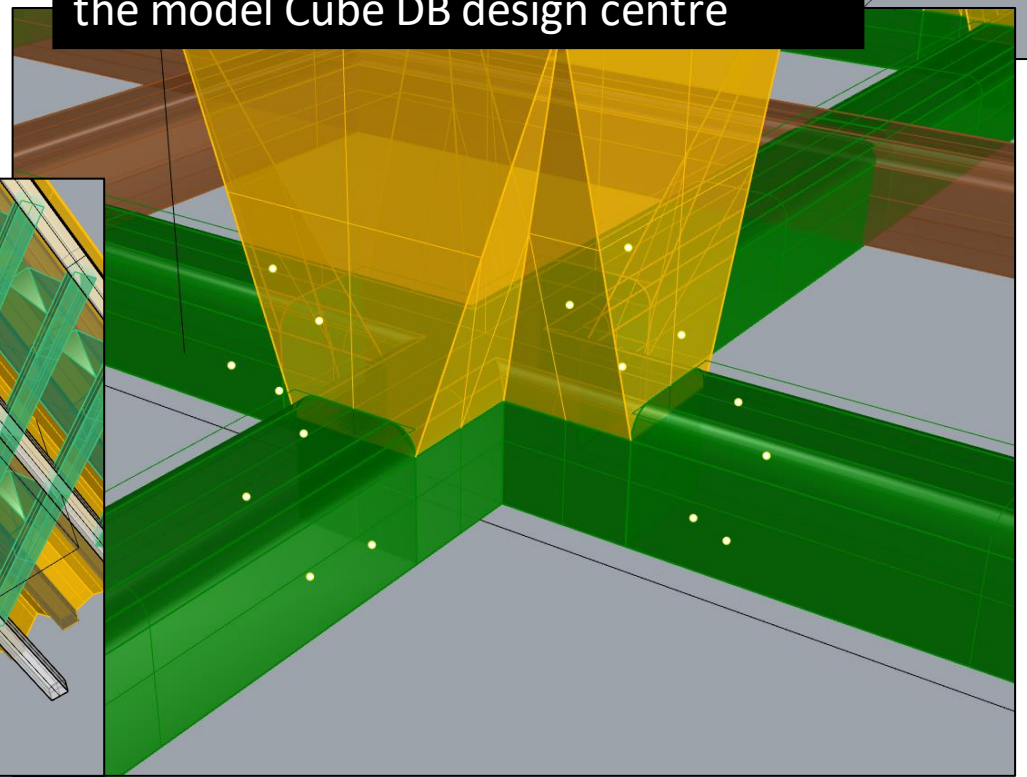


Locations for closure measurement at the model 24m x 30m ET design centre



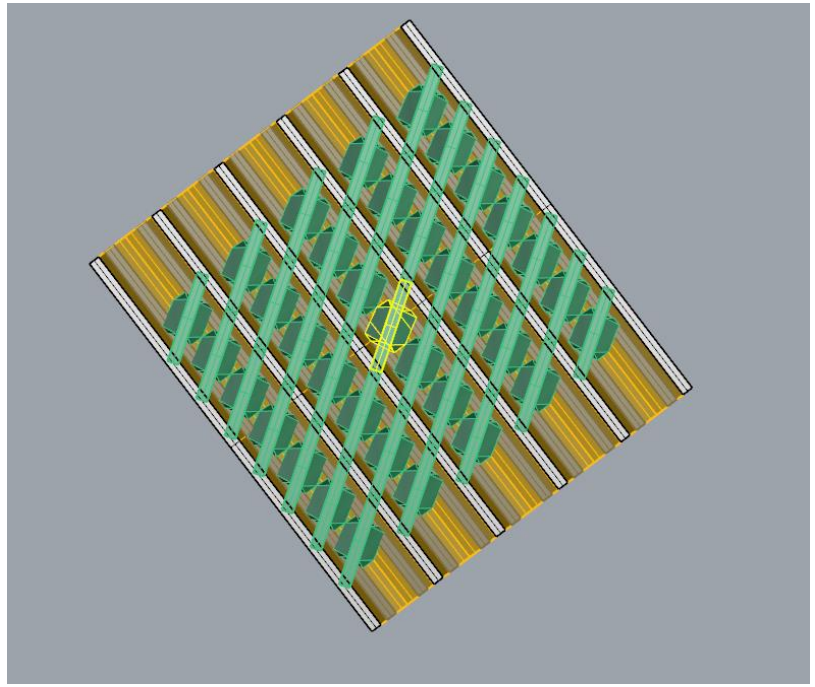


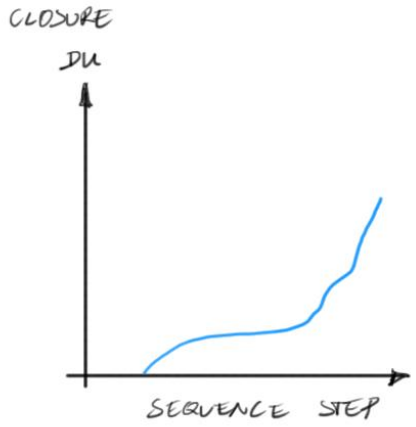
Locations for closure measurement at the model Cube DB design centre

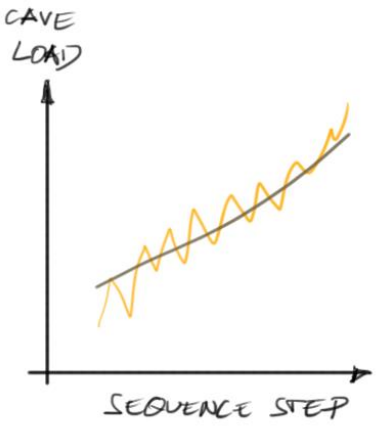


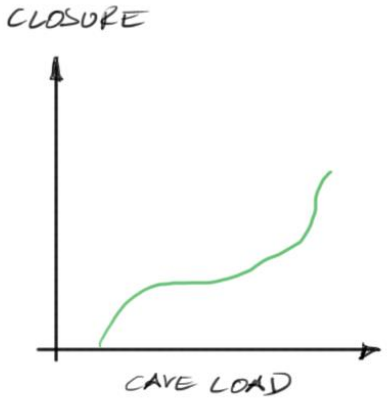
Data processing for a submodel / Performance parameter

- All data is evaluated for the center draw bell of the submodel only.
- The results of a submodel run are used to extract:
  - Drive closure at selected positions of the submodel from the time the rings are excavated
  - Cave load over the extraction sequence and the mine of live load history
- These two quantities (closure at a drive location and cave load) are used to create drive closure over cave load diagrams



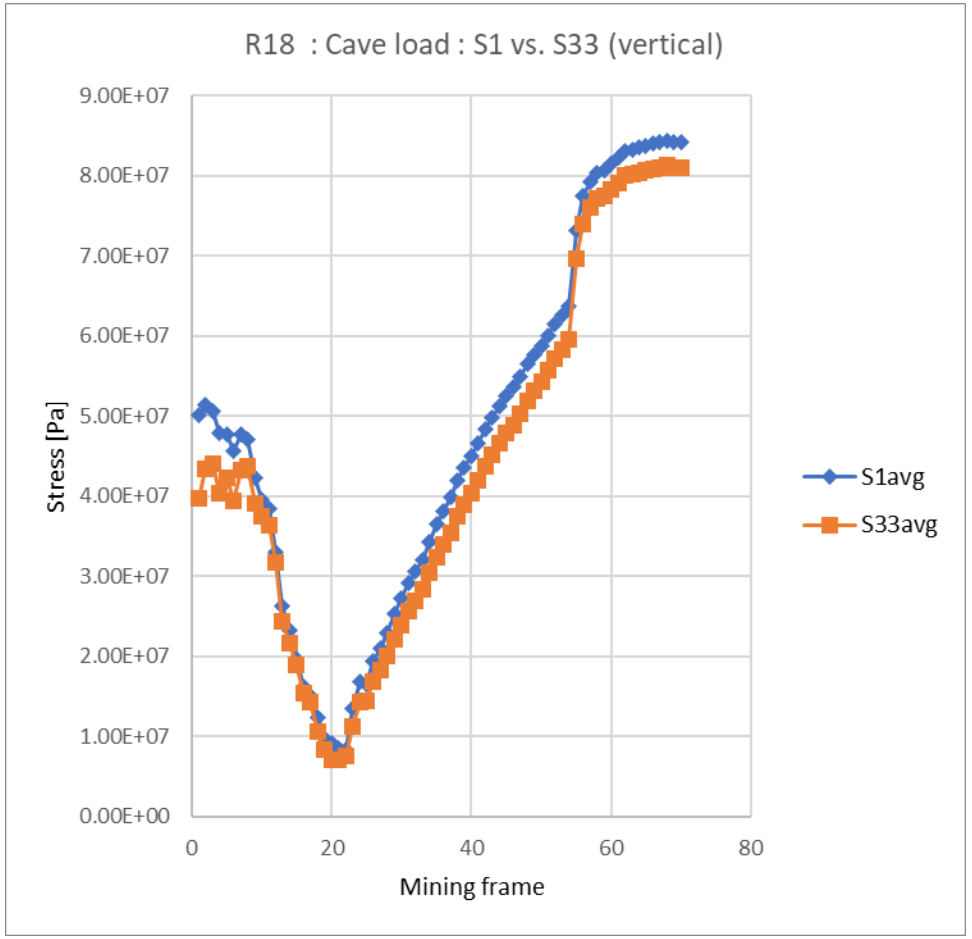






Measurement of cave load

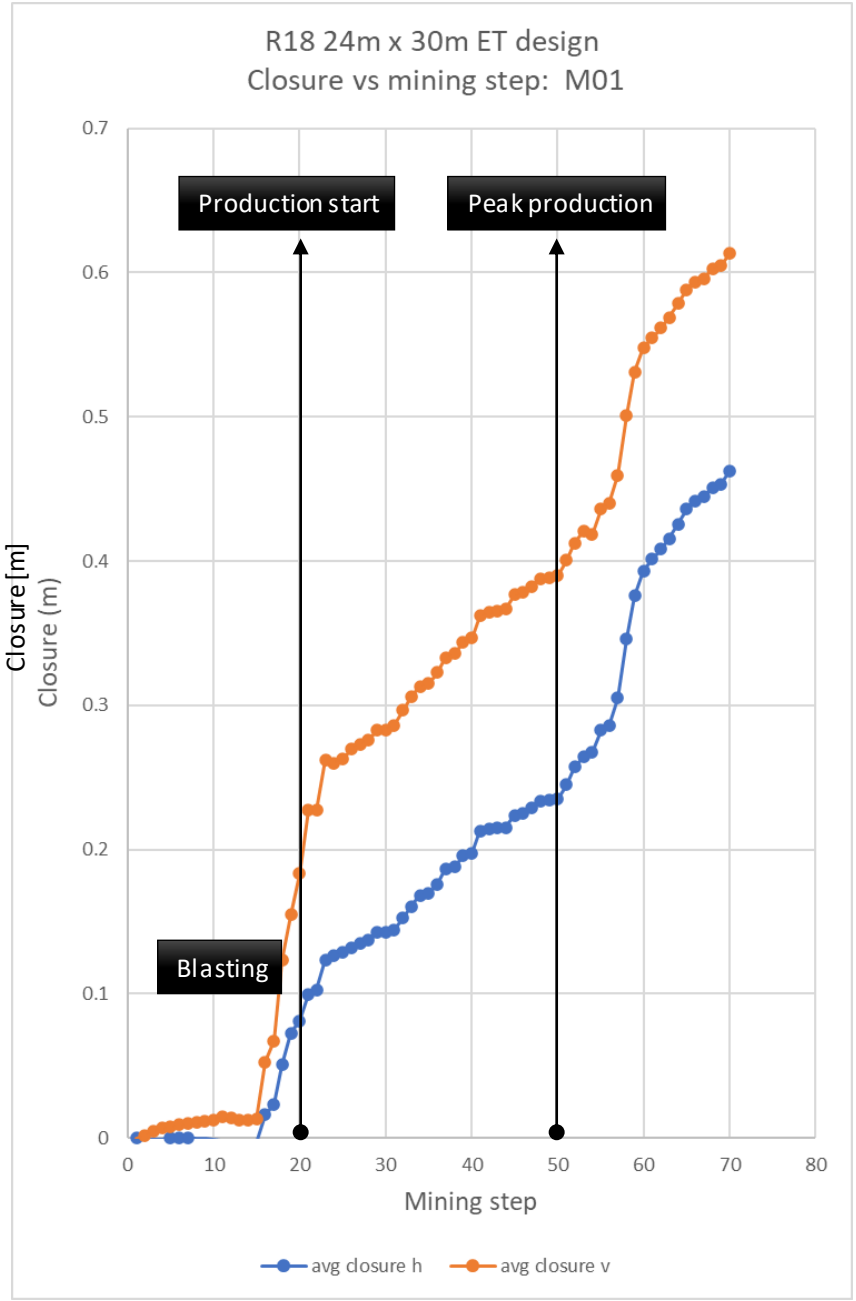
- The cave load is measured above the under cut rings in a point grid of 27 locations and averaged to provide a single representative value. The cave load shows of course some large spatial variability and time dependence from the current production. Here, for simplicity, we assume a statically resting cave at the end of each production cycle (quarterly mining steps)
- Initially the rock above the footprint shows the current intact rock stress conditions (that may have changed from the in-situ stress conditions due to mining nearby)
- During blasting the undercut the rock destress significantly and with cave initiation and growth the cave load increases as well
- S1 (major principal stress) and S33 (vertical stress) magnitudes are very similar, i.e. the major principal stress is vertical. S1 is used as cave load.
- All models (design and rock type) show qualitatively similar evolutions of cave load



Drive closure

- Drive closure was extracted for both model designs and both materials
- The picture to the left shows two examples for the averaged vertical and horizontal closure of the 24m x 30m ET design in the M01 rock type
- The early increase in closure is due to the blasting of the draw bells and rings an the blasting activity nearby and would not be accounted for as production related closure. This displacement during development would not be measured or impact stability and is excluded from the charts in the following slides (excluding slides 18 and 19).
- From frame 20 on the cave growth and the drive closure increases continuously

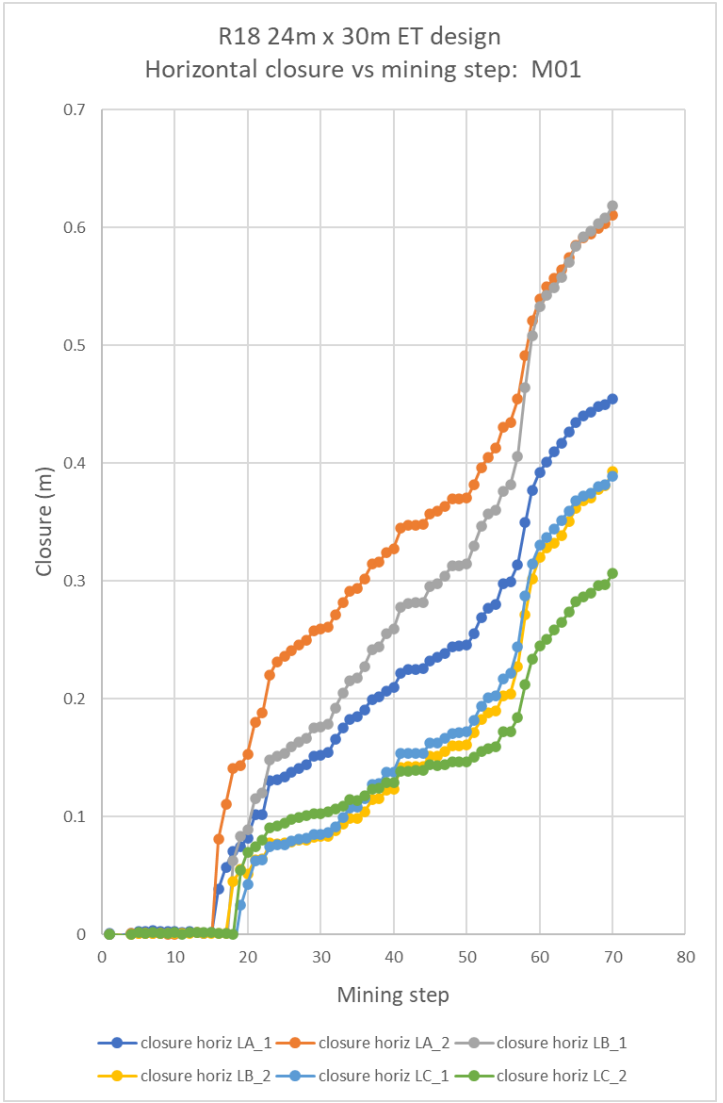
Example drive closure for the life-of-mine for the 24m x 30m ET design model (R18, M01)

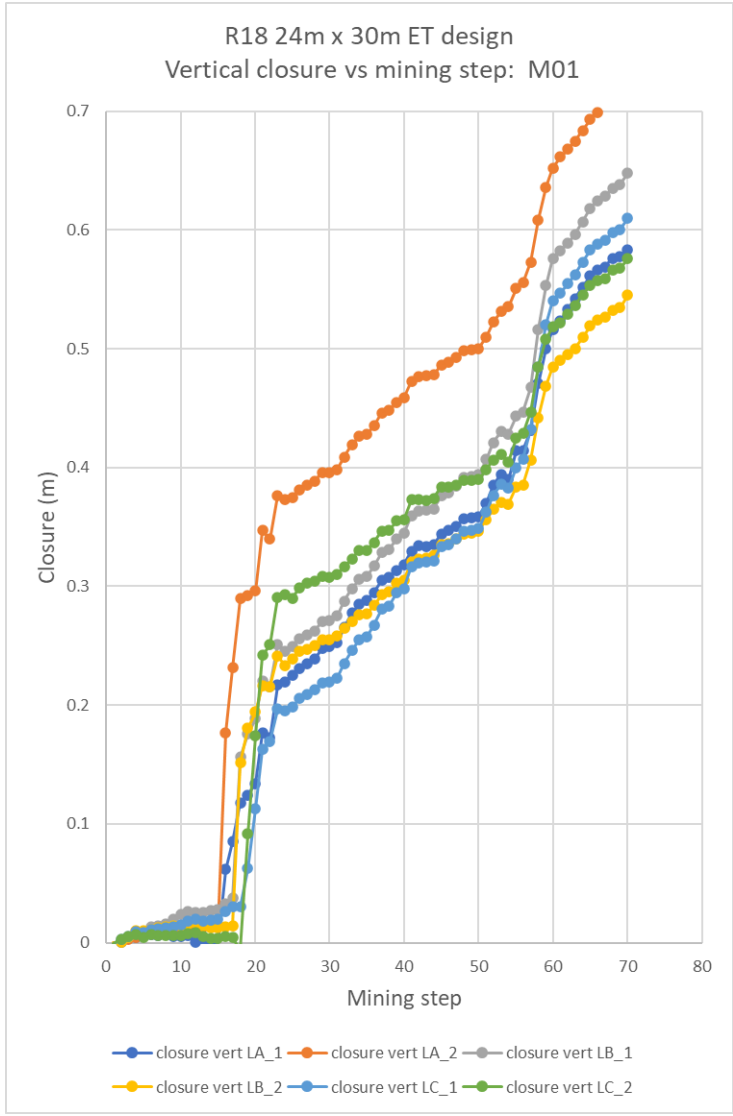


Drive closure : Spatial variability

- With the presence of a discontinuum fracture-network embedded into the rock mass one must expect a significant variability in the measured drive deformations
- The analysis of 6 different measurement locations for the 24m x 30m ET design shows a significant difference between smallest drive closure measured (~0.3m) and the maximum values observed (~0.7m).
- It is noted that a significant portion of this closure occurs during the excavation of the drive (<frame 20) and would not be measured by the mine in reality

Example drive closure for the life-of-mine for the 24m x 30m ET design model at different measurement locations(R18, M01)

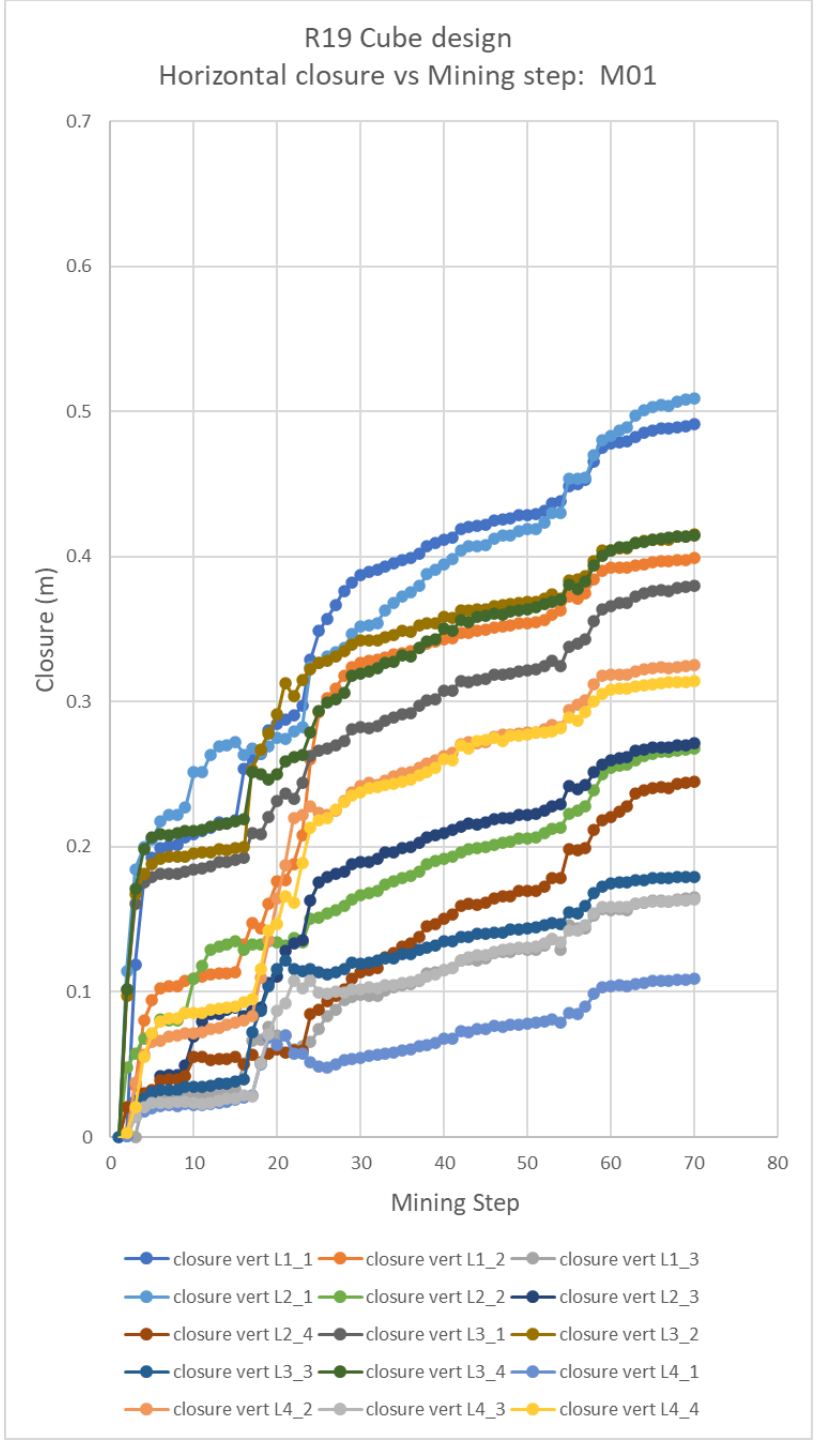


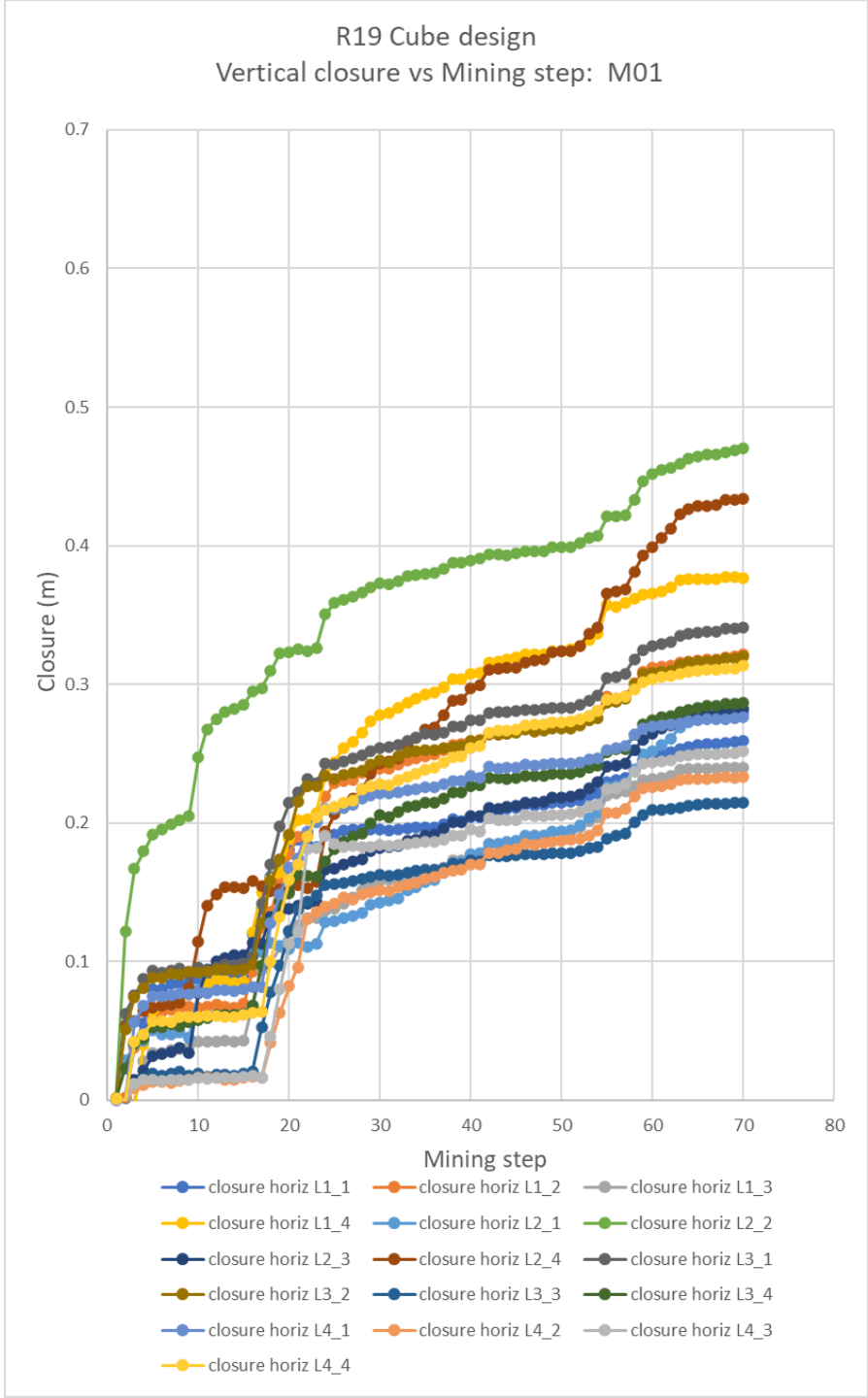


Drive closure : Spatial variability

Example drive closure for the life-of-mine for the Cube design model at different measurement locations (R19, M01)

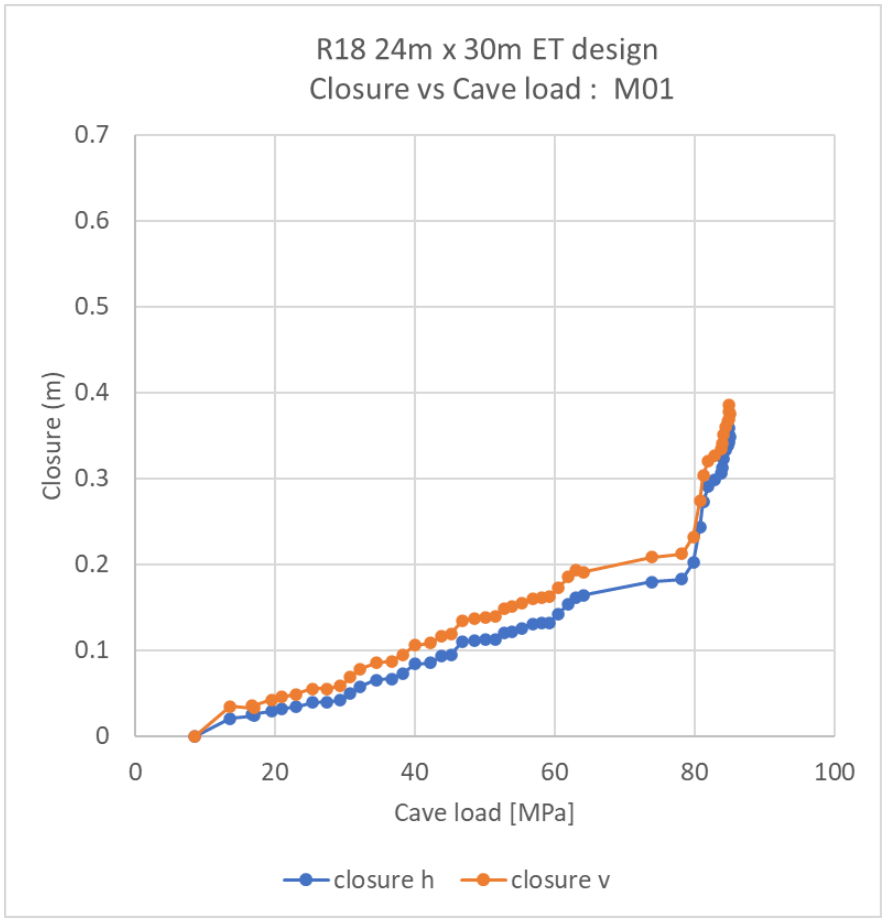
Includes closure on the drive during development (<model step 20)

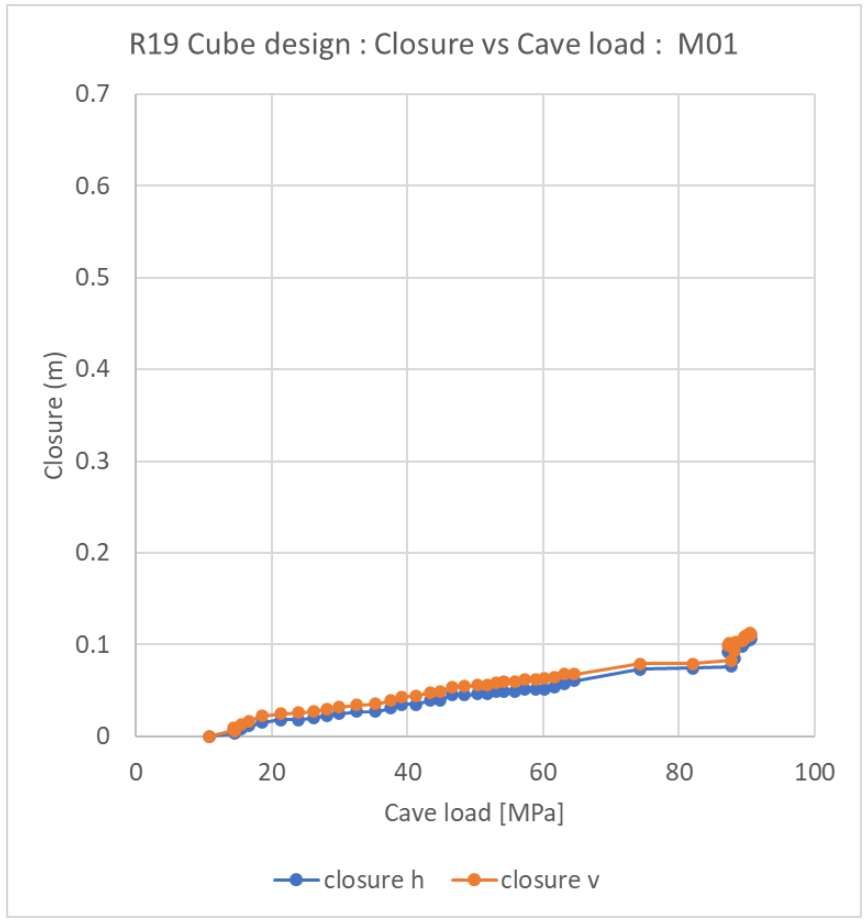




Drive closure vs Cave load (M01)

- Finally the drive closure average values can be correlated with the measured cave load for each production frame of the simulation: This allows a direct and very easy comparison of the two different design. Note: The picture below shows only drive closure after the development is completed and production started.

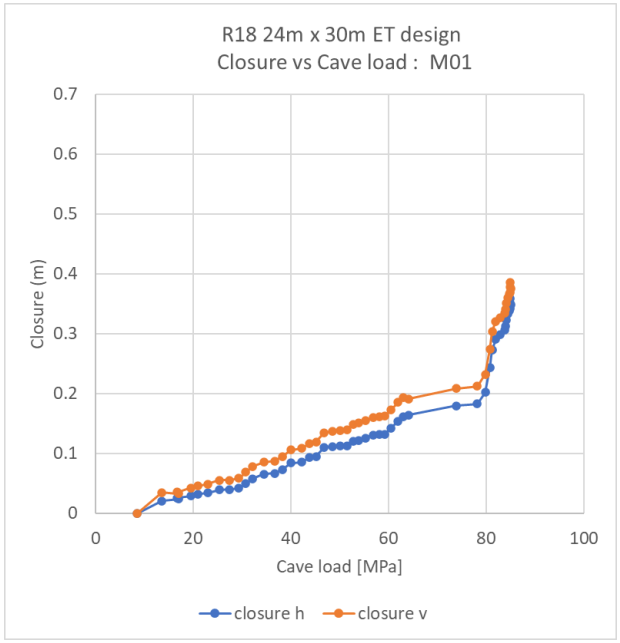


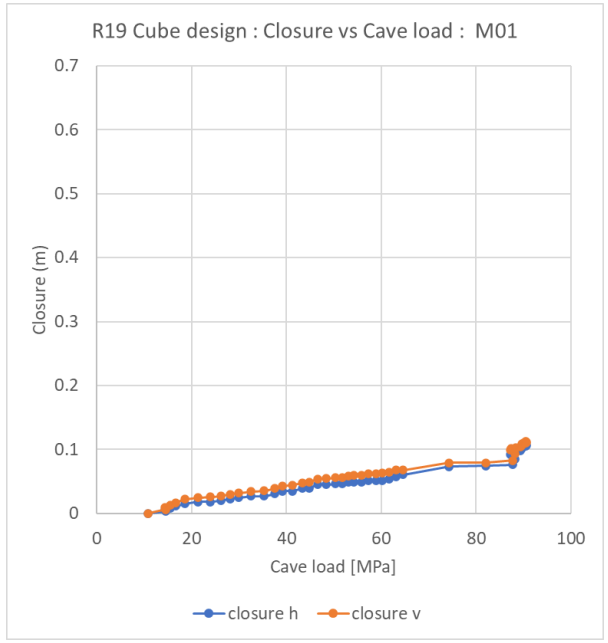


Drive closure vs Cave load : Conclusion

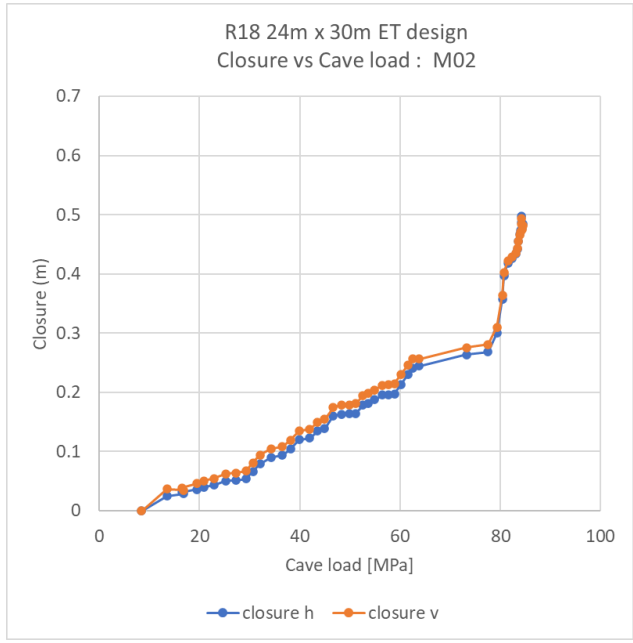
- The Cube DB design design shows significantly less closure at the draw point openings compare to the 24m x 30m ET design The increase of closure vs cave load is less steep and shows a smaller variability
- This behaviour is observed consistently for both materials and at each stage of production
- It must be noted that the damage and closure induced by the blasting of the DBs and under cut is similar if not more significant for the very large draw bells and rings of the Cube DB design. However, measured by drive closure performance only the Cube DB design is superior.
- The presence of a DFN still induces locally significant damage at the openings of the drawpoints and along the cross cuts for both designs which could present potential vulnerabilities
- Closure that occurs during drive excavation and development has been removed from the closure charts shown below as this effect cannot be measured UG

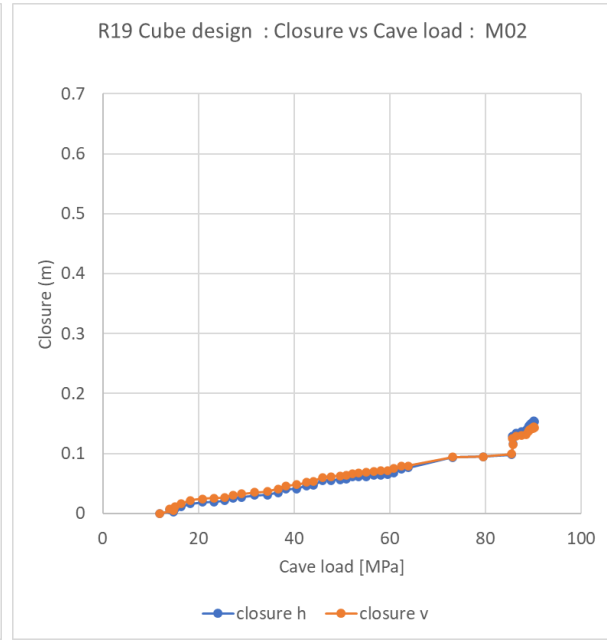
Drive closure and cave load M18 vs M19 (M01)





Drive closure and cave load M18 vs M19 (M02)



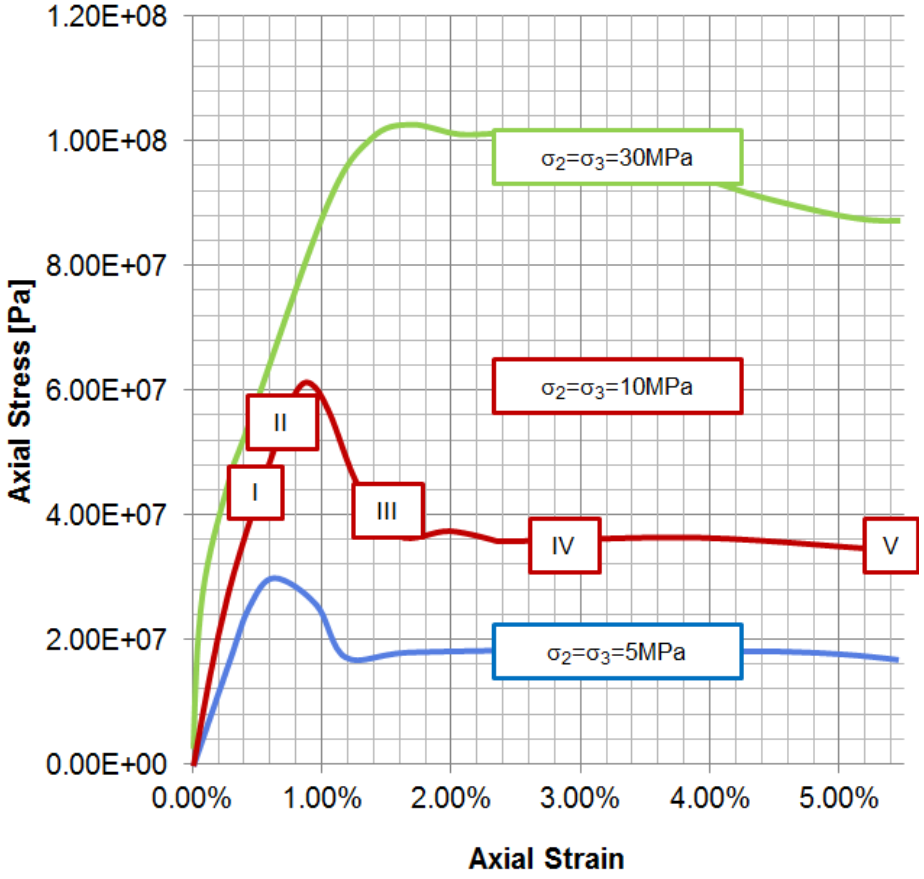


Rockmass damage

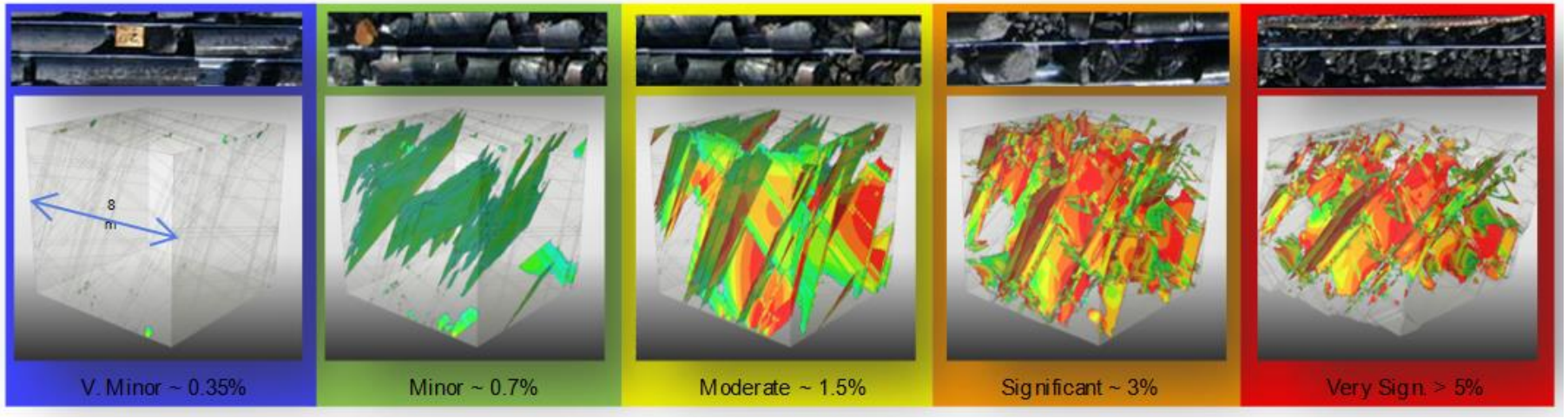
- **Damage is a measure of plastic strain.**
- **Technically:** Scalar measure of the plastic strain tensor is reported as rockmass damage:

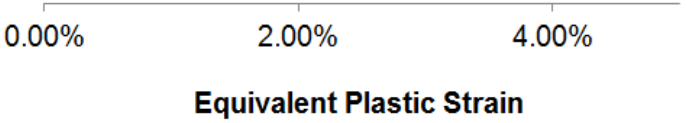
$$\epsilon_p = \mathrm{tr}(\boldsymbol{\epsilon_p})$$

- **Practically:** Rockmass damage indicates deformation. We could call this “movement”.
- We use damage because it is a good indicator of deformation and also because it is something we can readily recognise underground.
- Damage and deformation do not necessarily mean instability and/or failure. These are subject to interpretation in a mine-scale model.



Logarithmic damage scale





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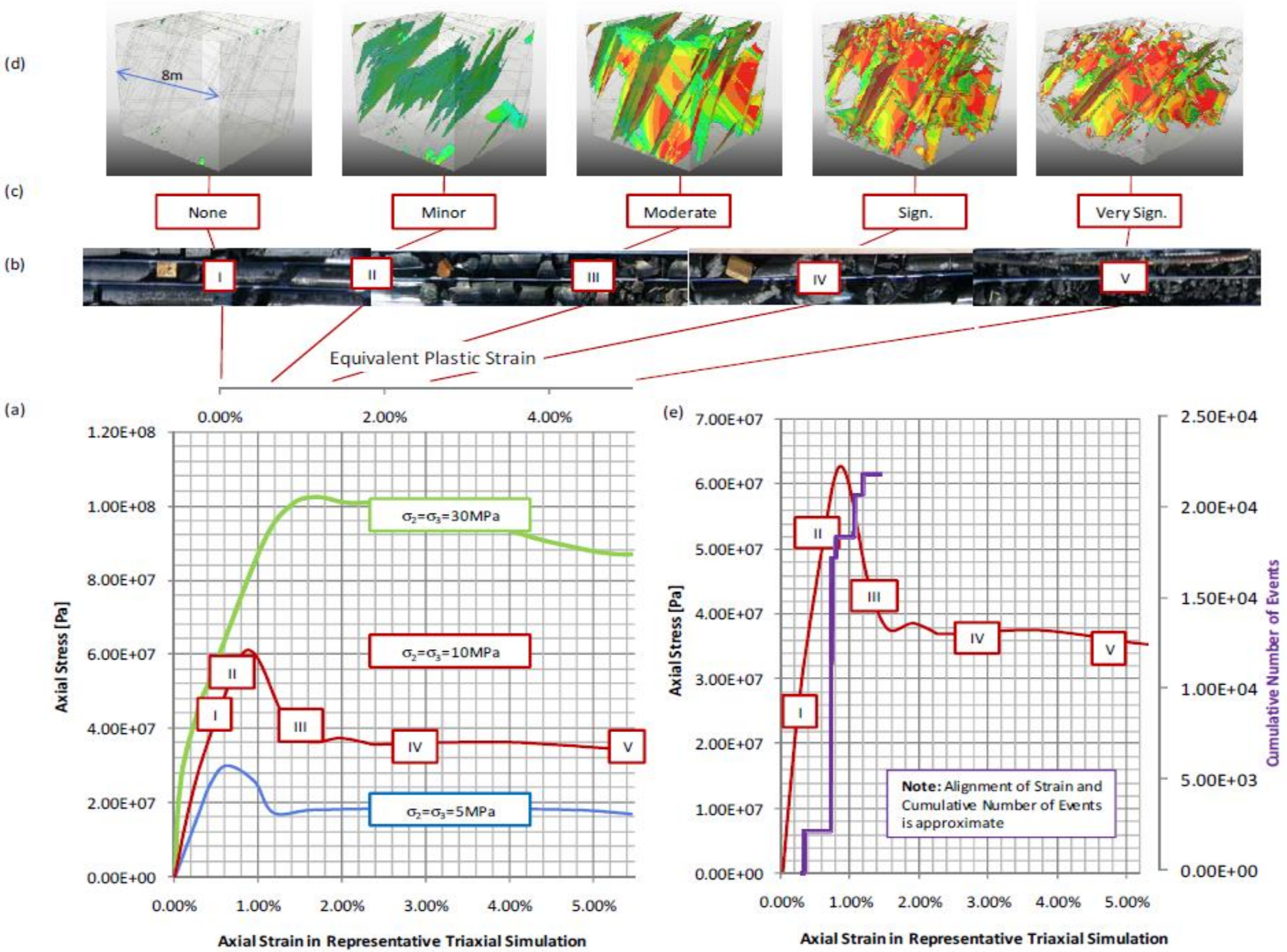


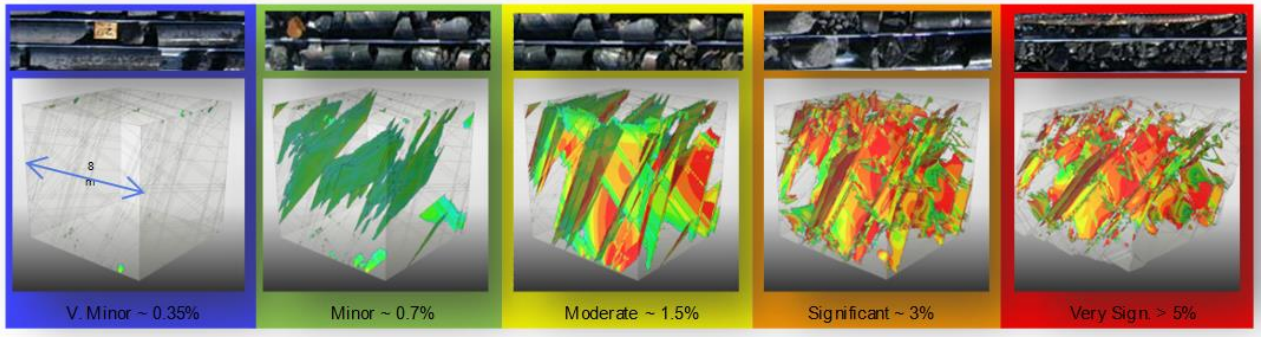
Beck, D.A., Reusch, F., Arndt, S., 2009, A Numerical investigation od scale effects on the behaviour od discontinuous rock, ARMA, Proceedings of 43rd US Rock Mechanics Symposium, Aheville, 2009

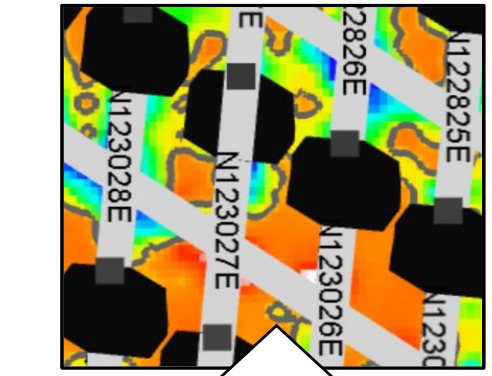
Rockmass damage & interpretation

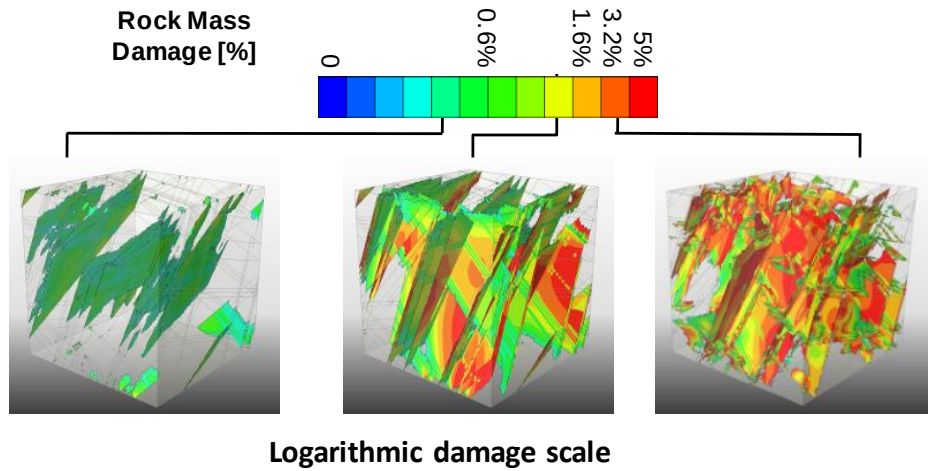
Damage levels in development are well defined by Sandy et al. (2010).

In open stopes:

1. Minor rockmass damage indicates a low likelihood of instability.
2. Moderate rockmass damage indicates an increased likelihood of instability, particularly in hangingwalls and crowns.
3. Significant rockmass damage is characterised by relatively high frequency of instability, leading to reduced recovery and productivity and higher dilution and costs.
4. Very significant rockmass damage is characterised by severe stability problems for open stopes and usually necessitates other mining methods.

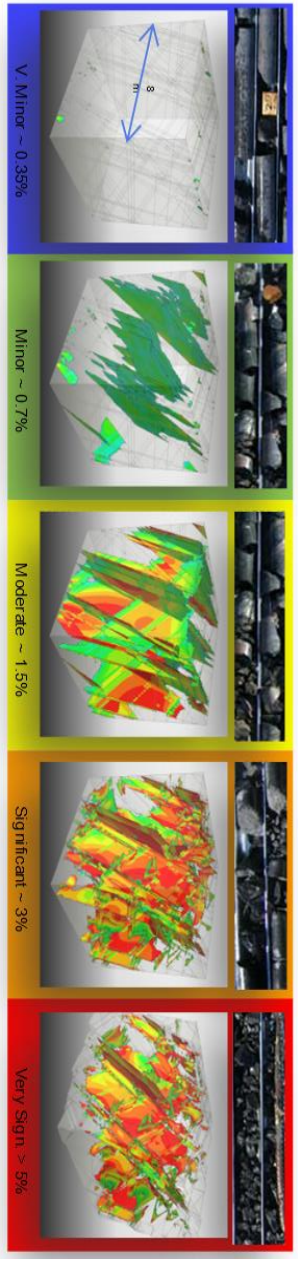


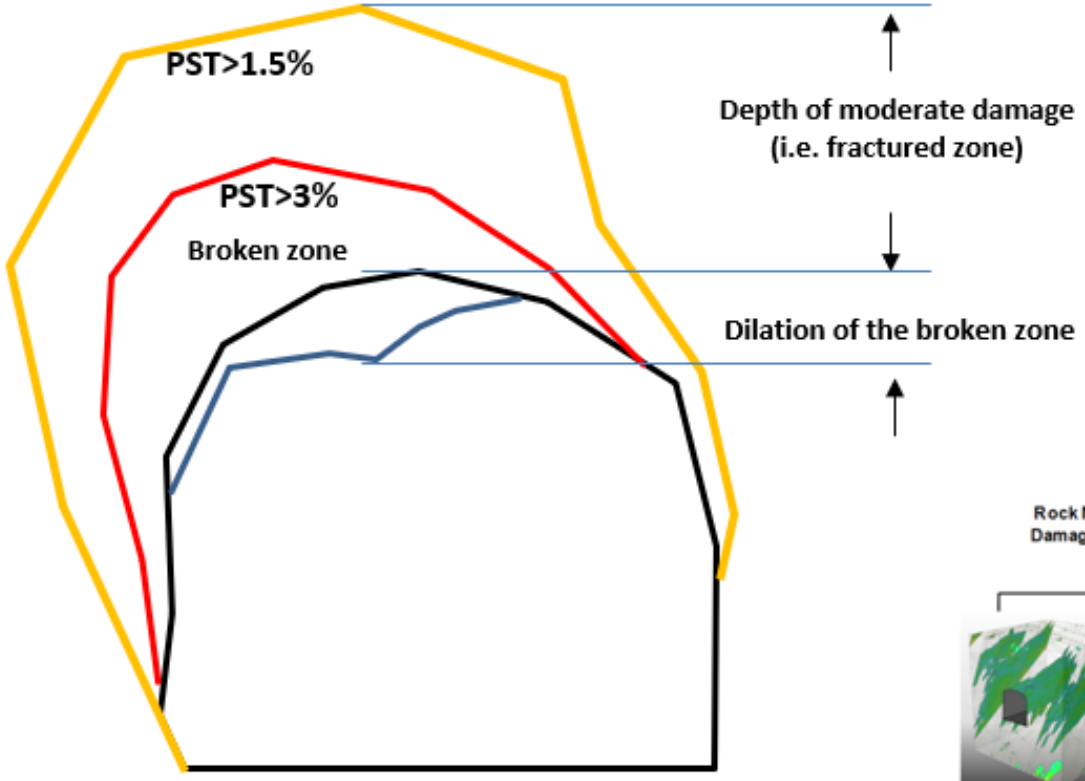




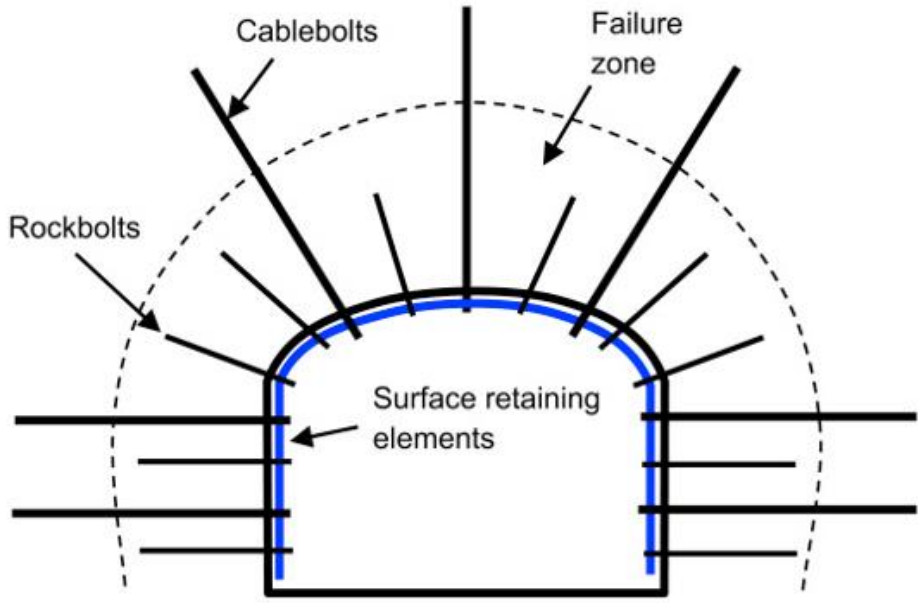
After Sandy et al (2010)

Damage Level	General Description	Example
S0	No visible damage	
S1	Minor damage	
S2	Moderate damage	
S3	Significant damage to excavations	
S4	Sever damage to excavations	
S5	Extreme damage to excavations Opening collapsed	

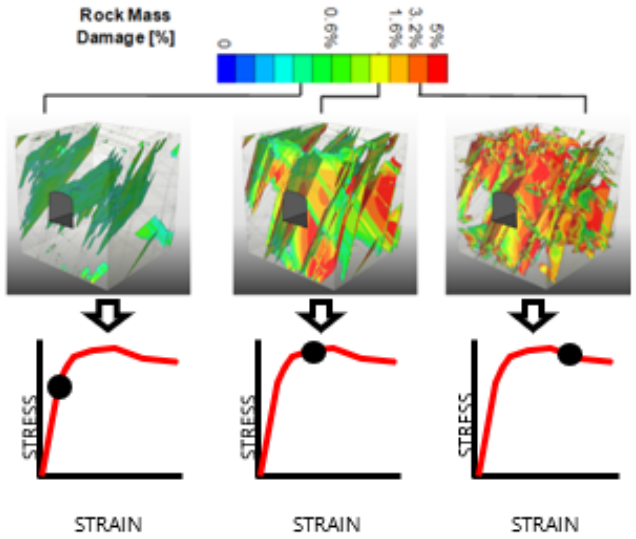




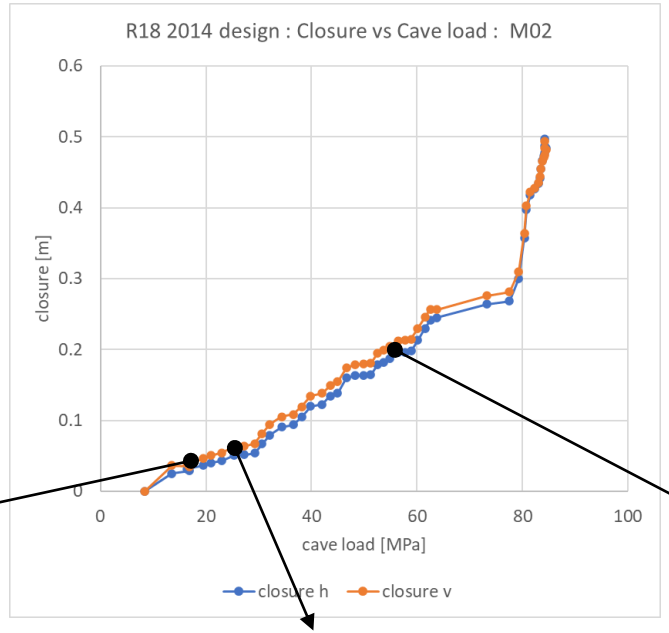
Damage around an excavation showing corresponding plastic strain values from the model forecasts

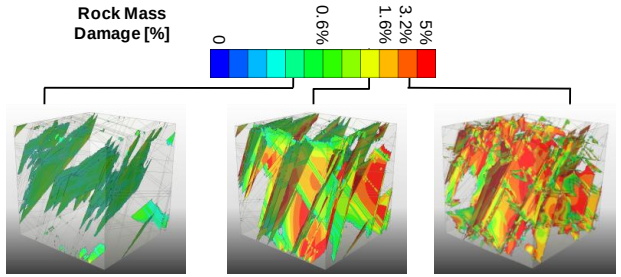


Ground support design concept, including depth of embedment and depth of fracturing of the rockmass

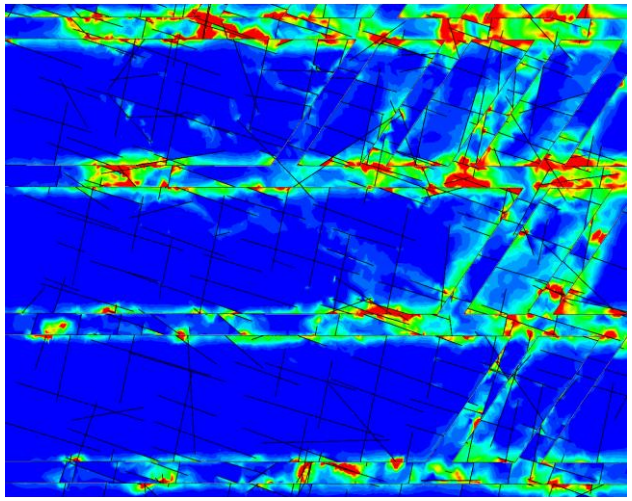


Examples for drive deformation and damage: 24 x 30m ET (M01) plan view





Developing and blasting the EL F015



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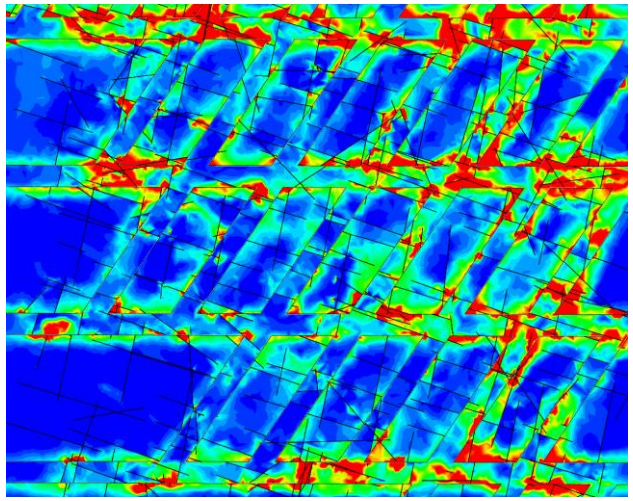
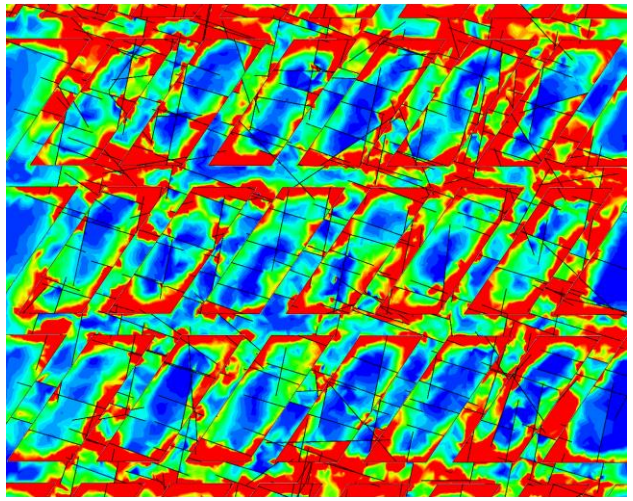
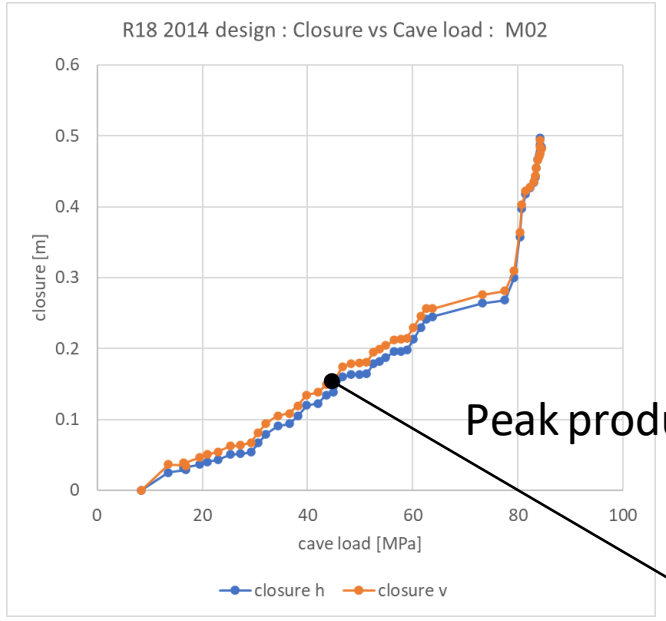


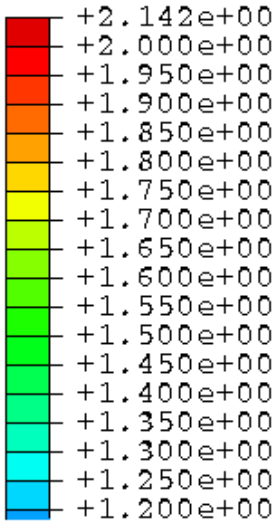
Peak production F050



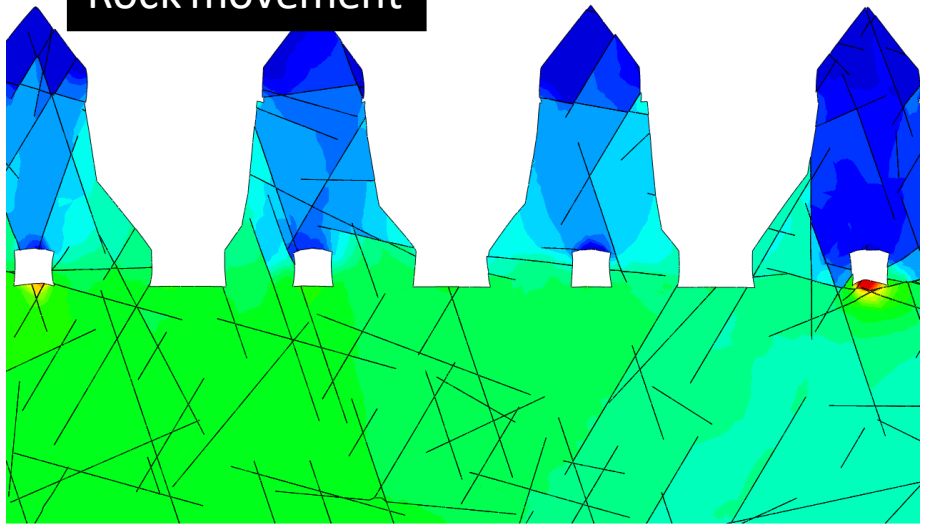
Examples for drive deformation and damage: 24 x 30m ET (M01) : Location 1

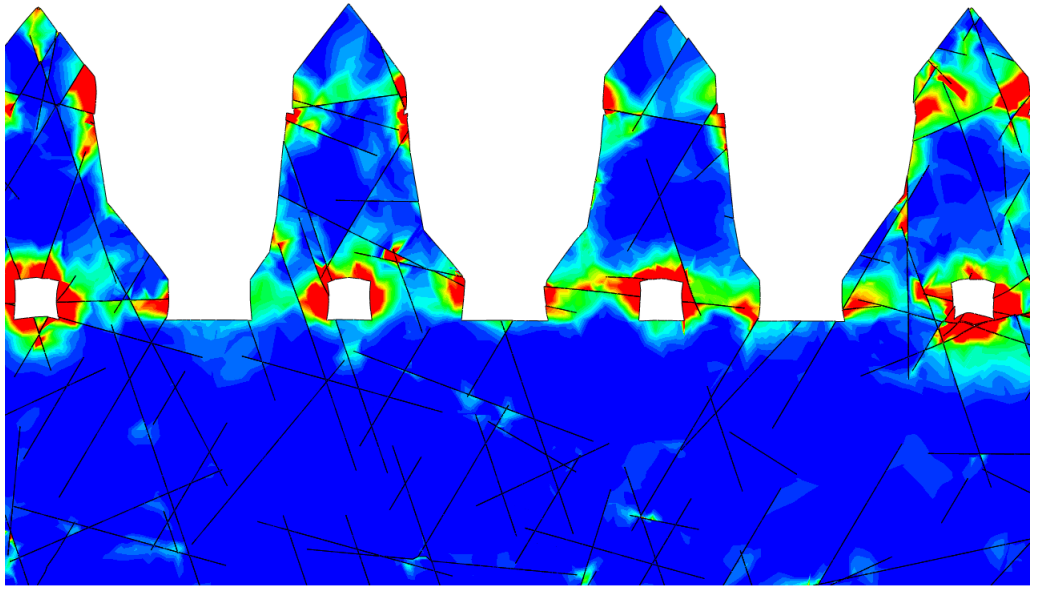


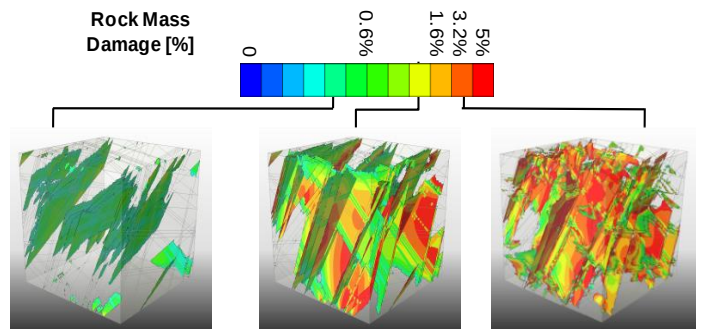
Peak production F050



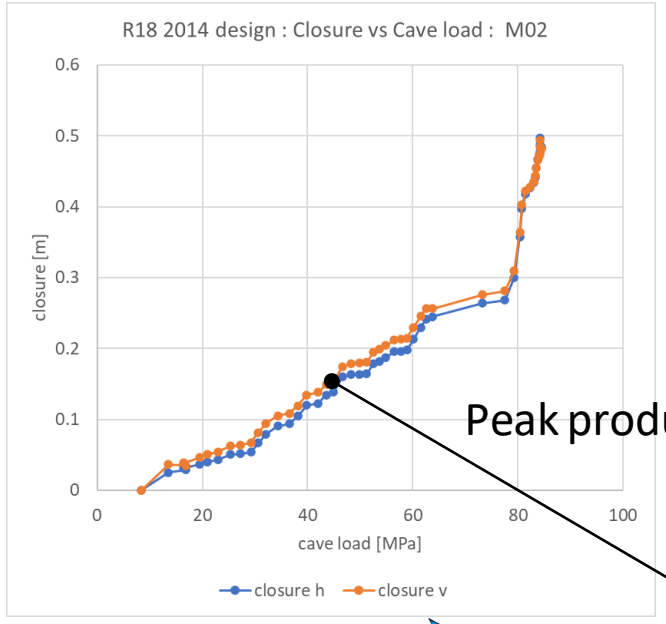
Rock movement







Examples for drive deformation and damage: 24 x 30m ET (M01) : Location 2



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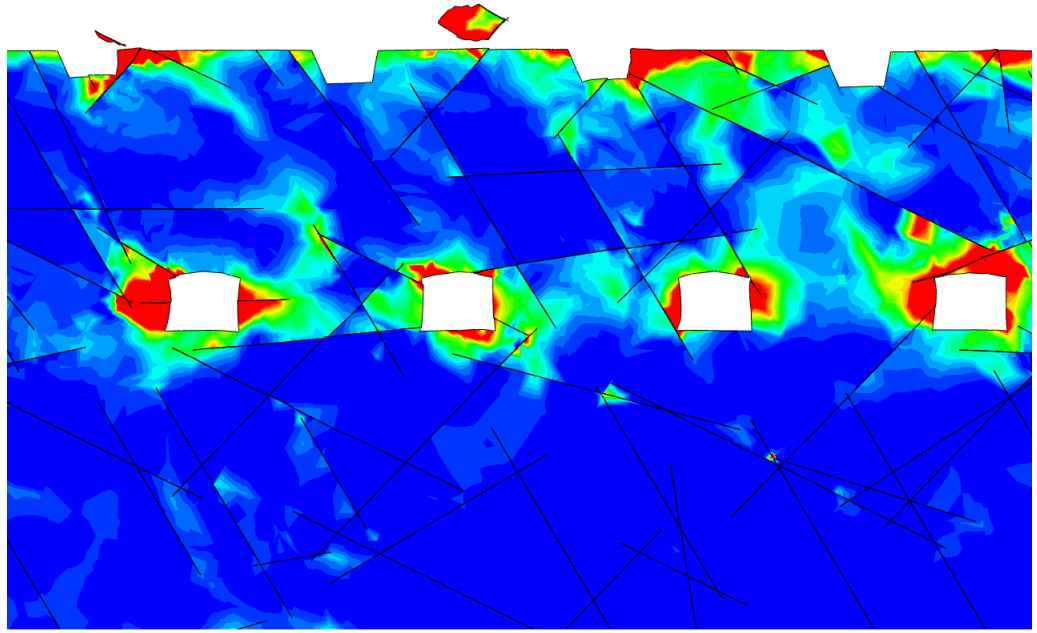
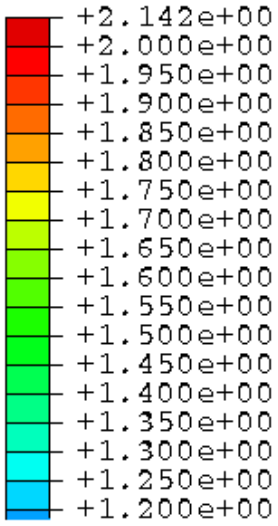
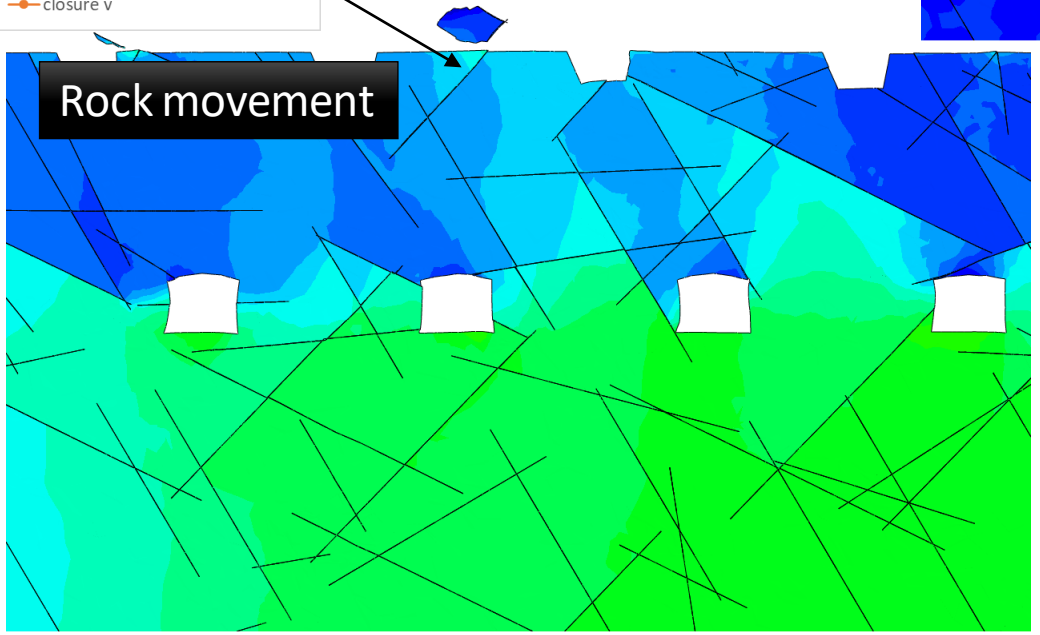
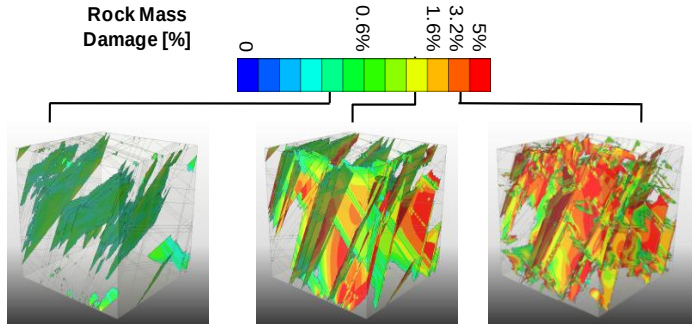
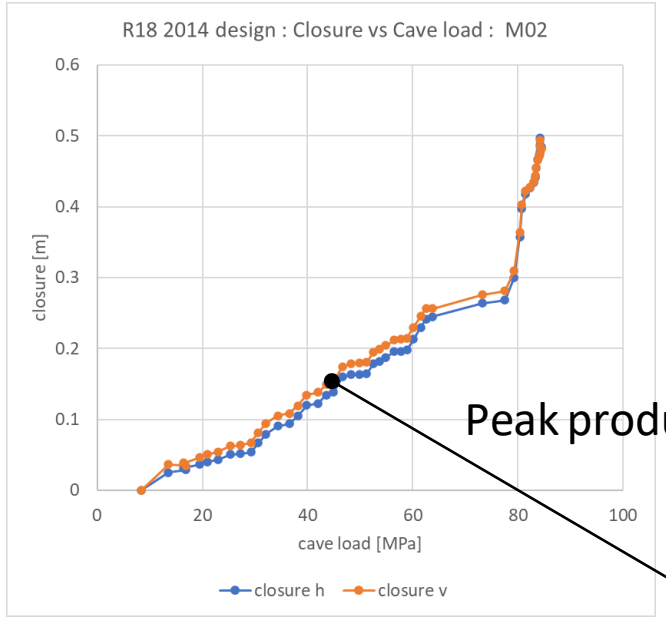








Examples for drive deformation and damage: 24 x 30m ET (M01) : Location 3



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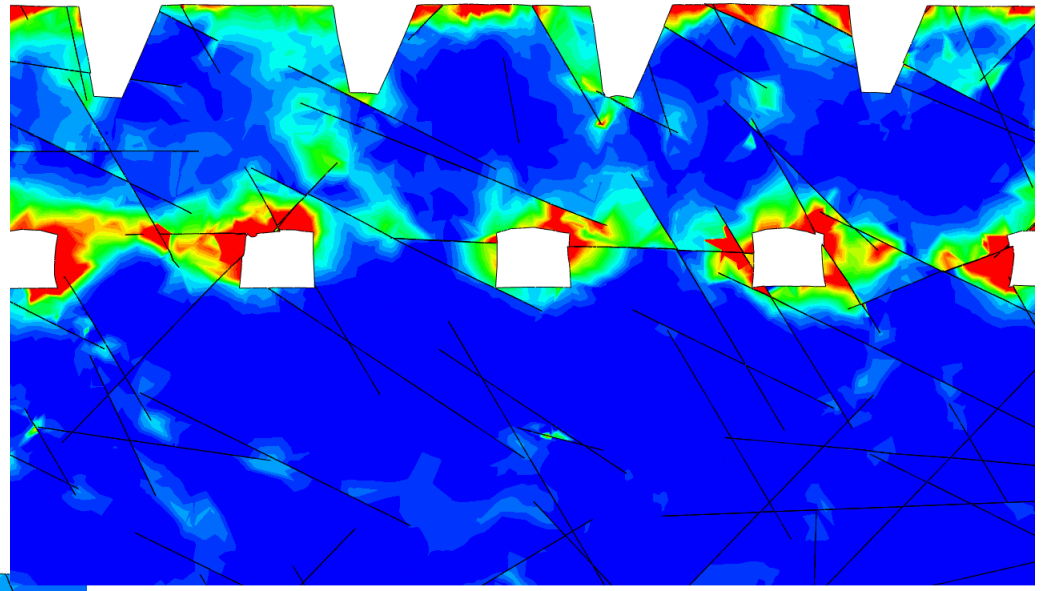

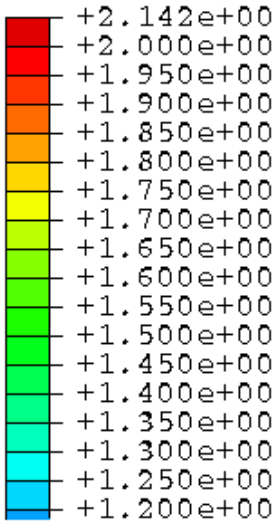

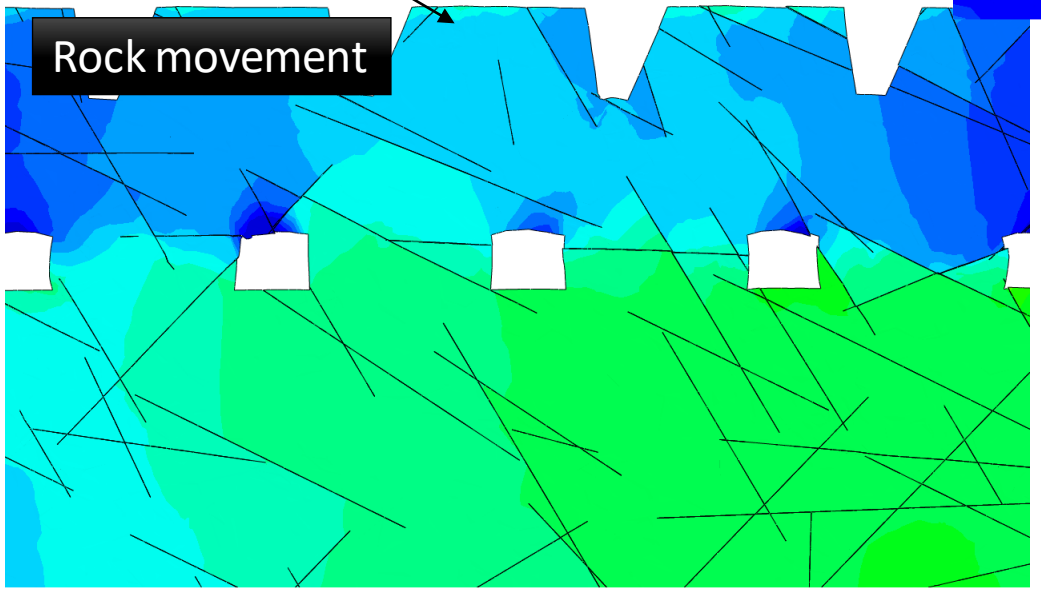

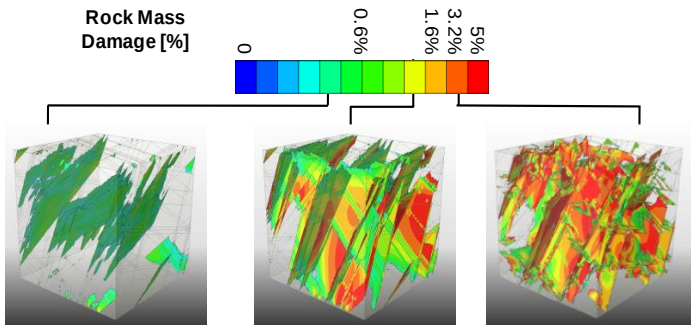

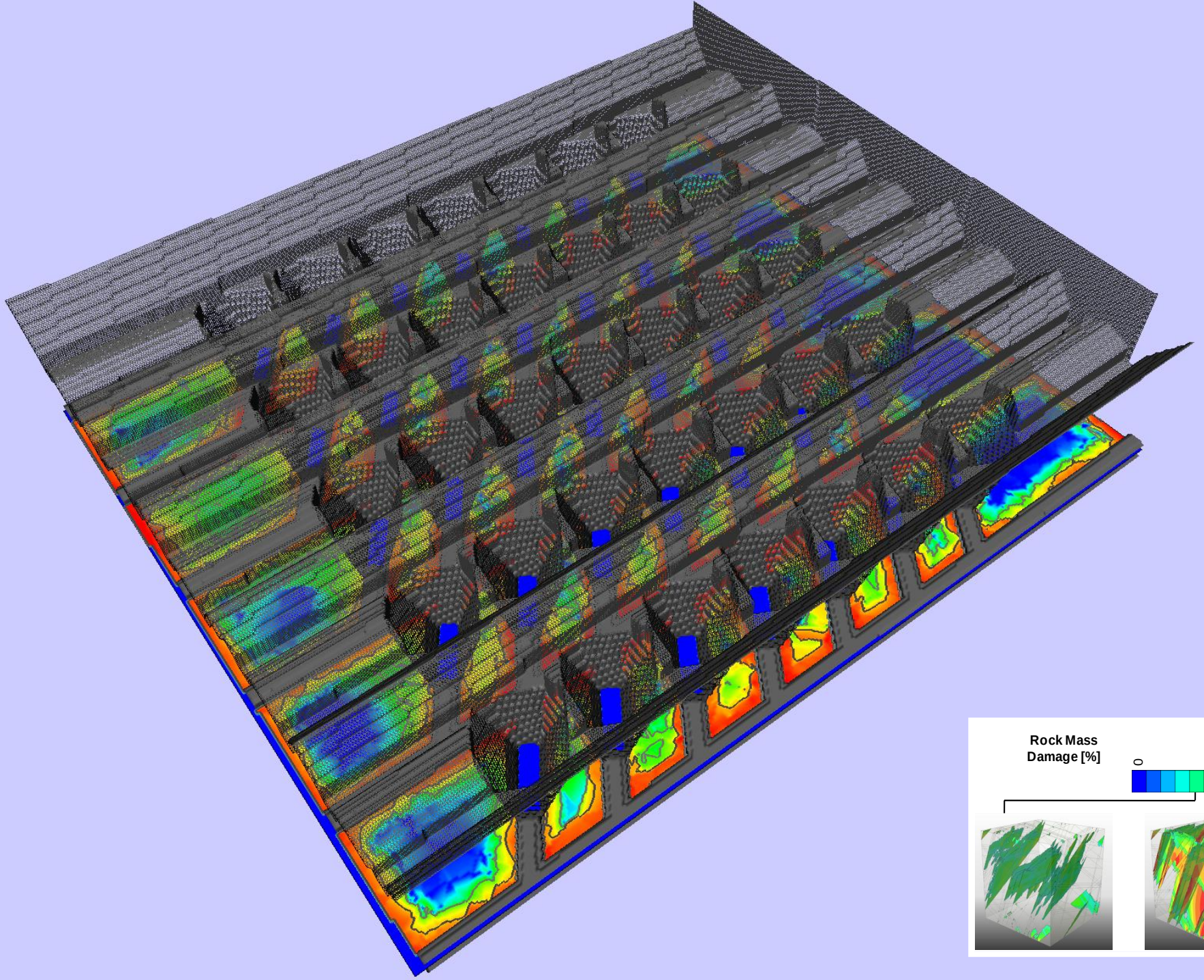

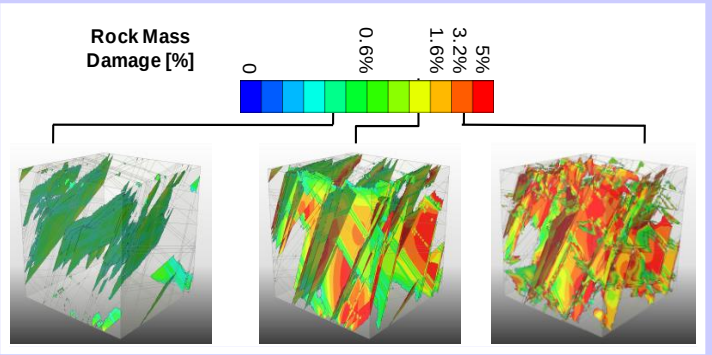
Rock Mass
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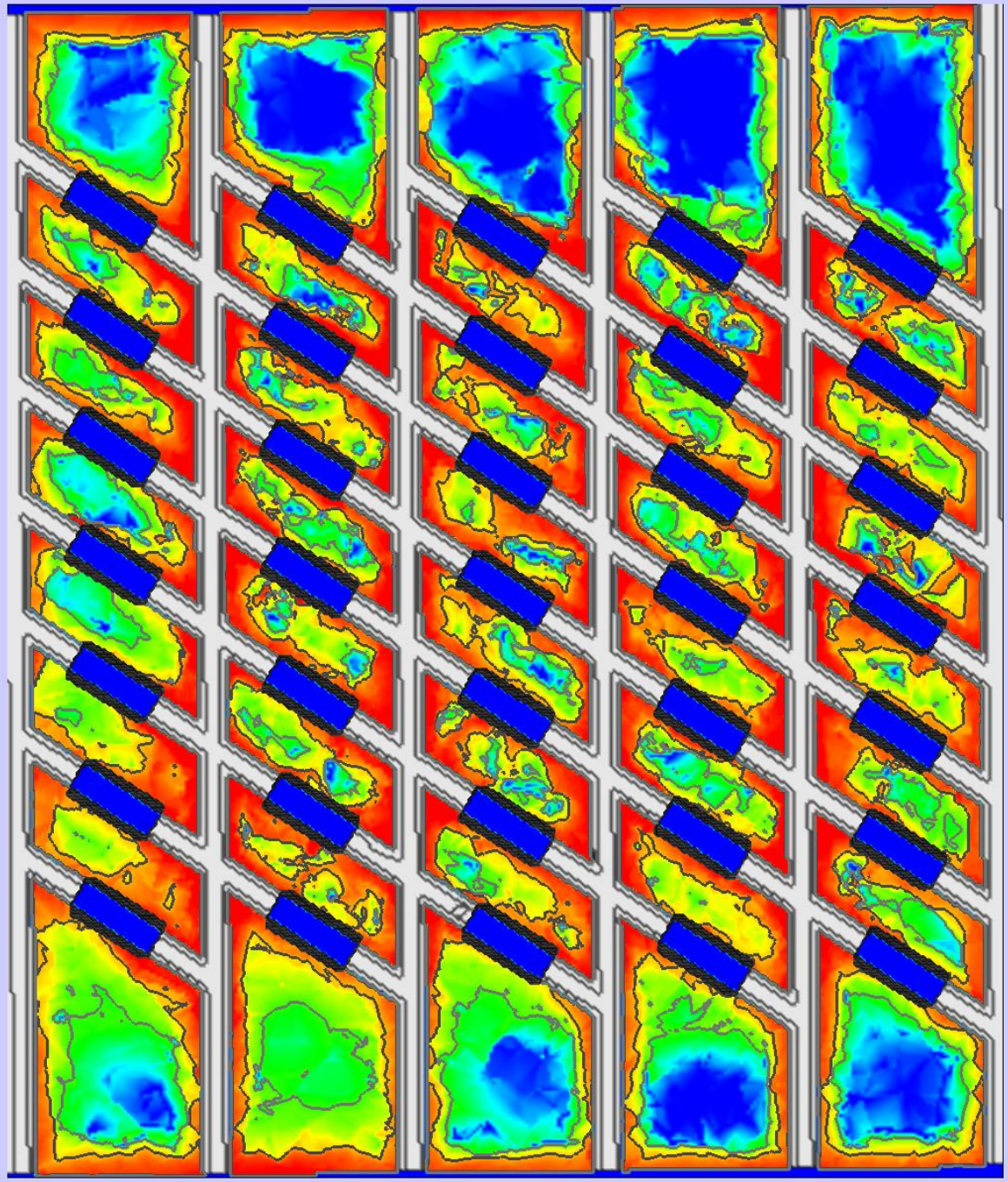
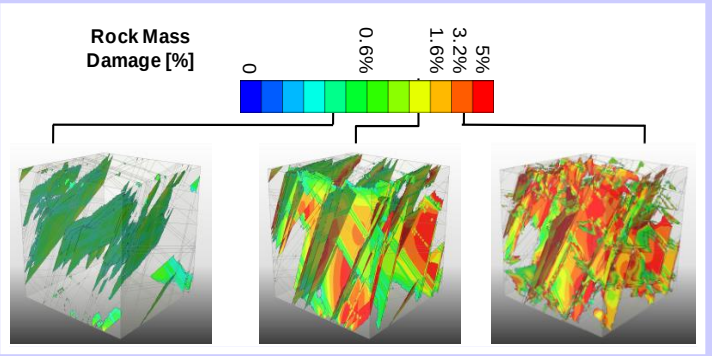
1.6%
3.2%
5%

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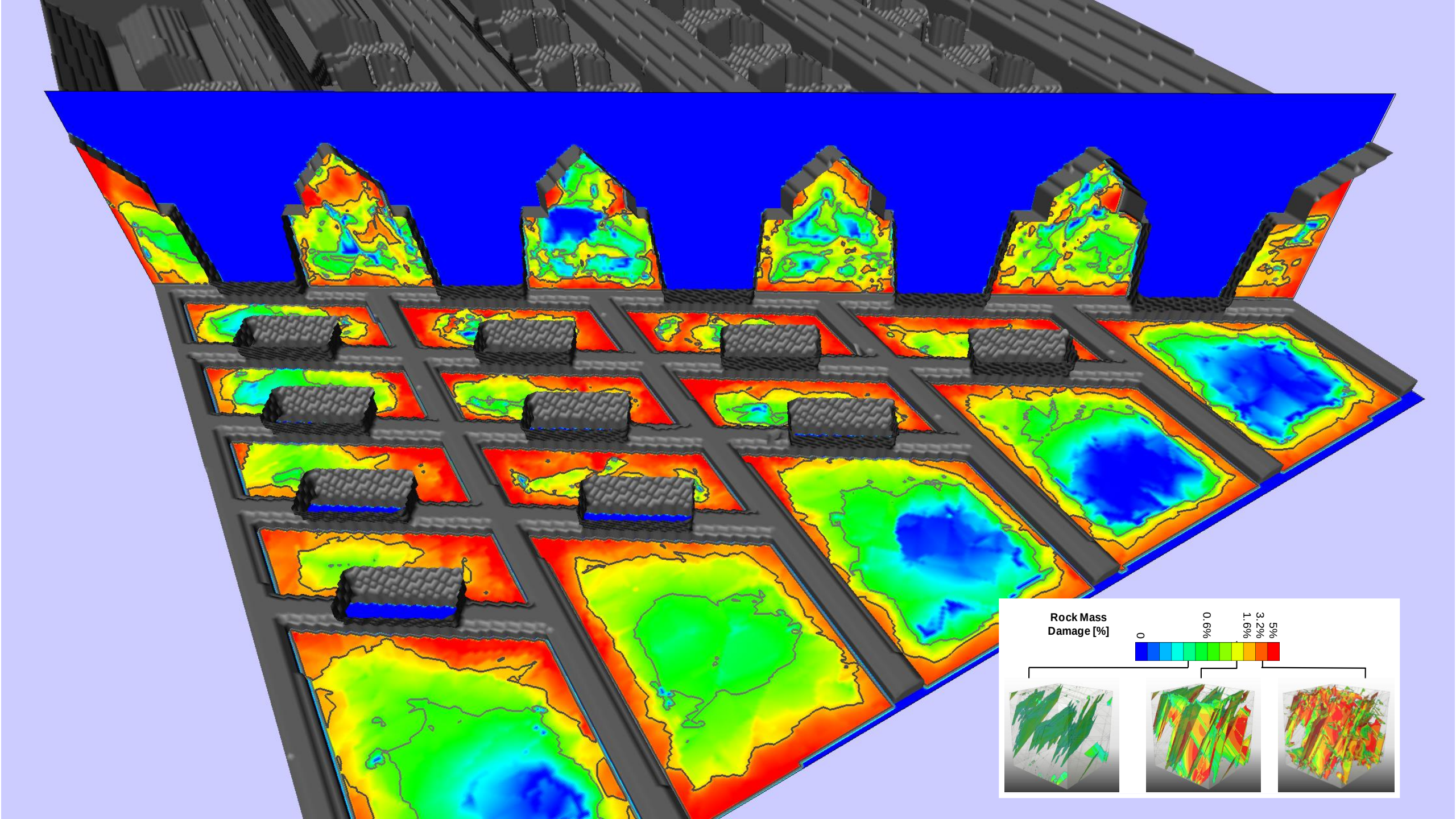
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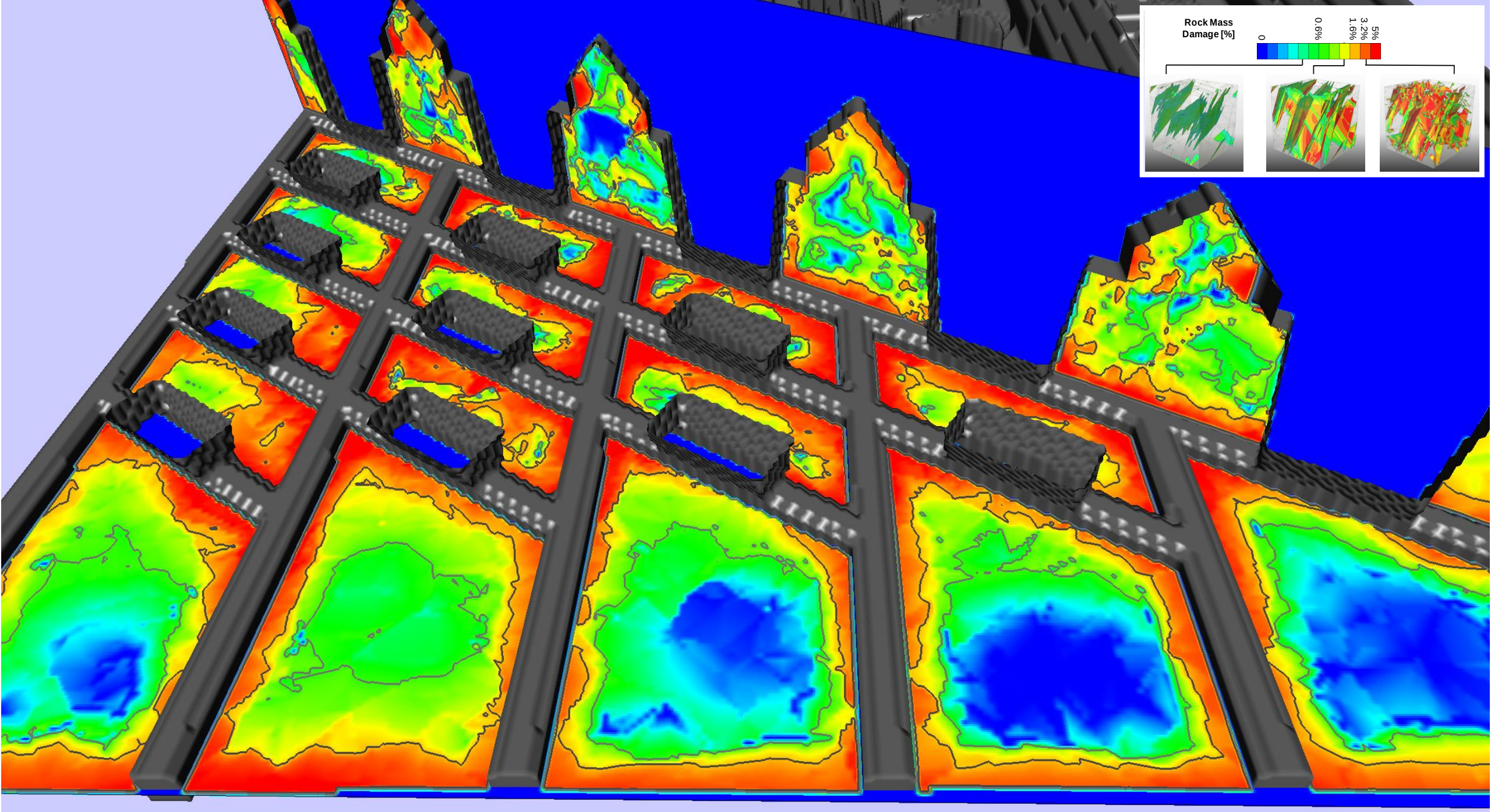
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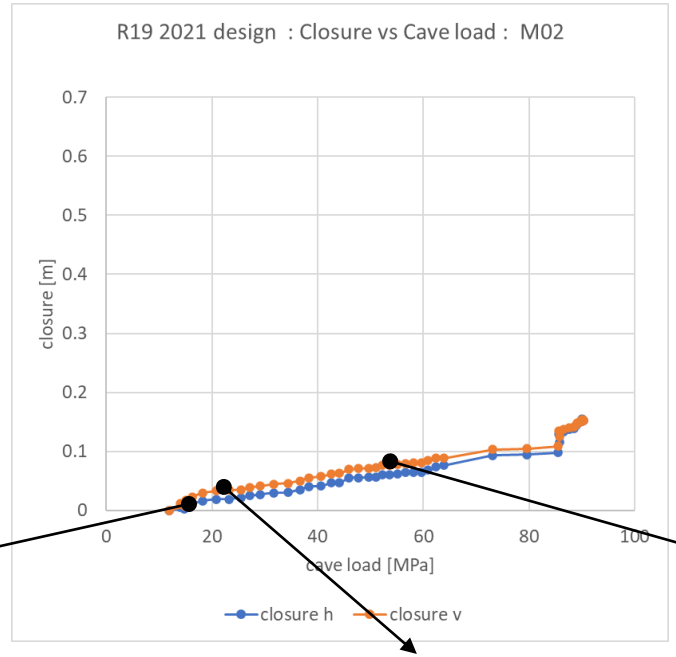
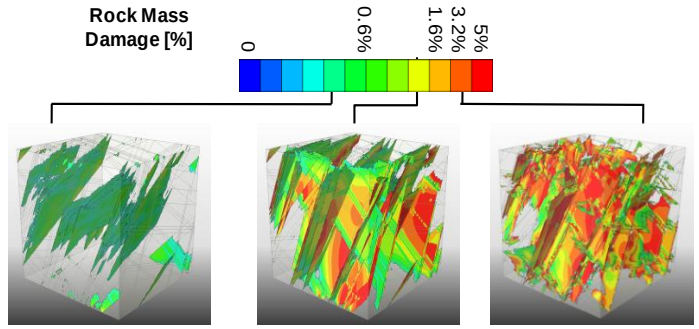
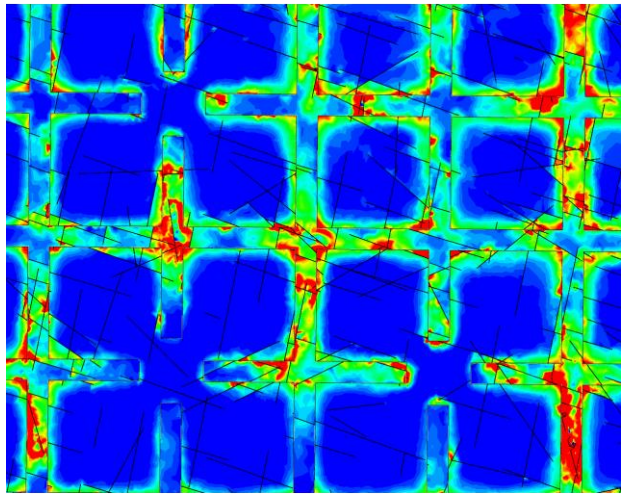
Examples for drive deformation and damage: R19 M01 plan view

2021 design





Developing and blasting the EL F015



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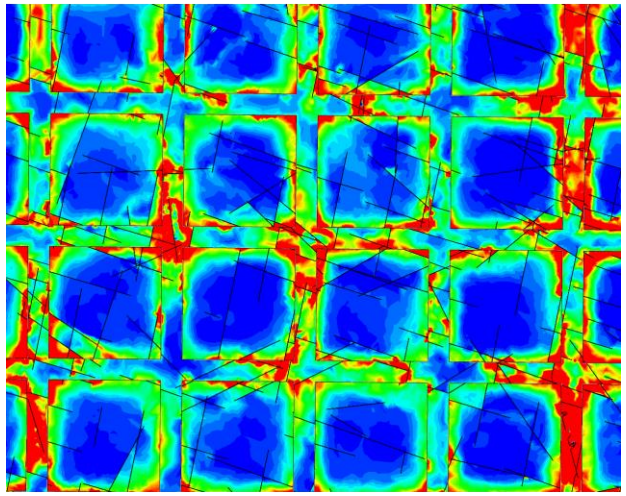

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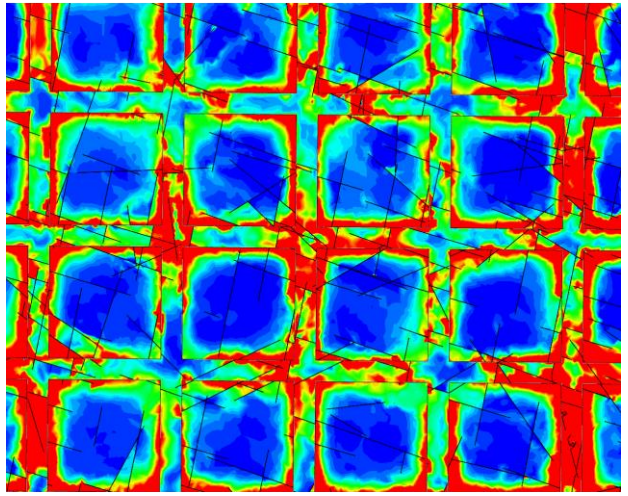
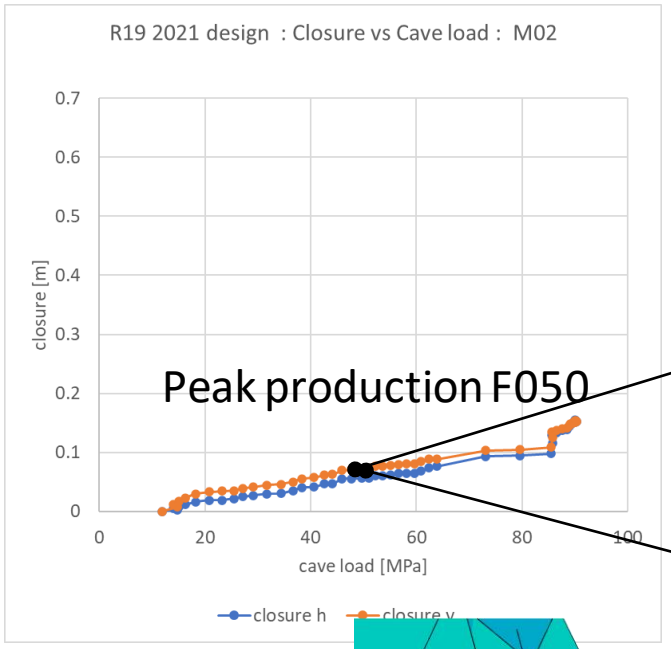


Examples for drive deformation and damage: Cube design (M01) : Location 1



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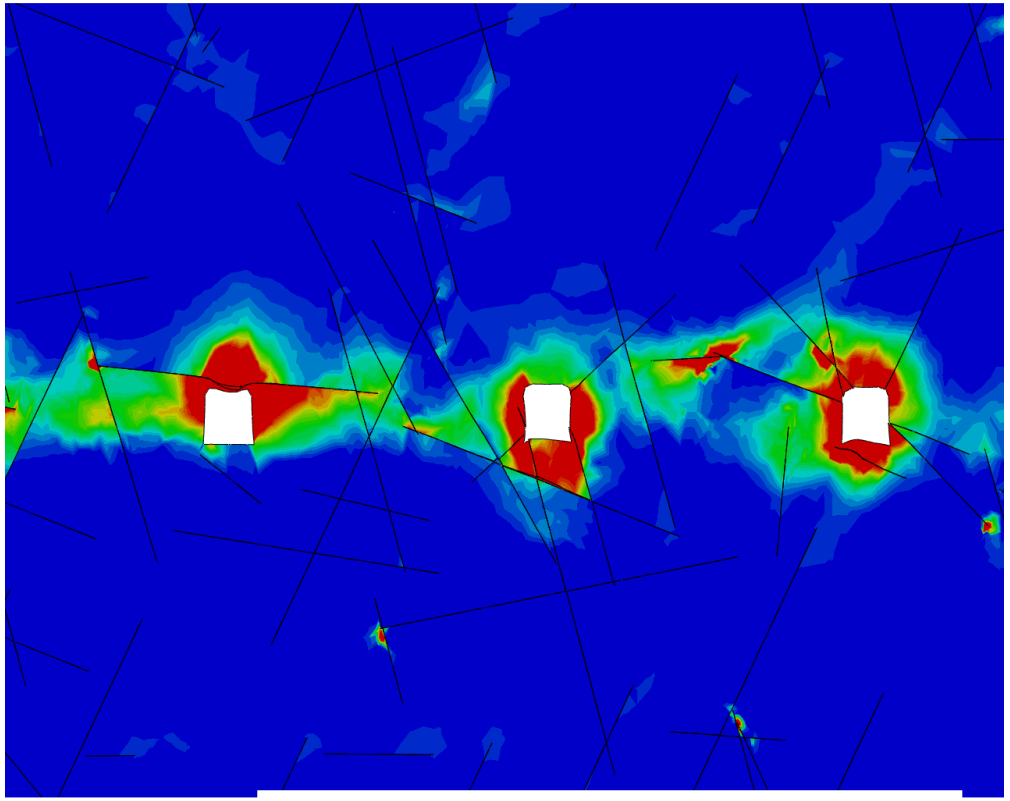
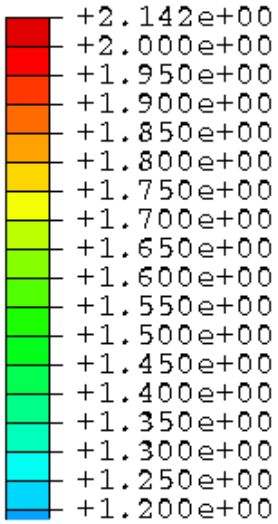
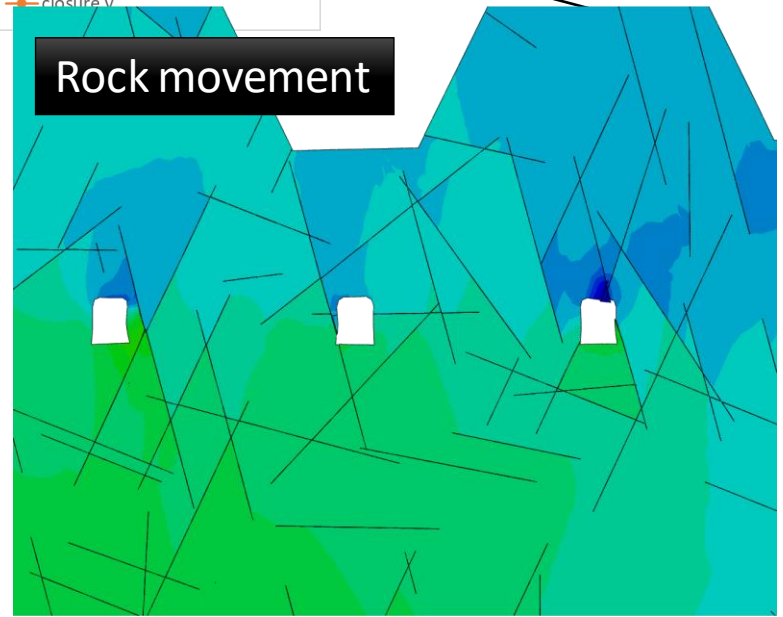
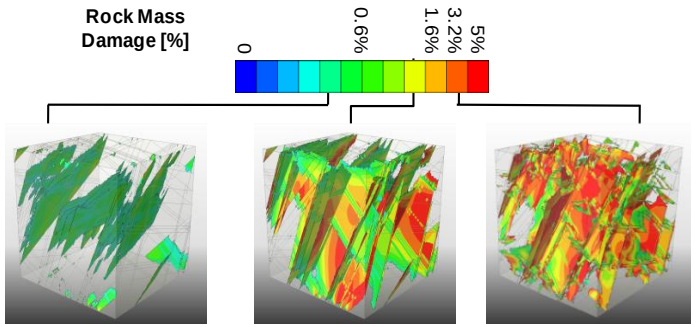
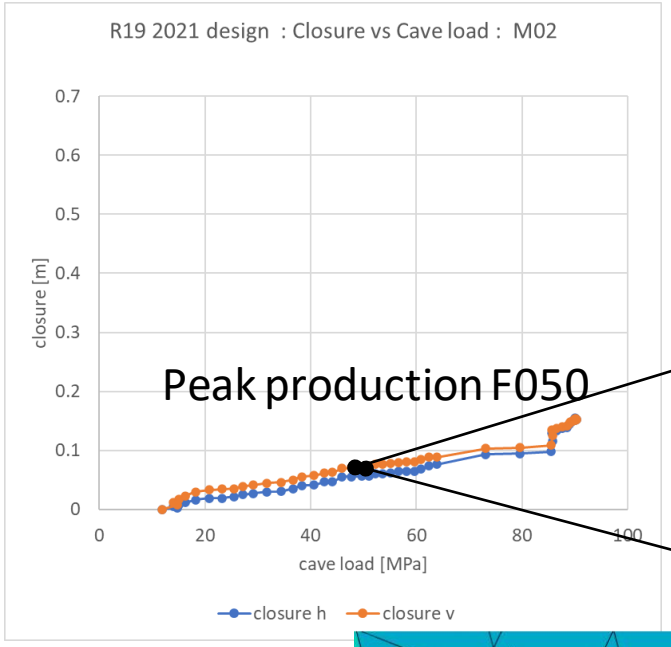




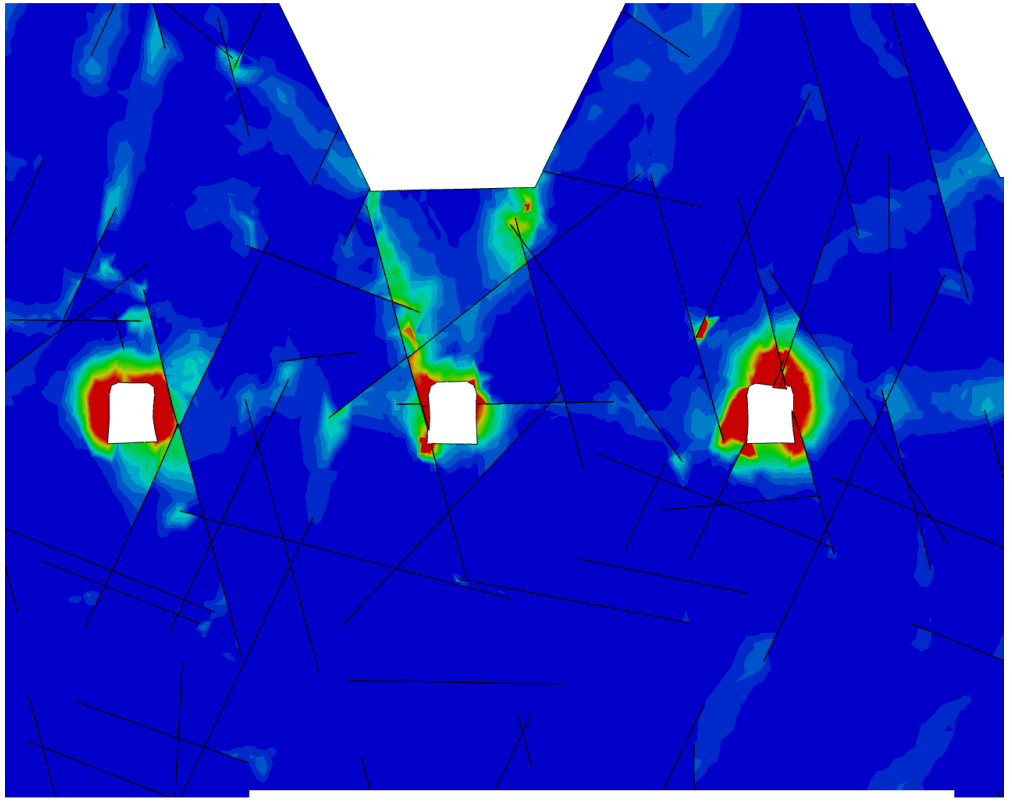


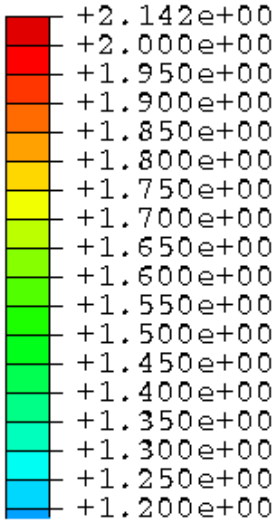


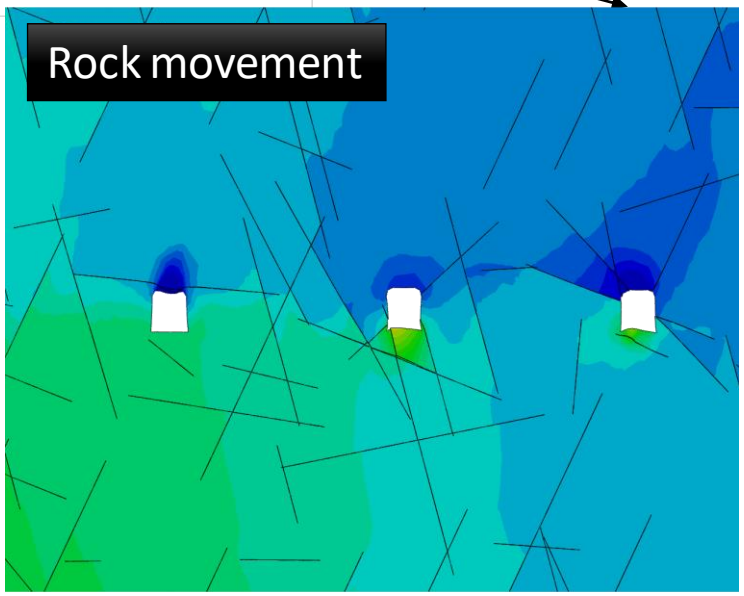
Examples for drive deformation and damage: Cube design (M01) : Location 2

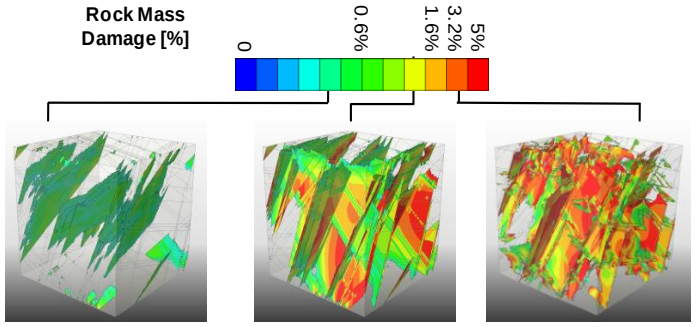


Peak production F050

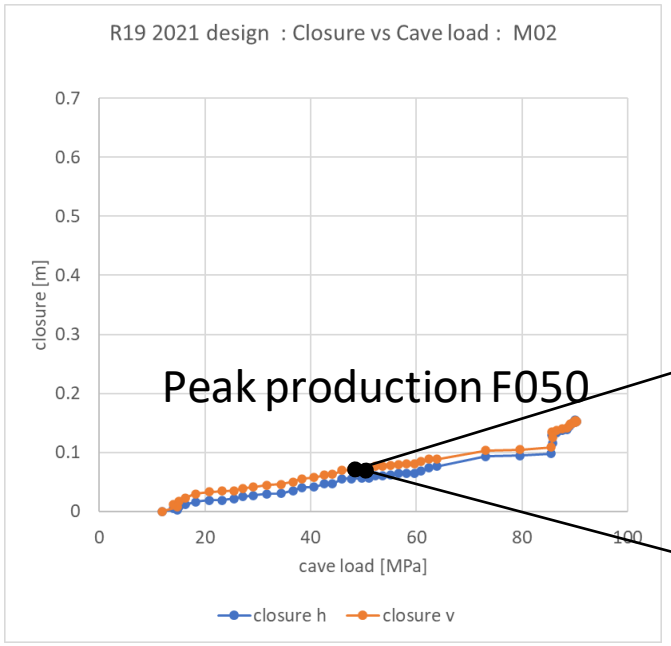






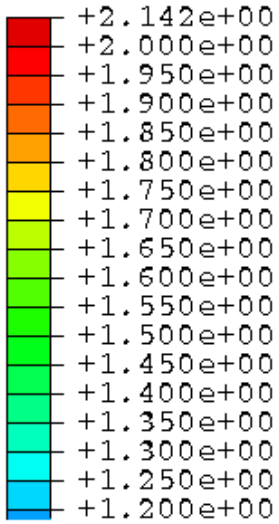


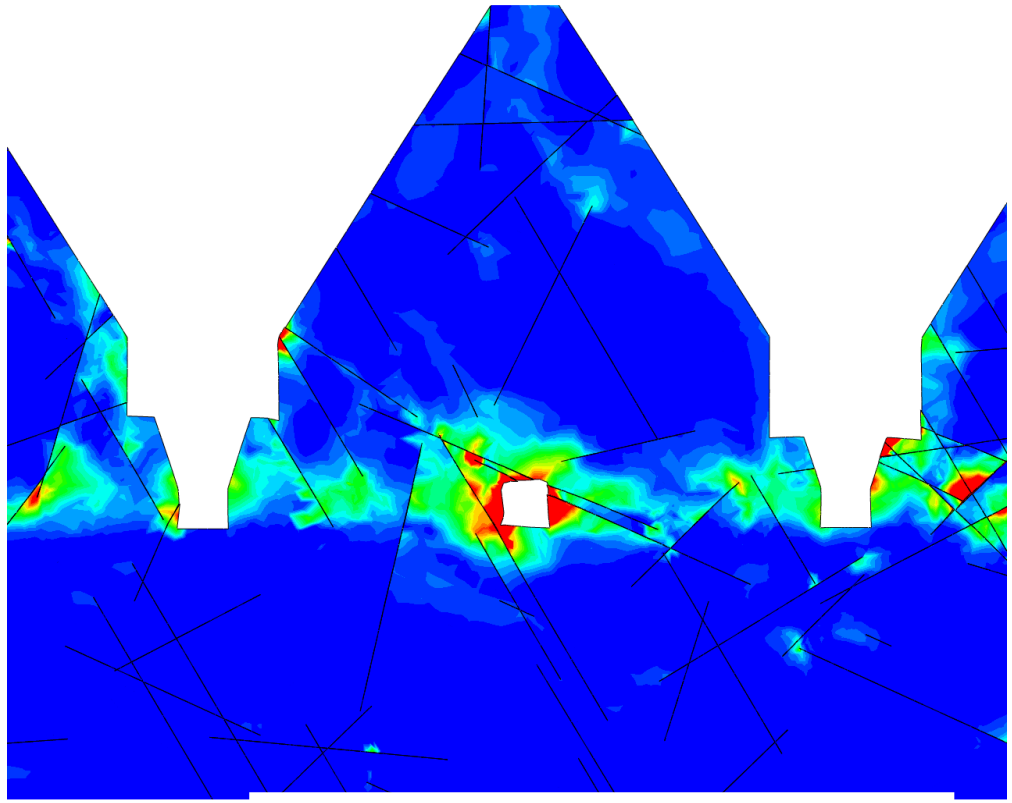
Examples for drive deformation and damage: Cube design (M01) : Location 3

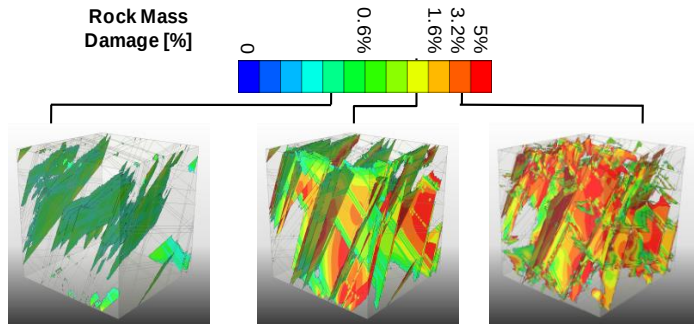


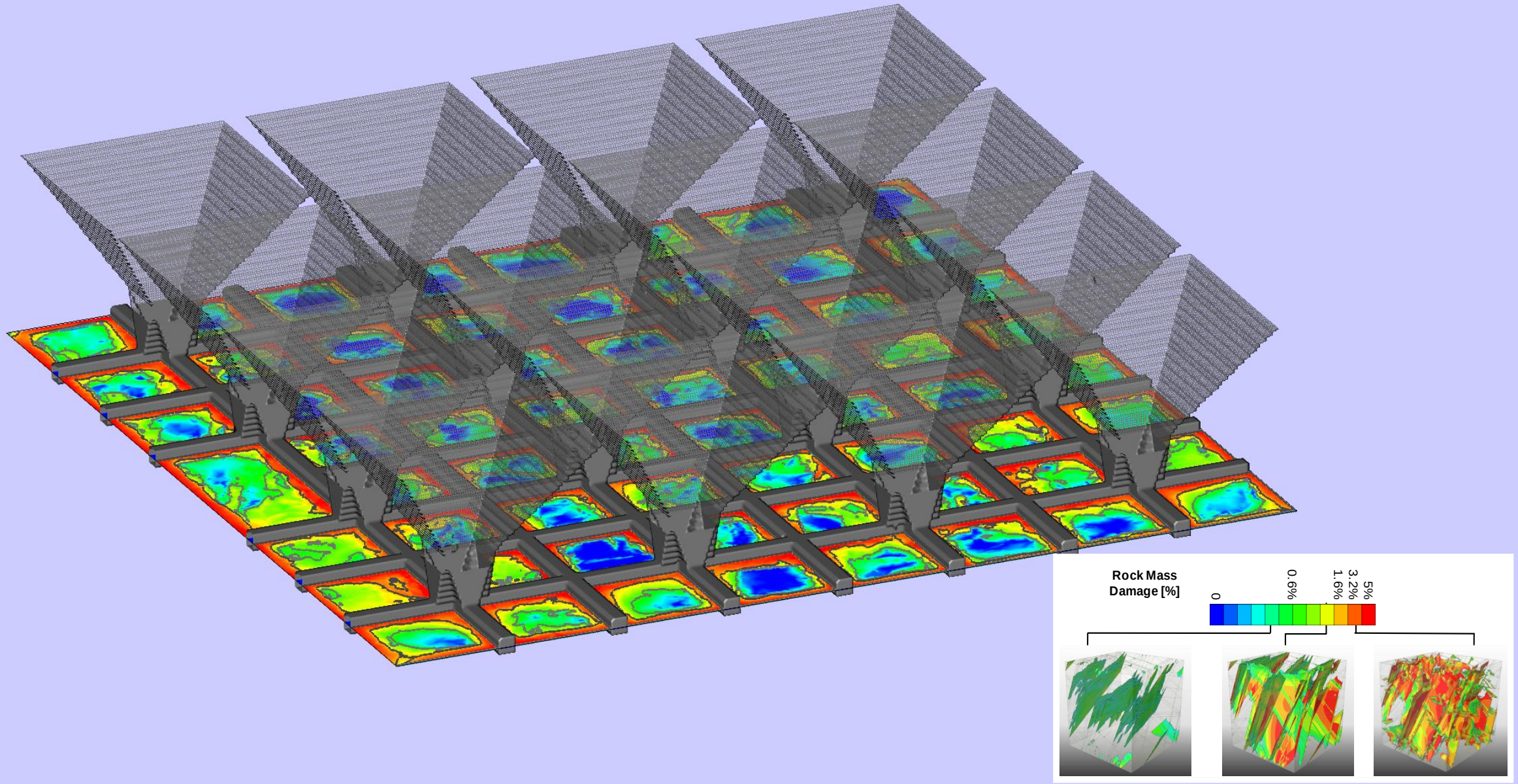
Peak production F050

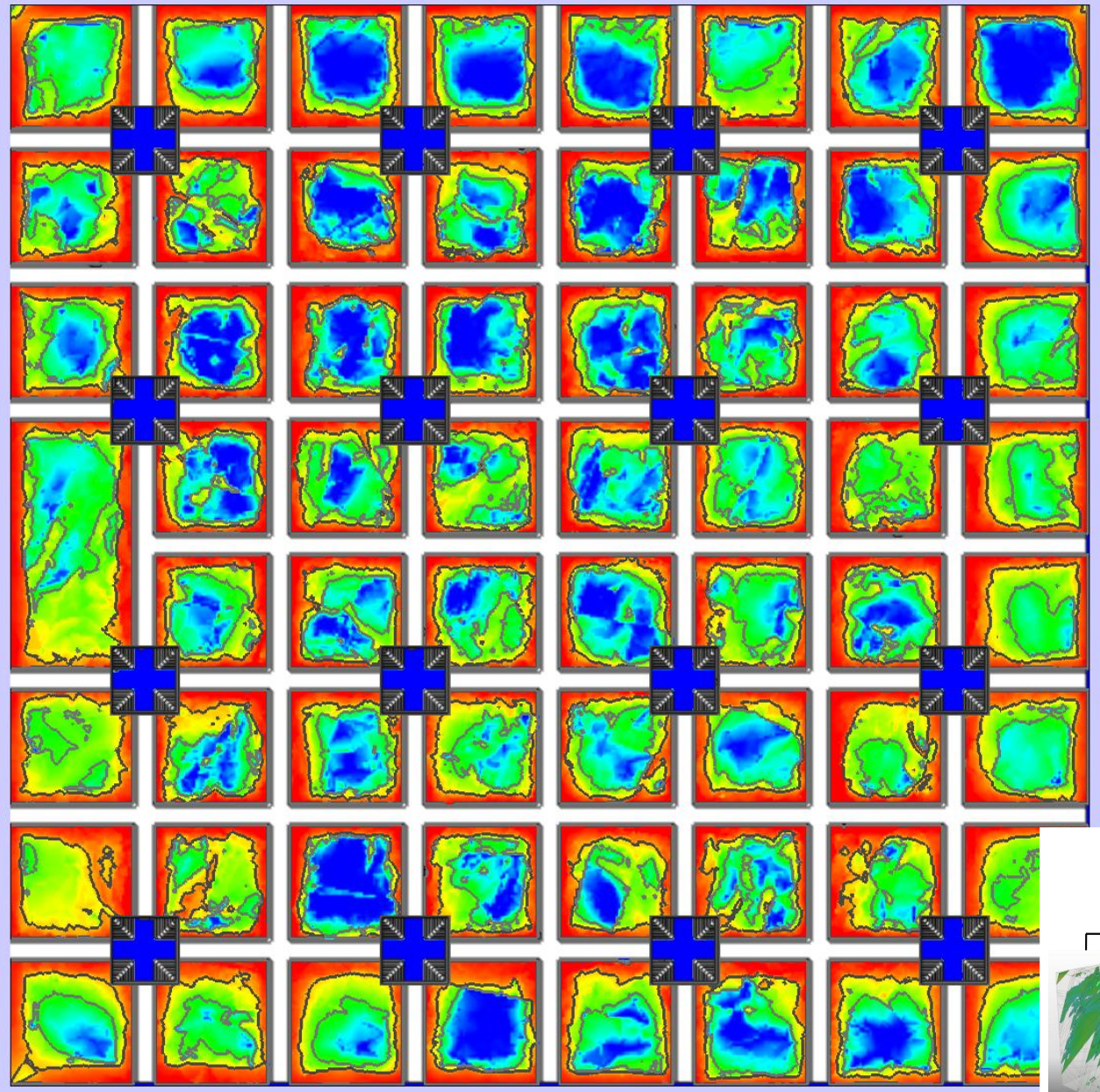
Rock movement

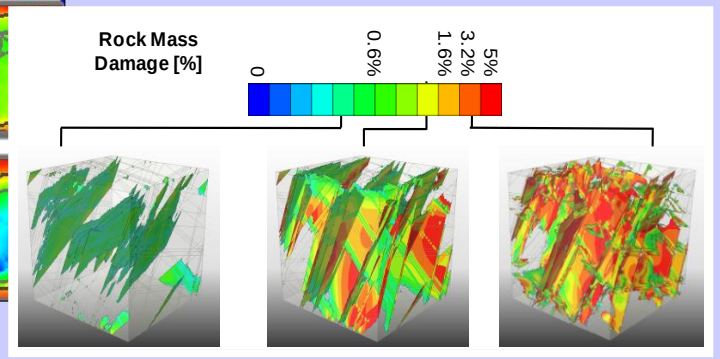


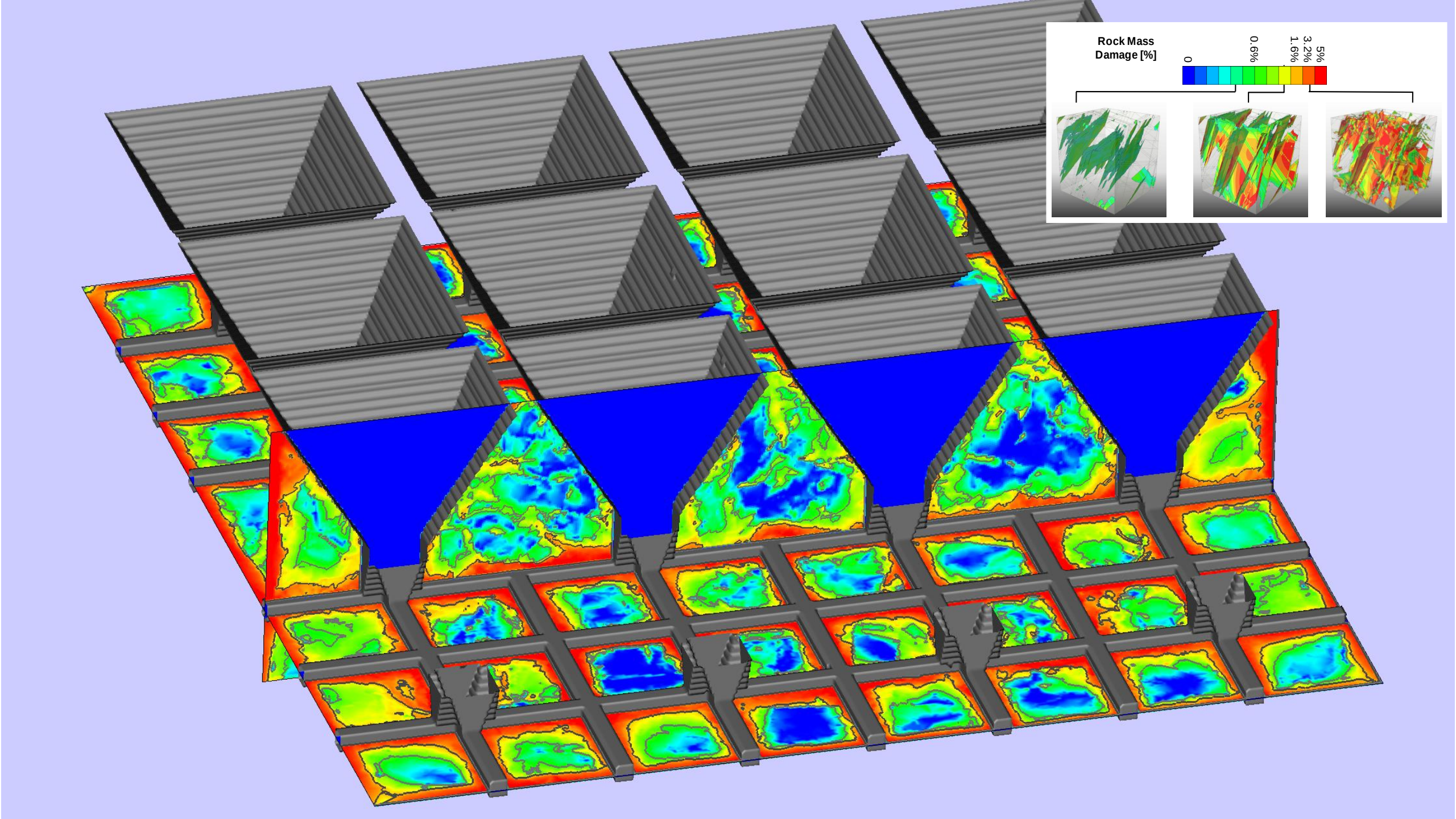


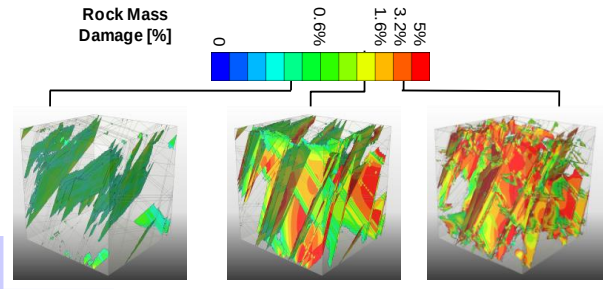



Rock Mass
Damage [%]
0
0.6%
1.6%
3.2%
5%




Rock Mass
Damage [%]
0
0.6%
1.6%
3.2%
5%


Rock Mass
Damage [%]
0
0.69%
1.69%
3.2%
5%


Rock Mass
Damage [%]
0
0.6%
1.6%
3.2%
5%

