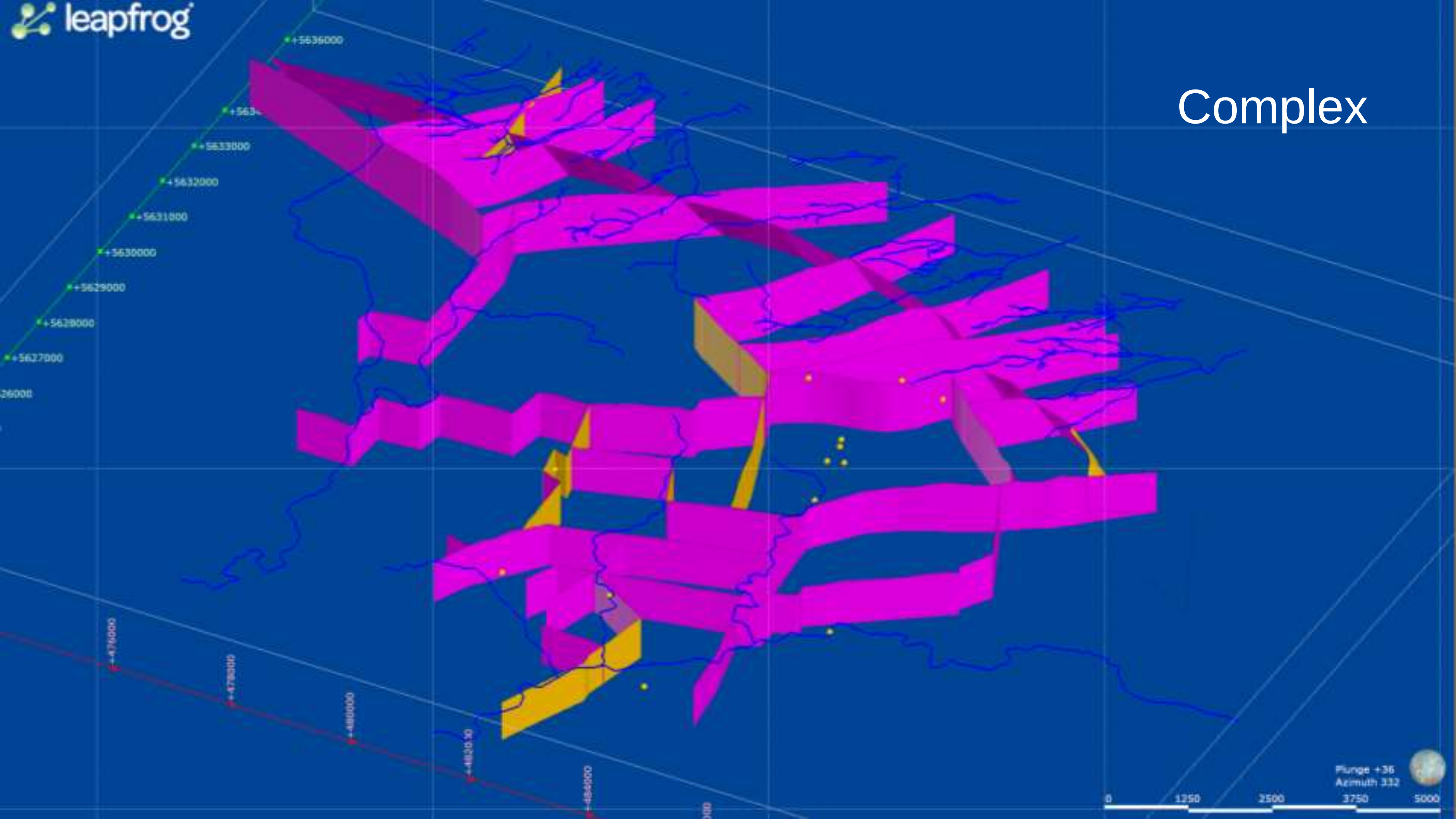
Modelling Groundwater Flow in Hard Rock Environments

Alexander Renz, DHI, Munich, Germany

Part 1

Representing Complex Geology

Complex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+5633000
+5632000
+5631000
+5630000
+5629000
+5628000
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+476000
+478000
+480000
+484000
Plunge +36
Azimuth 332
0
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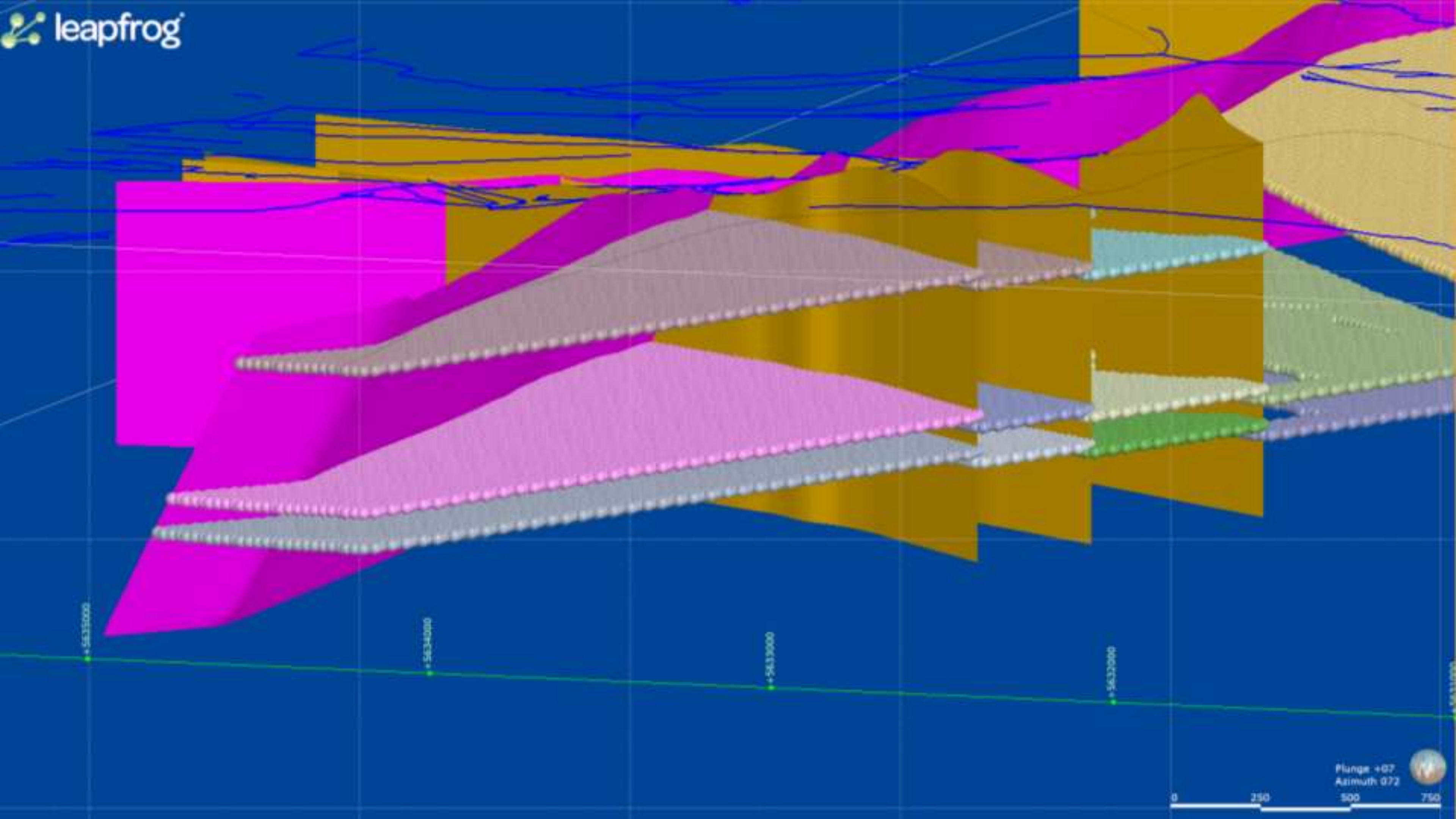
2500
3750
5000


leapfrog
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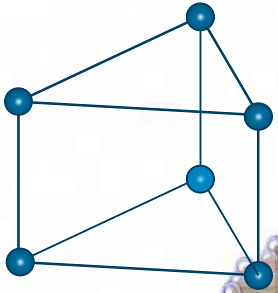
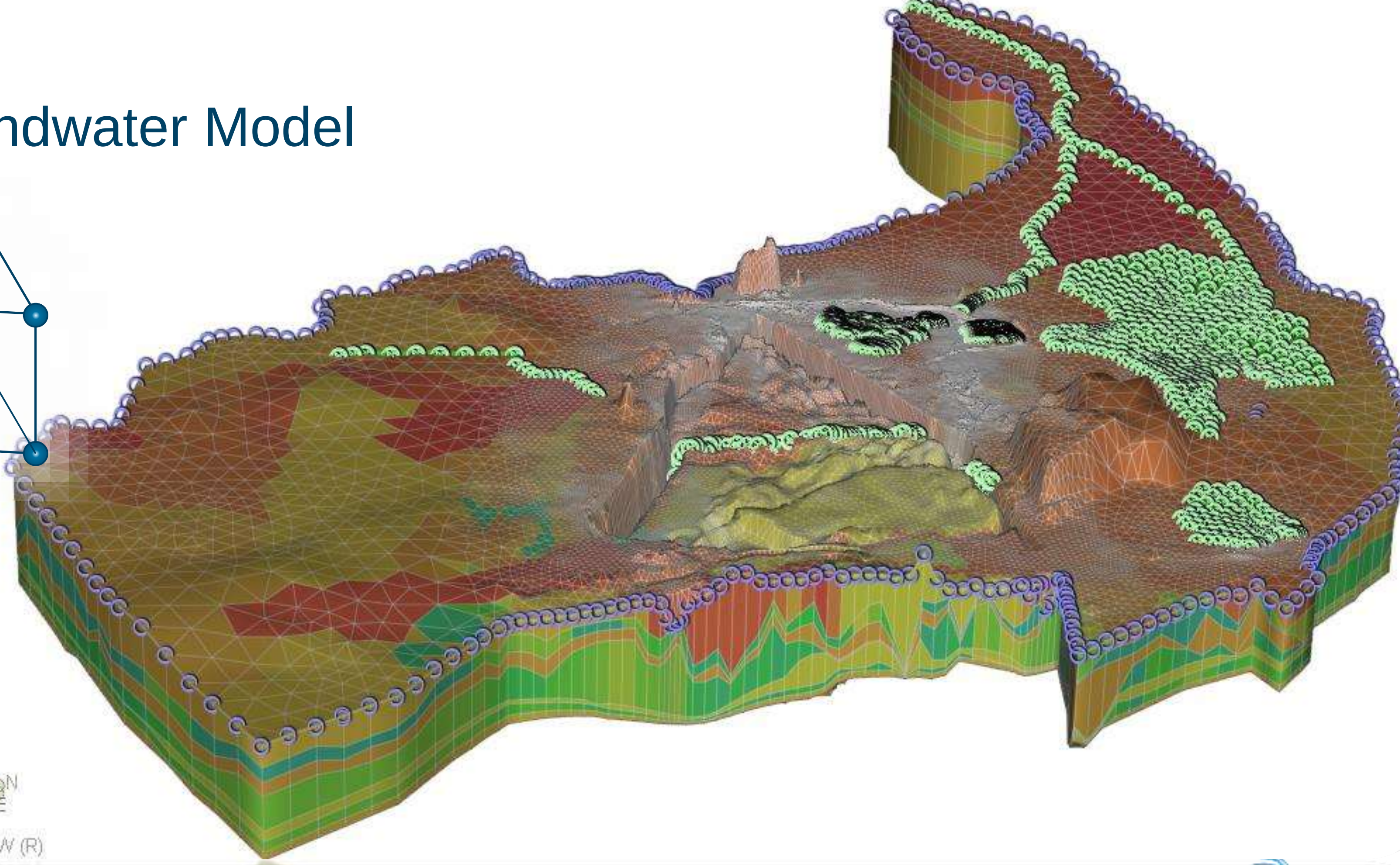
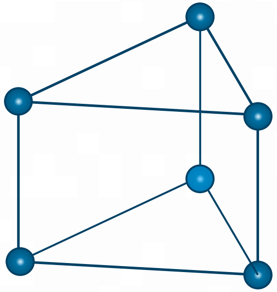
+5634000
+5633000
+5632000
Plunge +07
Azimuth 072
0
250
500
750

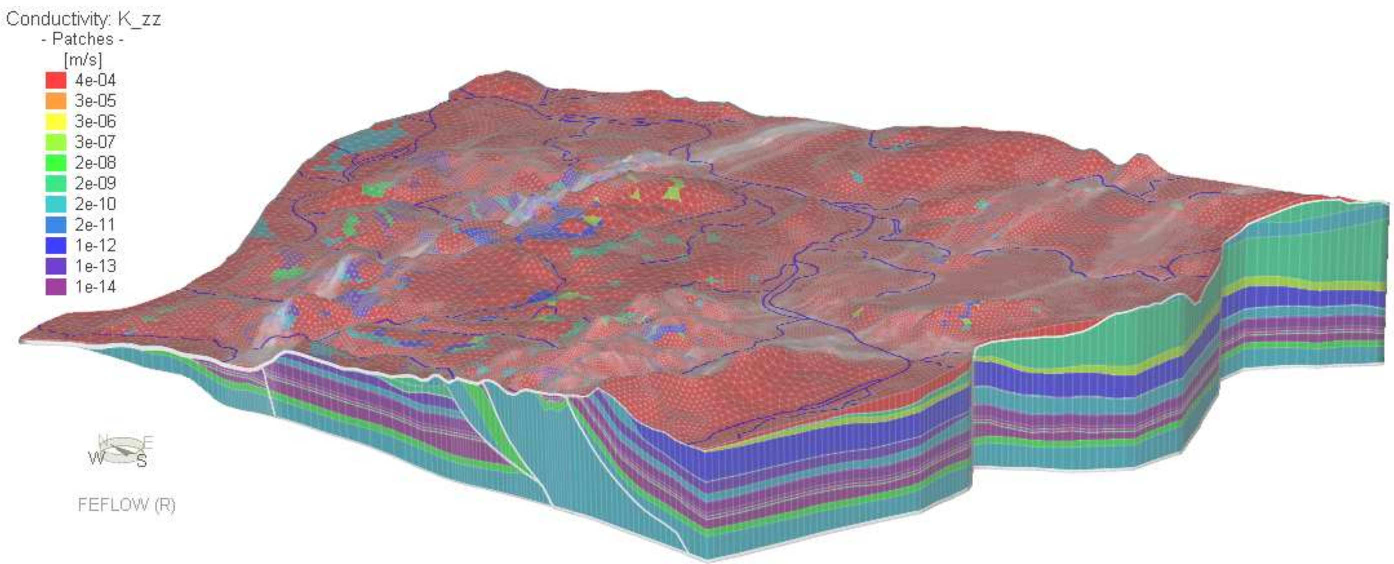
3D Groundwater Model





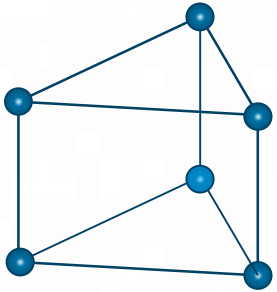
3D Groundwater Model



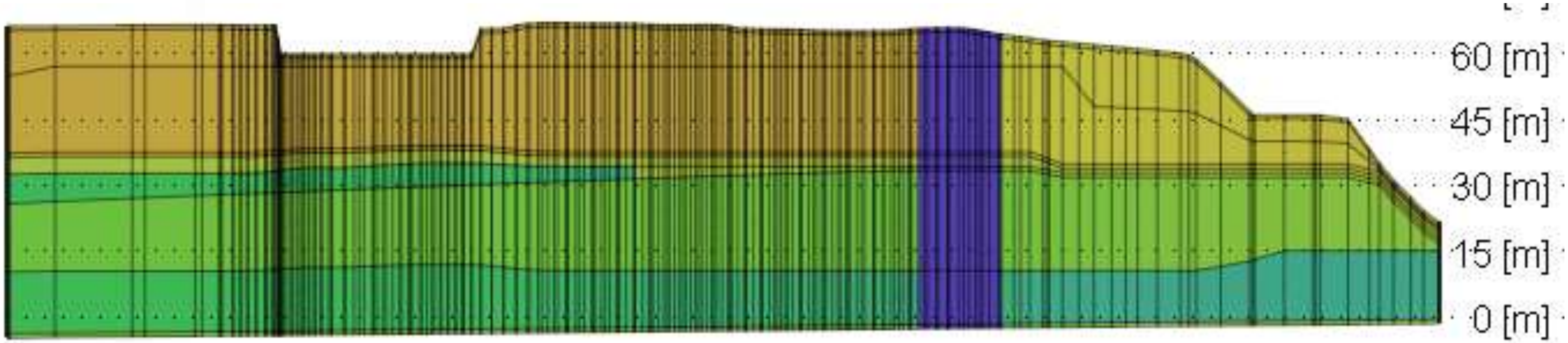


Multi-Faulted Regional Groundwater Model, Switzerland

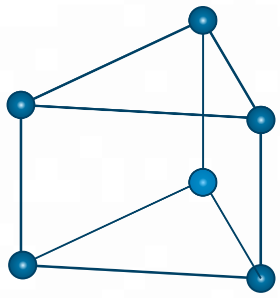
3D Groundwater Model

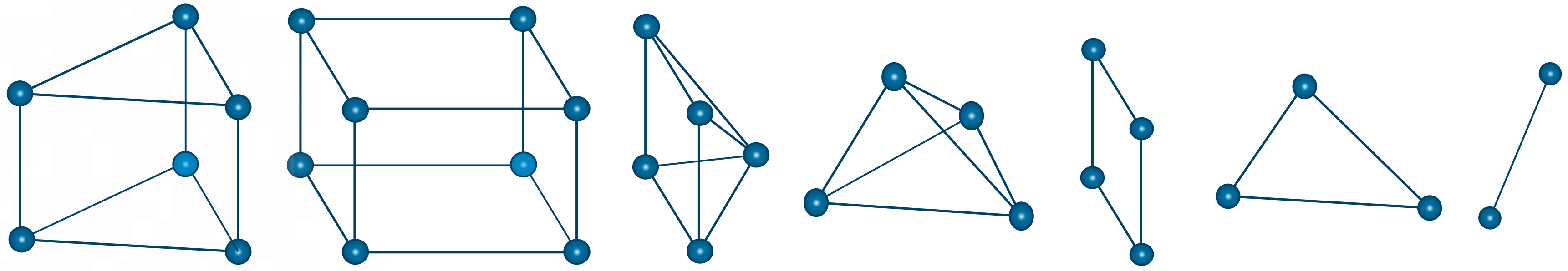


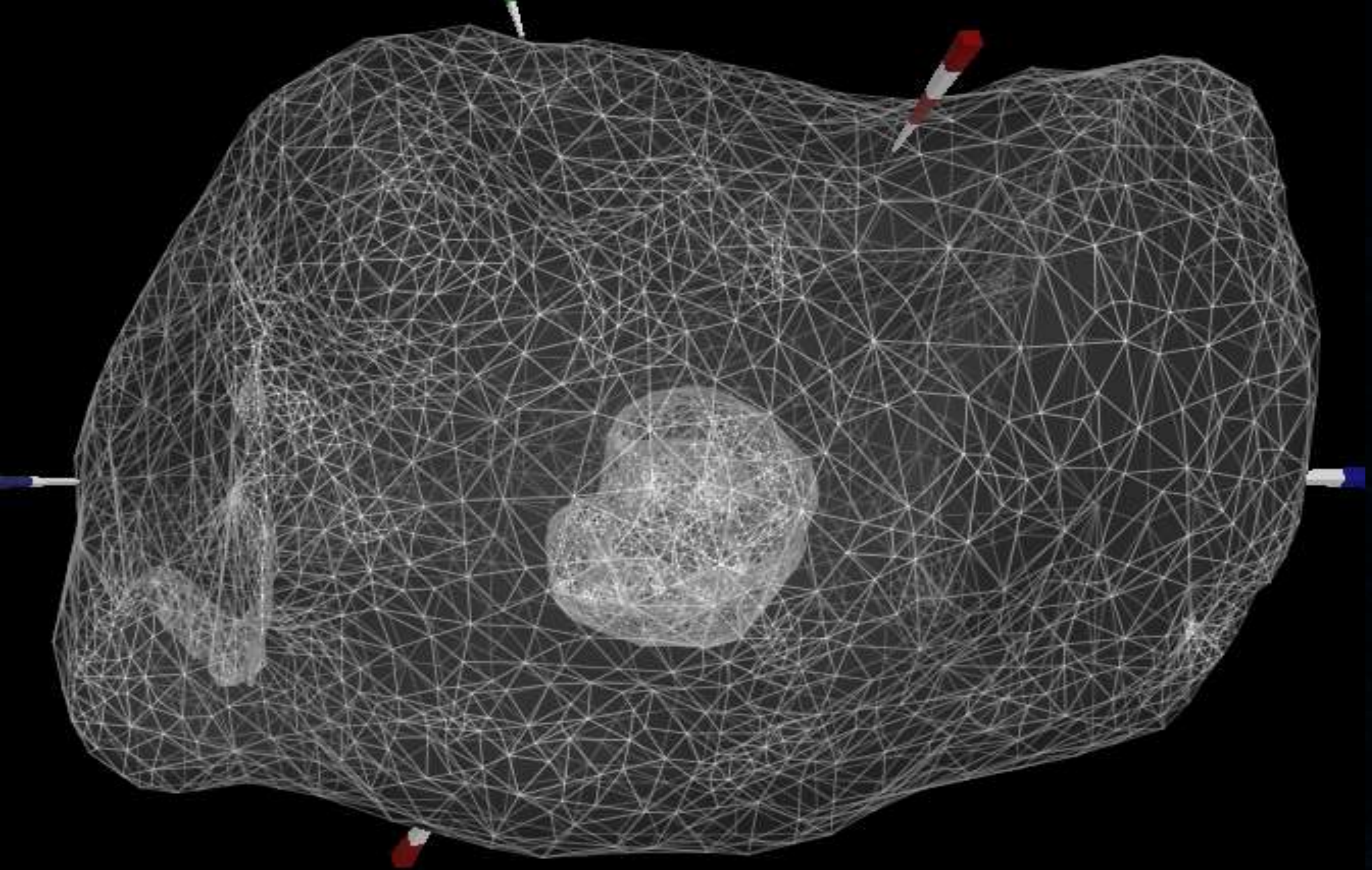
- Continuous Layers
- Vertical Walls

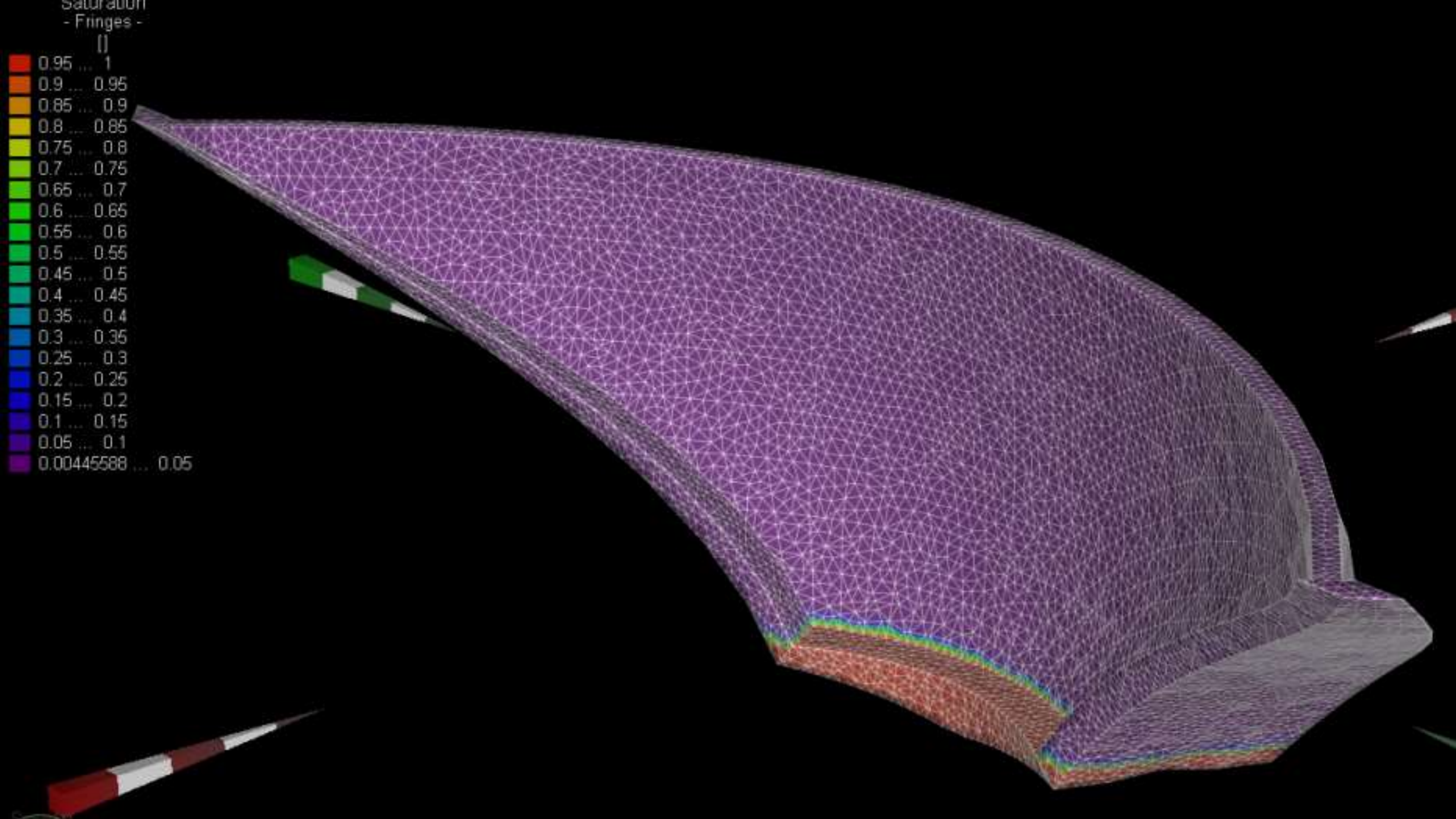


Unstructured Meshes








Saturation
- Fringes -
[]
0.95 ... 1
0.9 ... 0.95
0.85 ... 0.9
0.8 ... 0.85
0.75 ... 0.8
0.7 ... 0.75
0.65 ... 0.7
0.6 ... 0.65
0.55 ... 0.6
0.5 ... 0.55
0.45 ... 0.5
0.4 ... 0.45
0.35 ... 0.4
0.3 ... 0.35
0.25 ... 0.3
0.2 ... 0.25
0.15 ... 0.2
0.1 ... 0.15
0.05 ... 0.1
0.00445588 ... 0.05

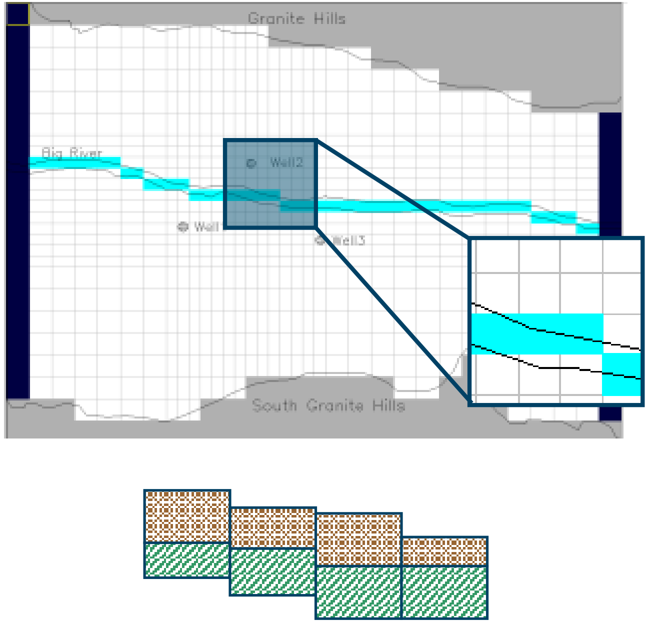
All Problems solved?

Creating Computation Meshes

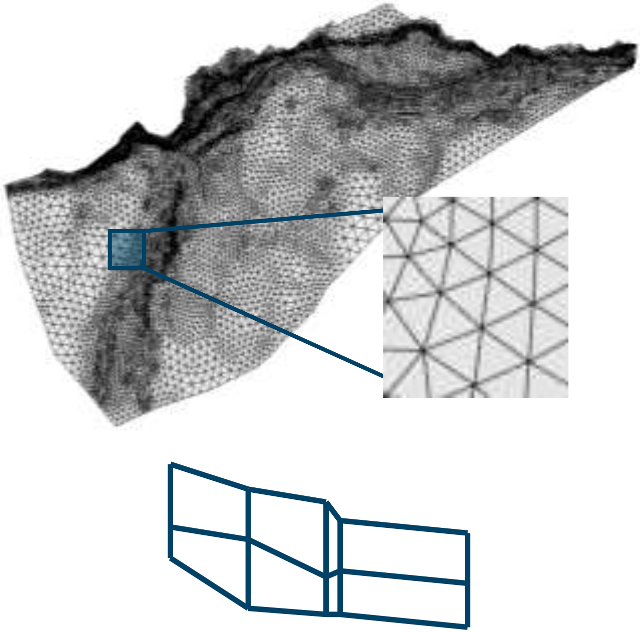
Traditional Layered Meshes

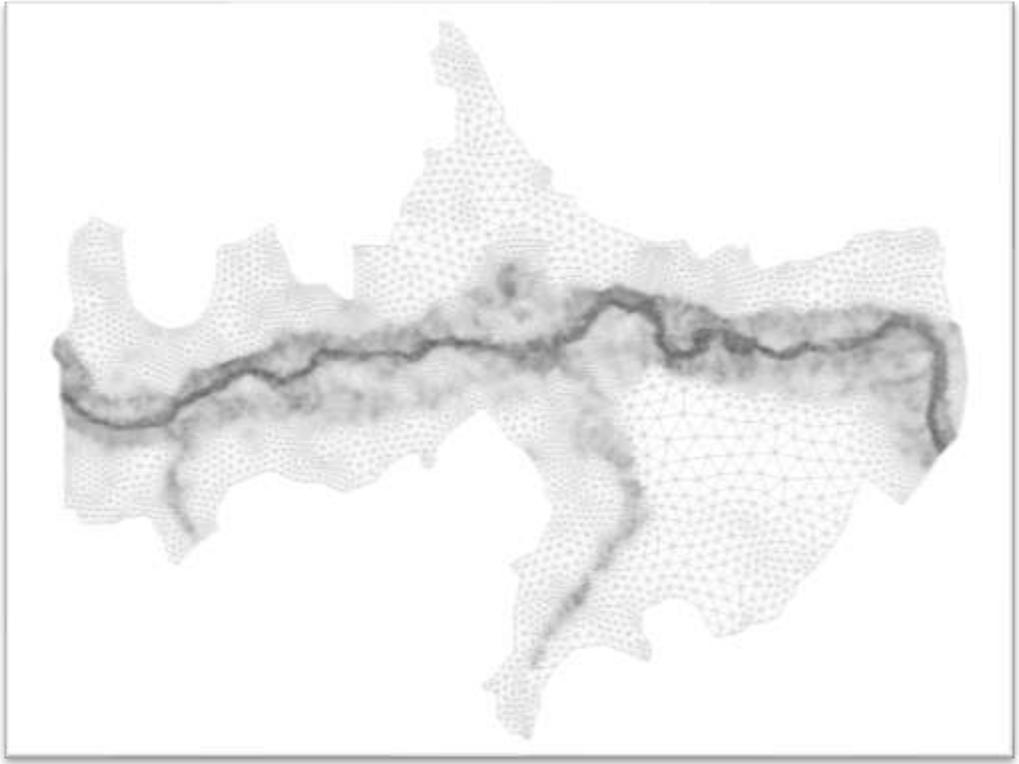
Mathematical Approach

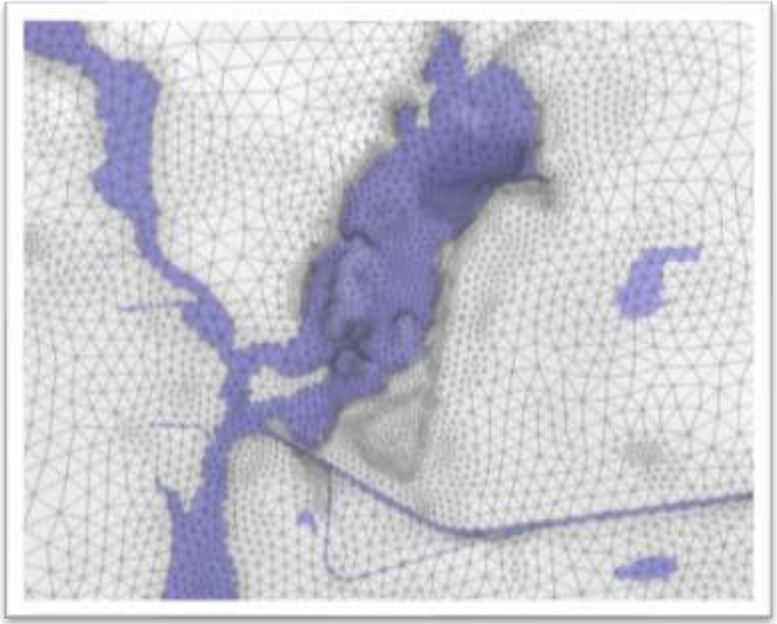
- Finite Differences Method



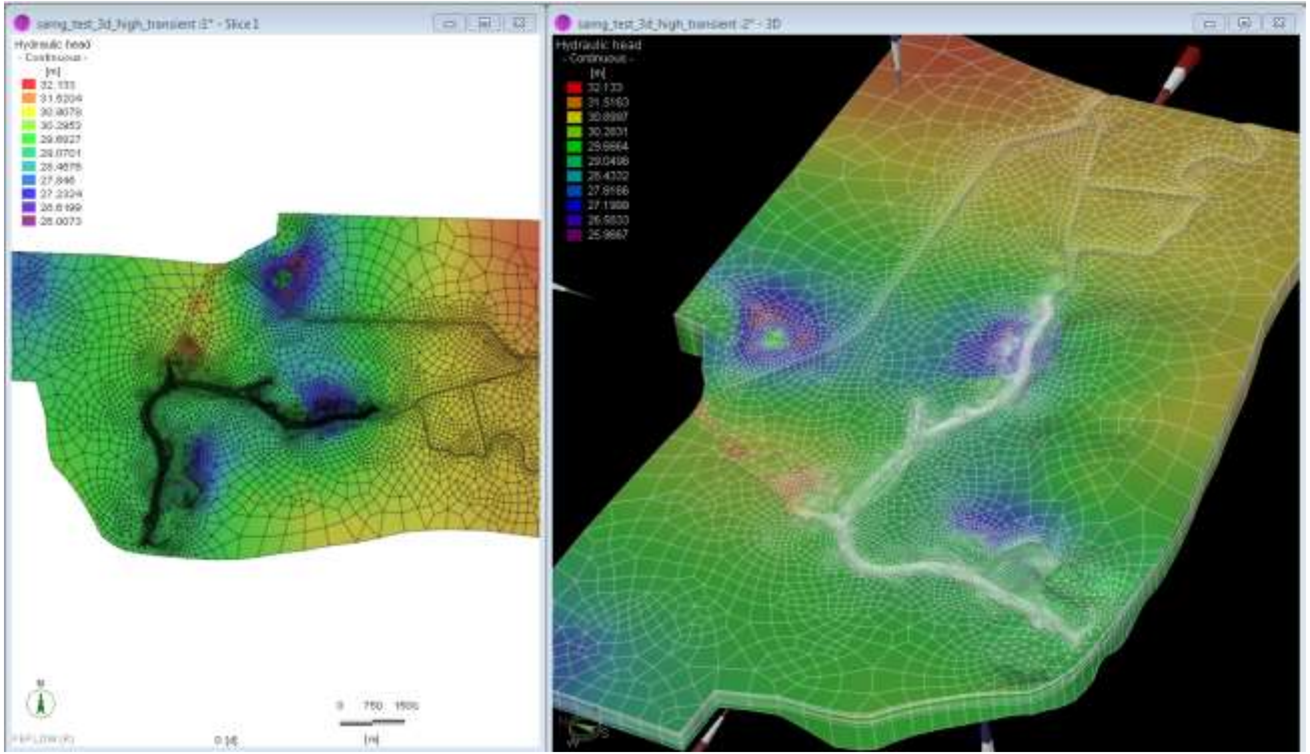
- Finite Element Method



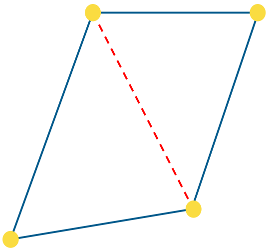




2.5 D Mesh (Layered Mesh)

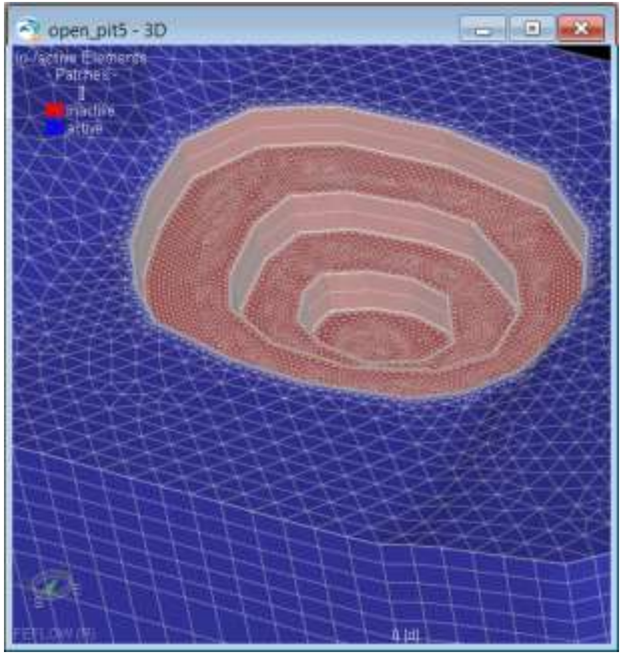


2 Triangles →
1 Quadrangle



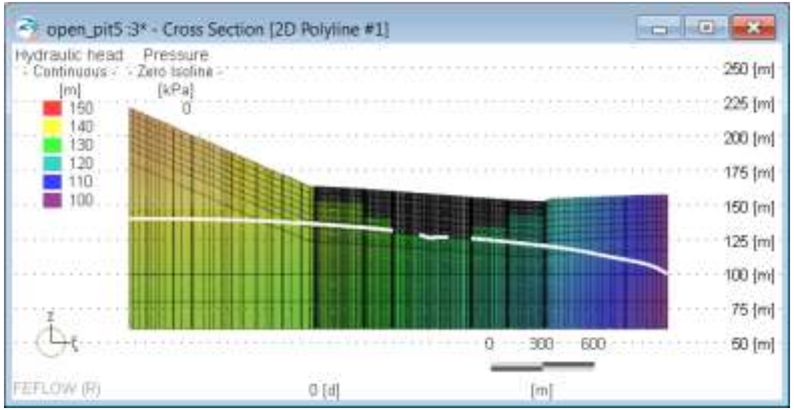
Element Deactivation

- Create Caveats in Mesh, e.g. for pit mines or tunnels
- Permanent or temporary



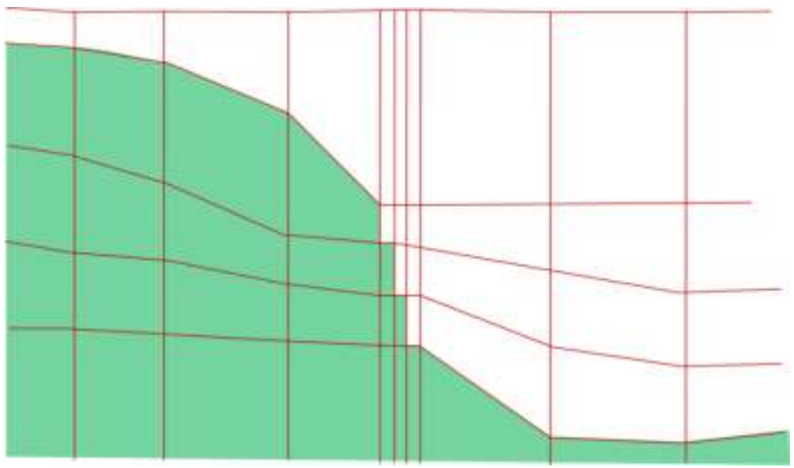
Element Deactivation

- Remove unwanted layers (Top / bottom only)



Steep Interfaces

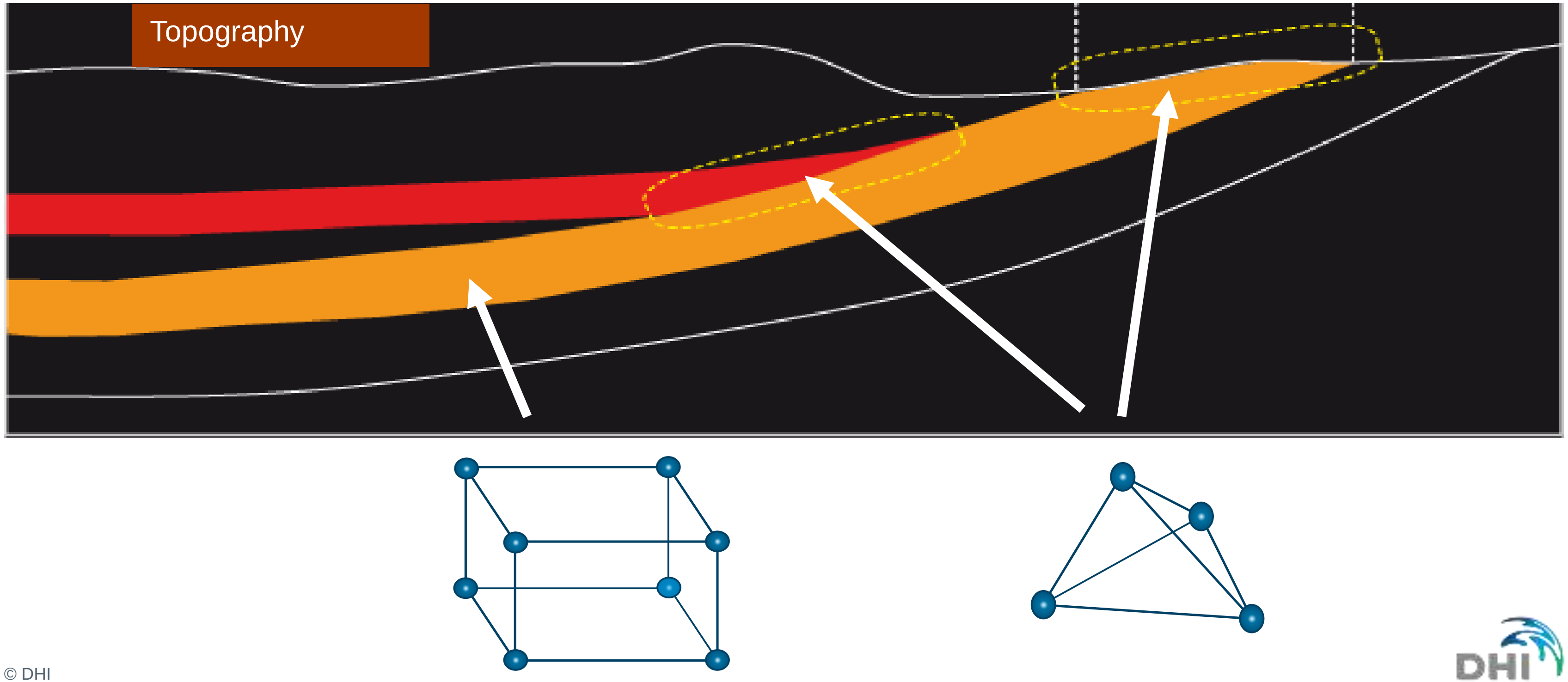
- moderate inclination:
  Layer Elevation
- steep inclination:
  step layout



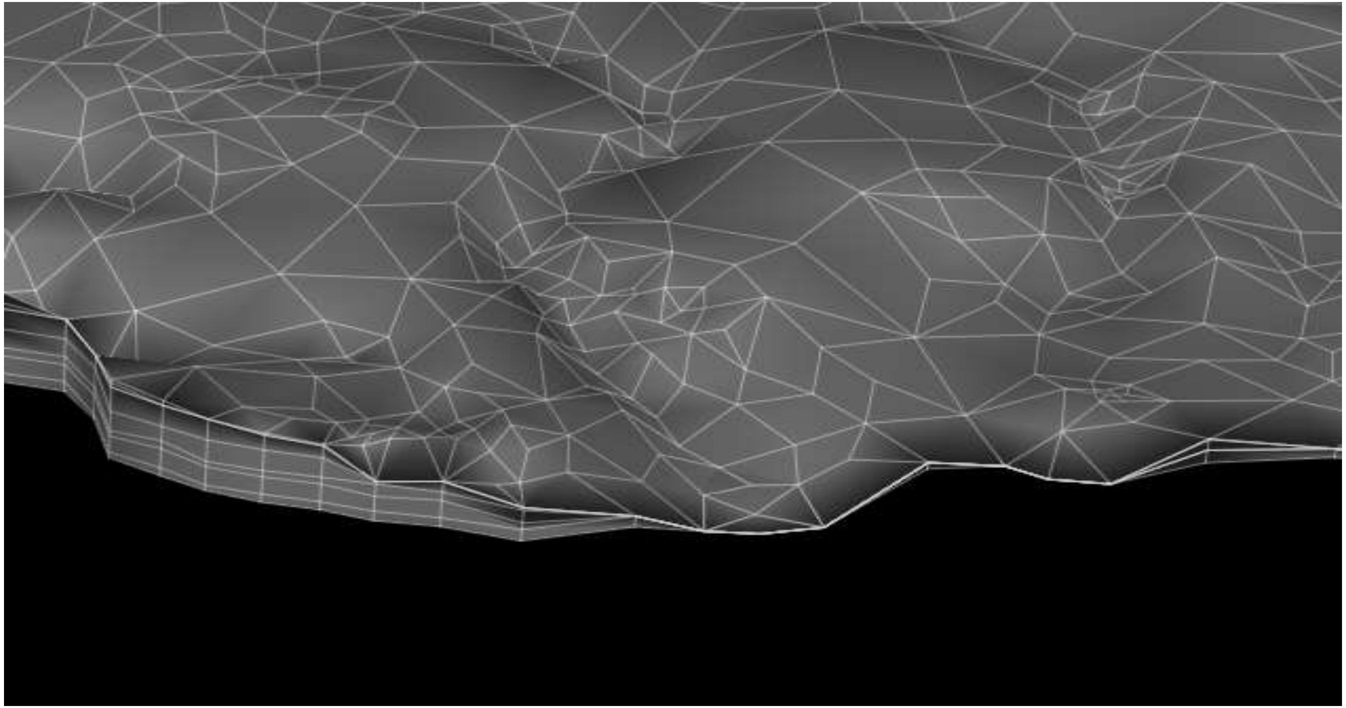
Creating Computation Meshes

Layered Meshes with local remeshing

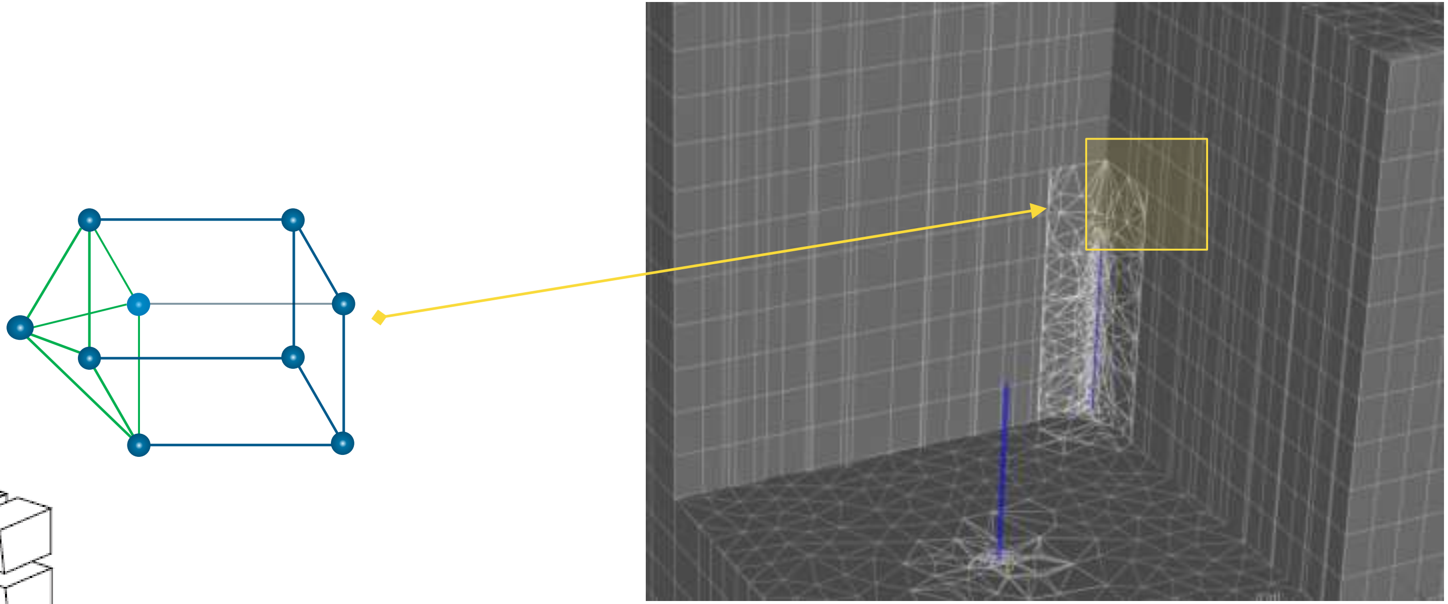
Pinching

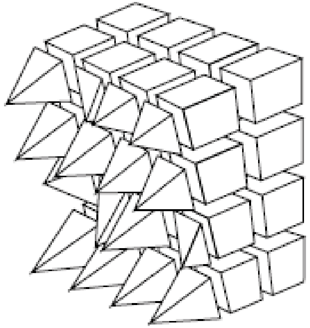


Pinching



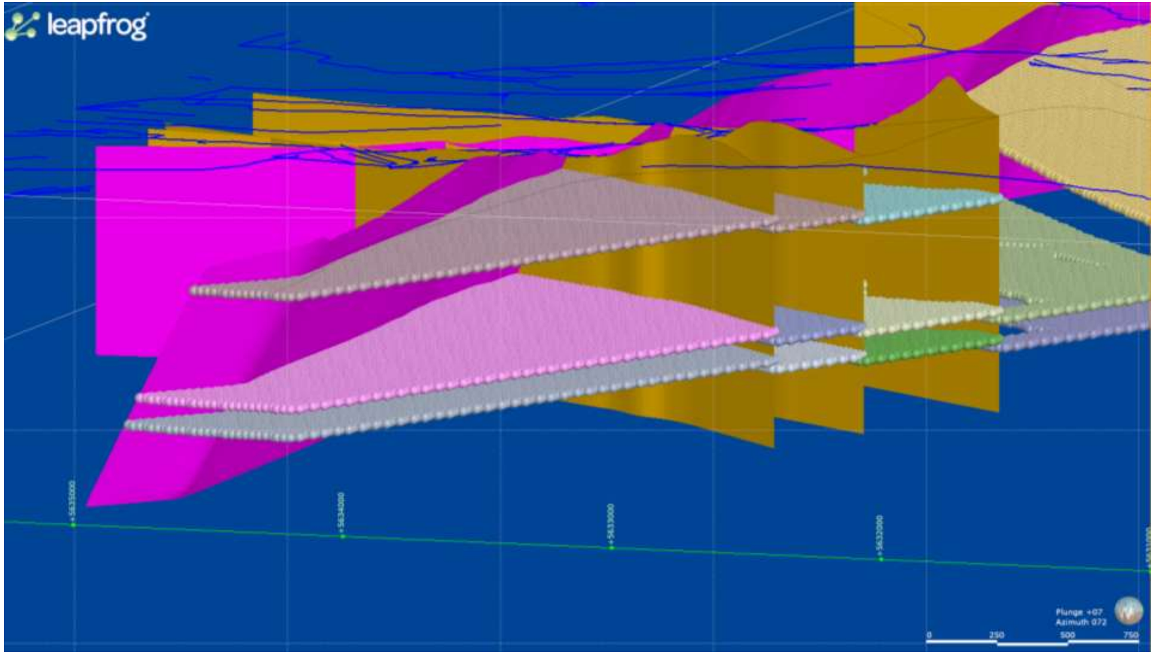
Local Re-Meshing





Creating Computation Meshes

Non-Layered (Fully Unstructured) Meshes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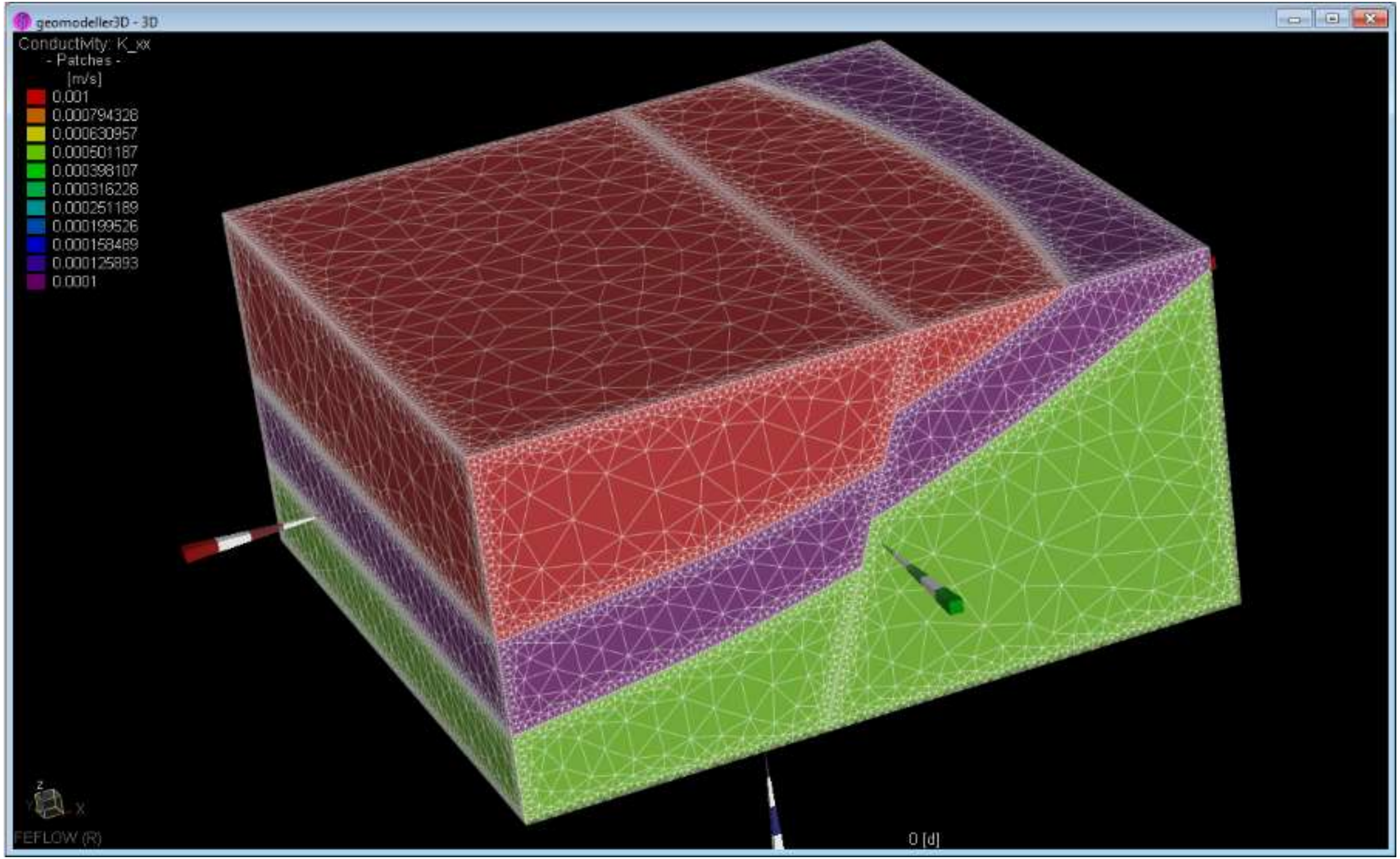
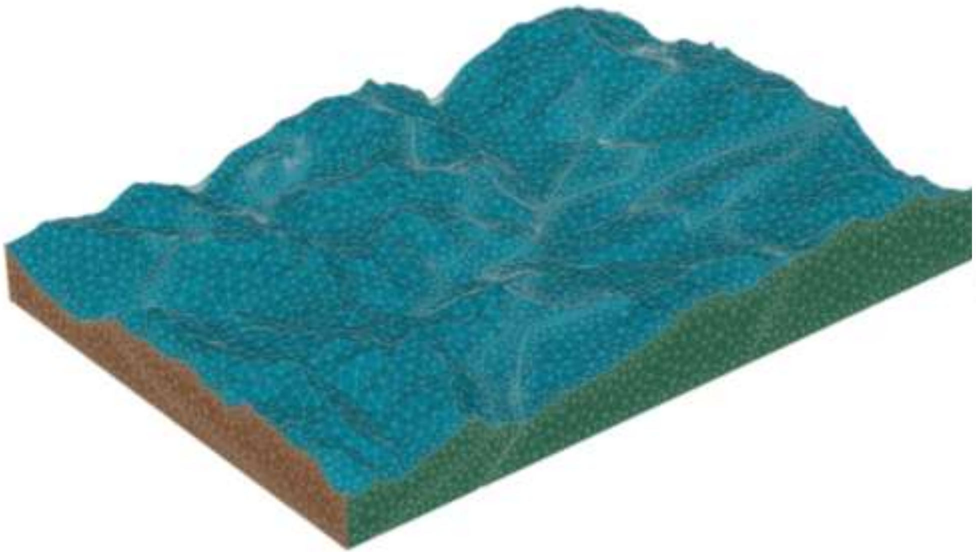
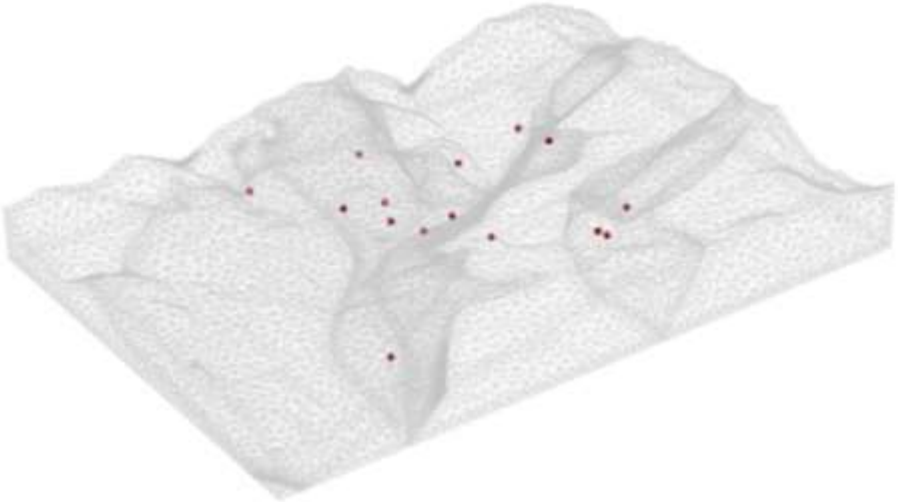
+5635000
+5634000
+5633000
+5632000
Plunge +07
Azimuth 072
0
250
500
750


geomodeller3D - 3D
Conductivity: K_xx
- Patches -
[m/s]
0.001
0.000794328
0.000630957
0.000501187
0.000398107
0.000316228
0.000251189
0.000199526
0.000158489
0.000125893
0.0001
FEFLOW (R)
0 [d]

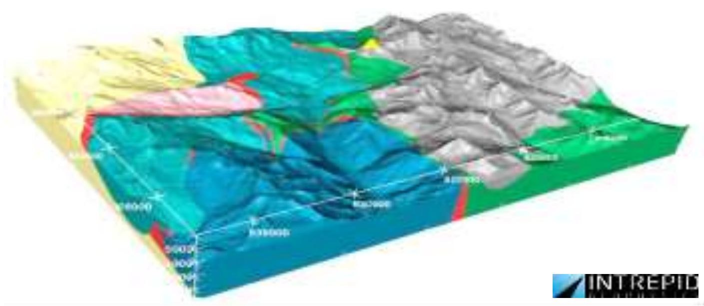
Non-Layered Meshed

- Geological contacts (volumes)
- Insets such as well locations

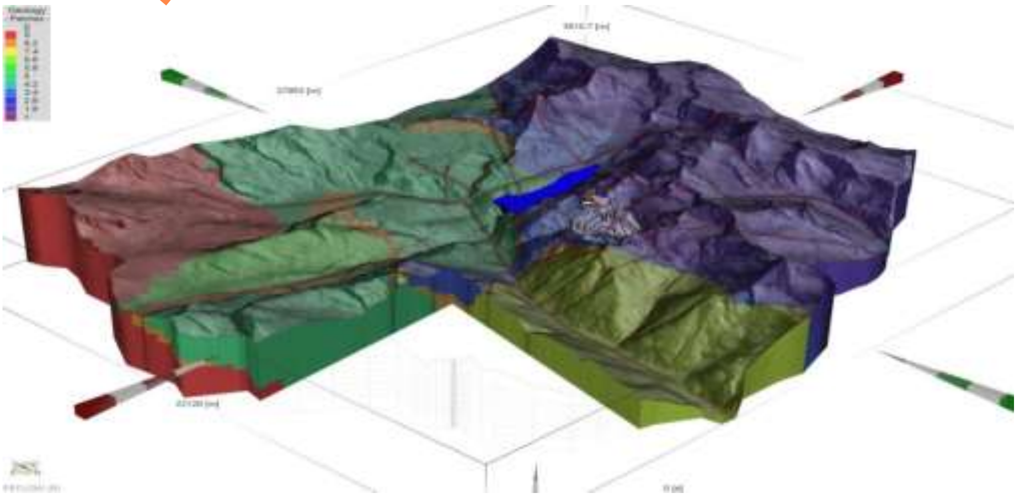



Non-Layered Meshed

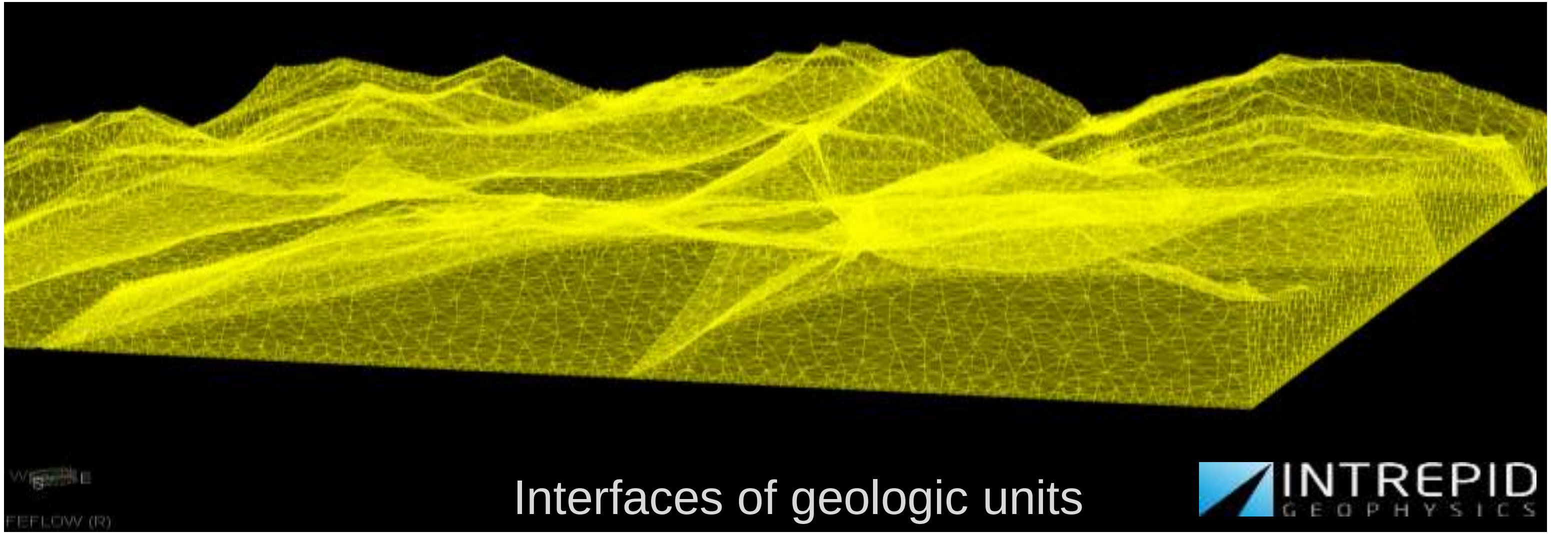
Computation mesh for numerical model



Structural Geologic Model

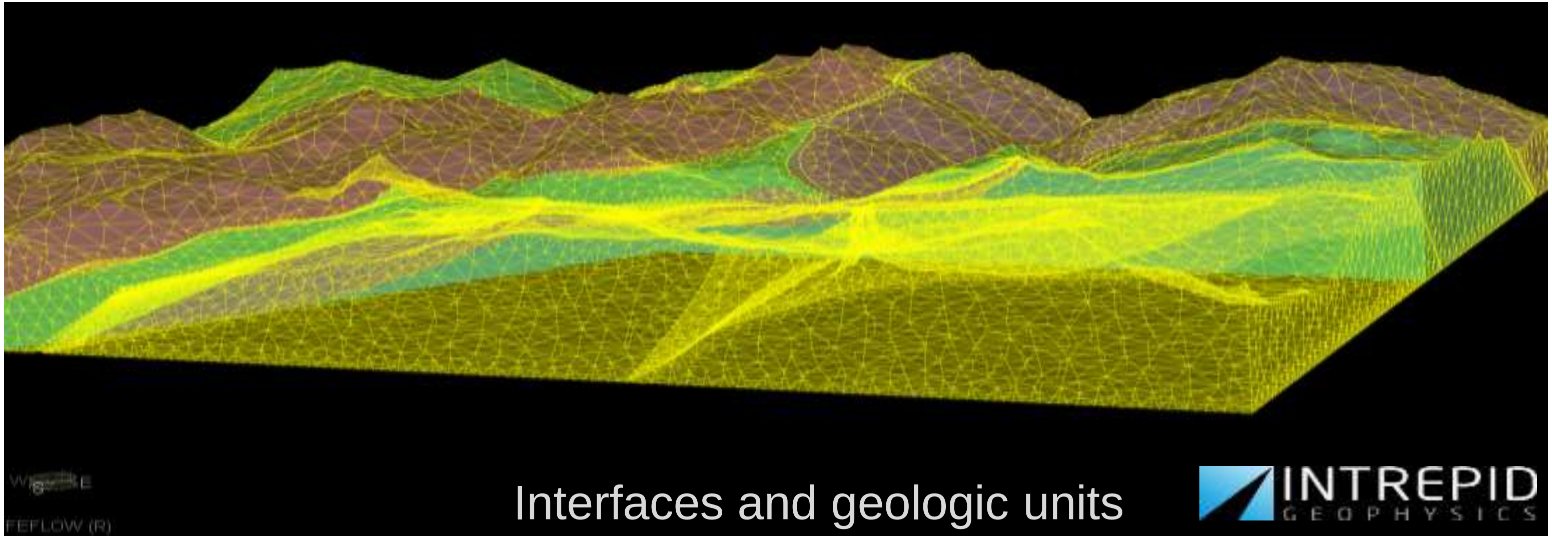


Non-Layered Mesh

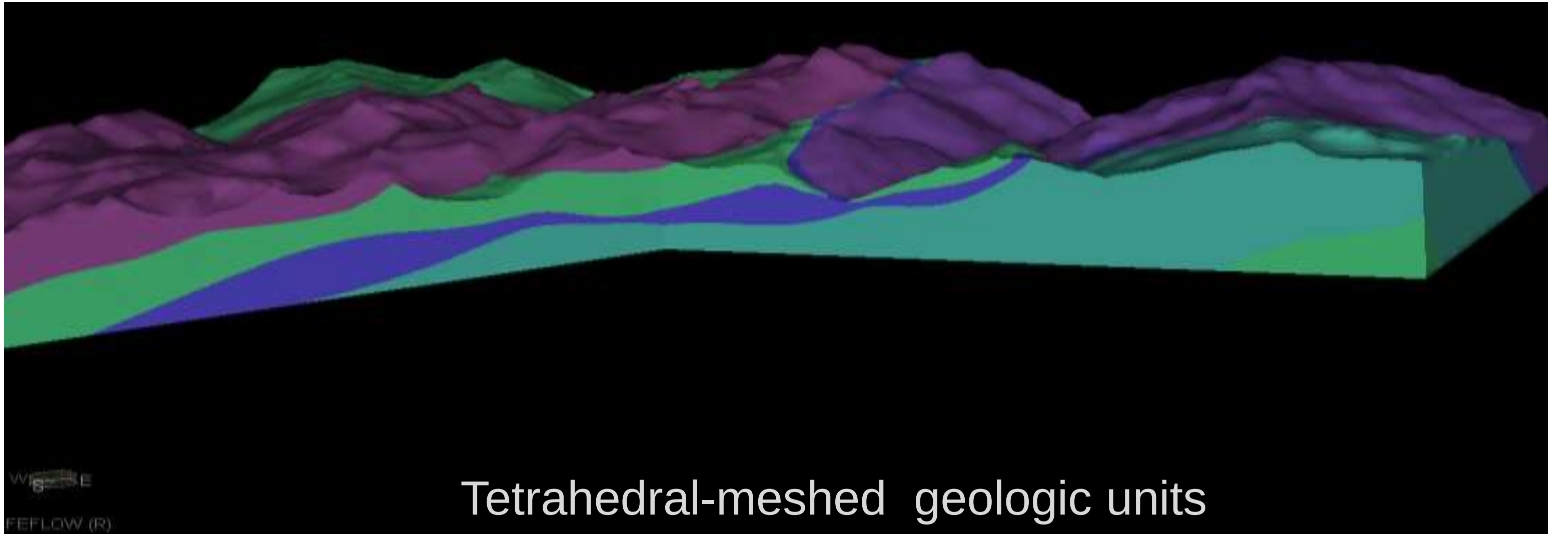


Interfaces of geologic units

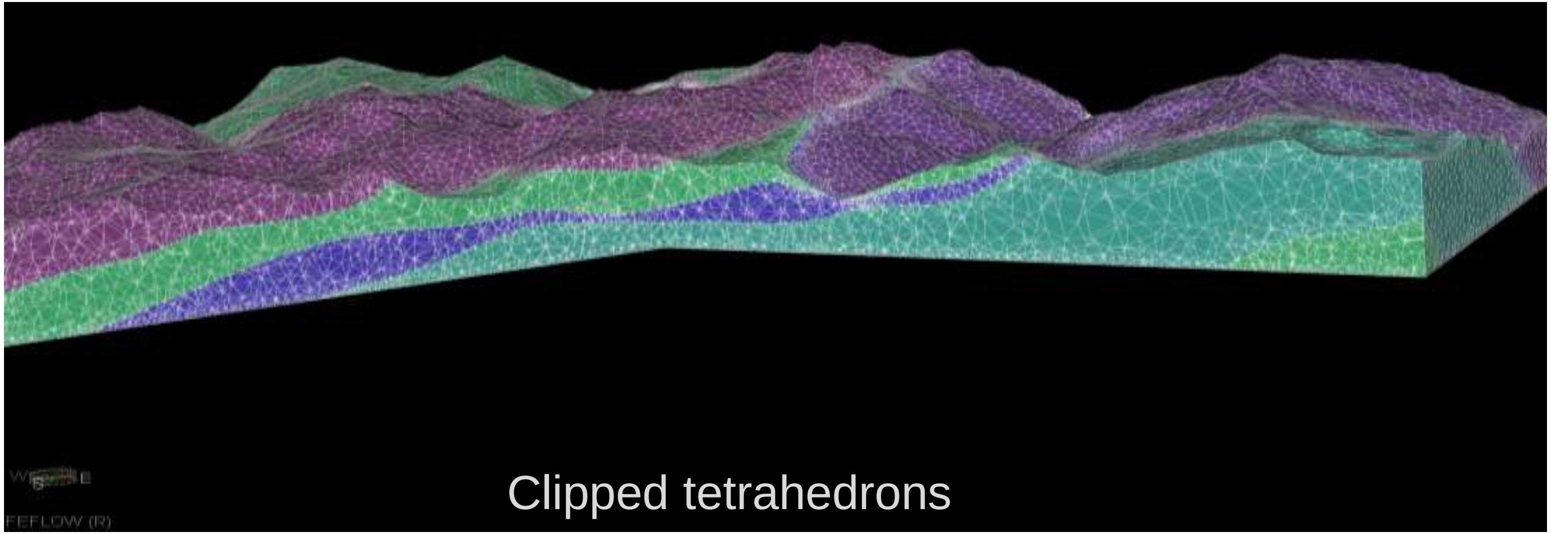
Non-Layered Mesh



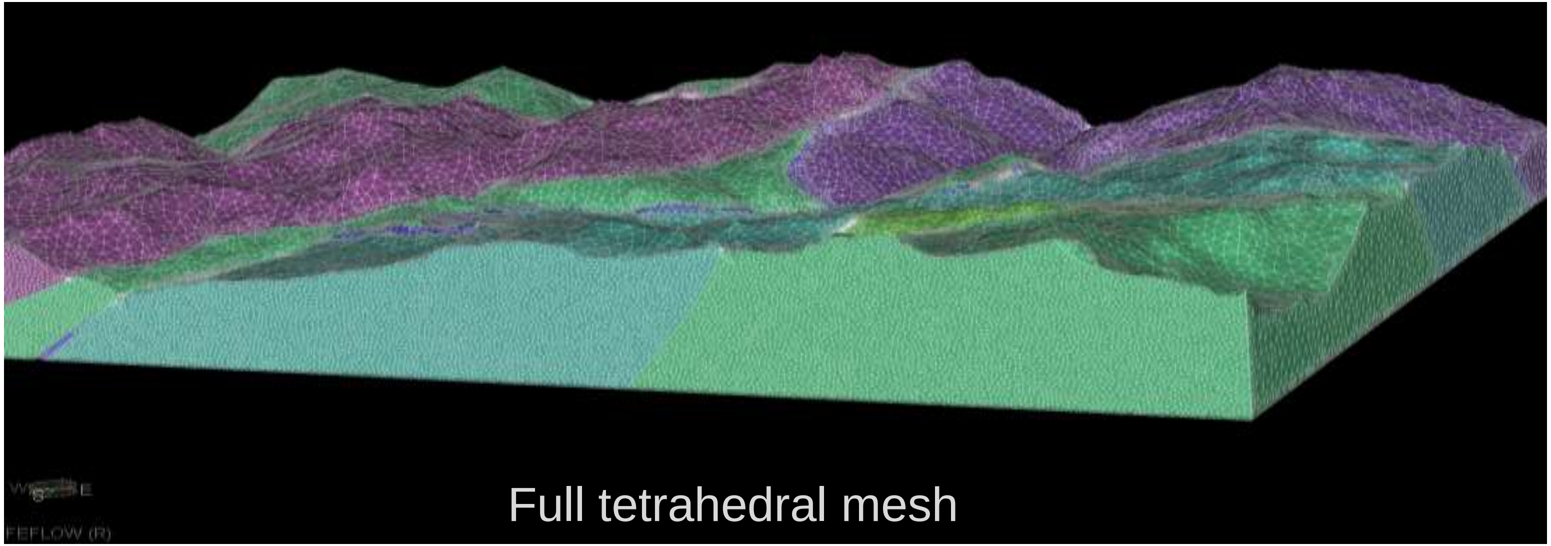
Non-Layered Mesh



Non-Layered Mesh



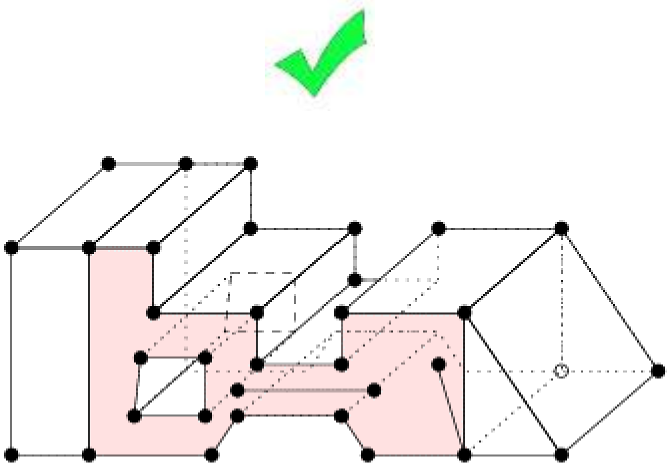
Non-Layered Mesh

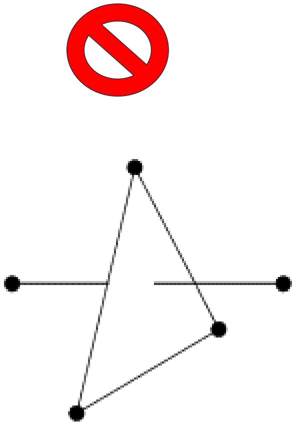


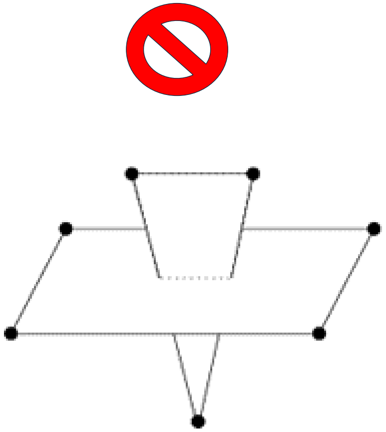
Full tetrahedral mesh

Challenges

Piecewise Linear Complexes (PLC)

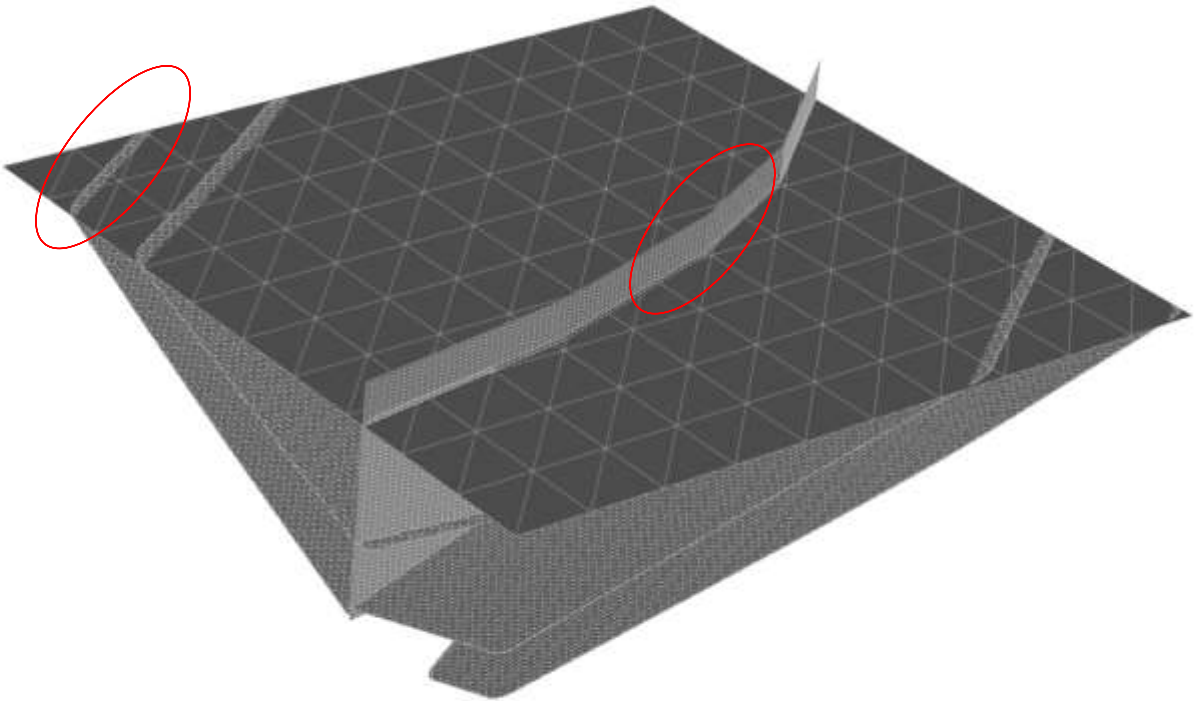




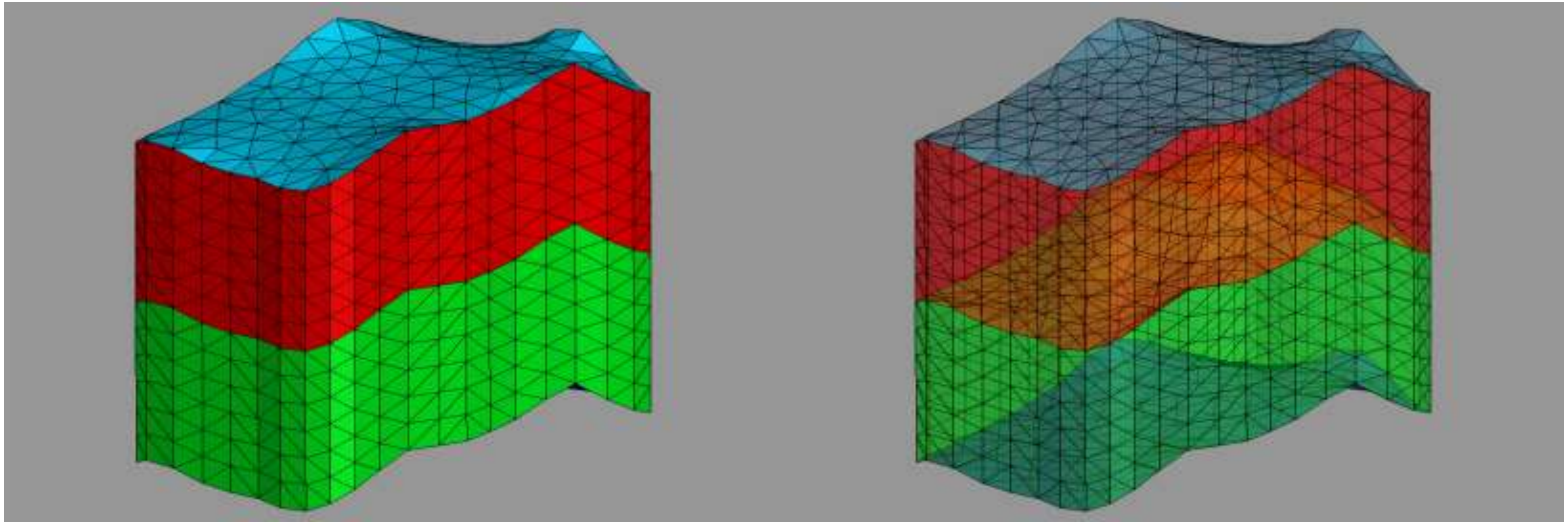


http://wias-berlin.de/software/tetgen/plc.html

The Problem of Self-intersecting Surfaces



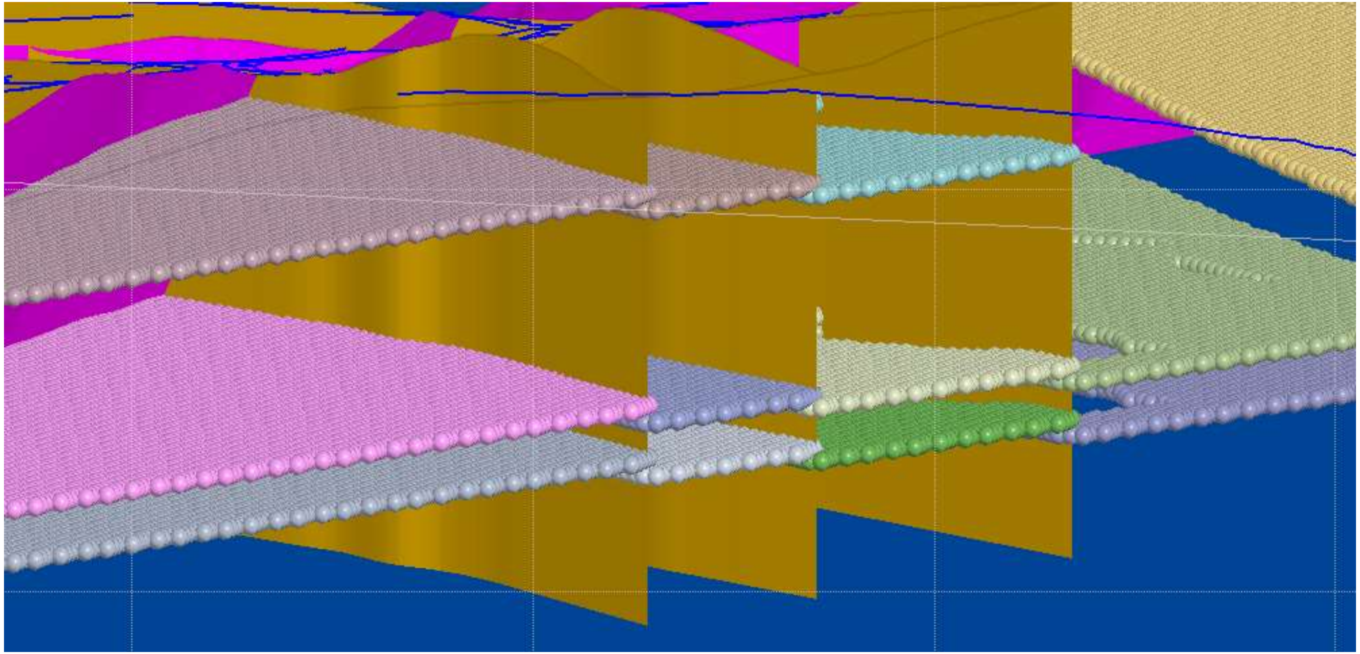
Closed and Consistent Volumes



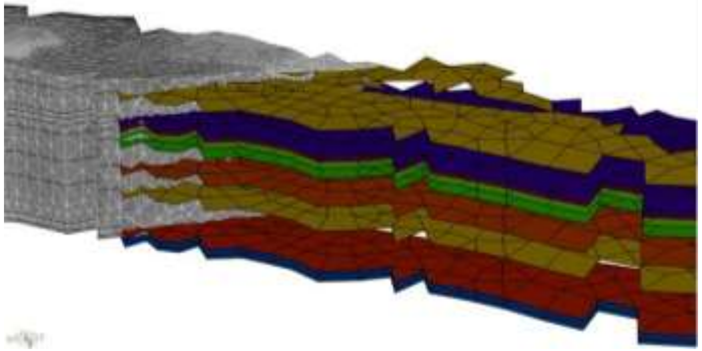
Example Case

DHI In-House Solution with TetGen

Consideration of Fault Offsets

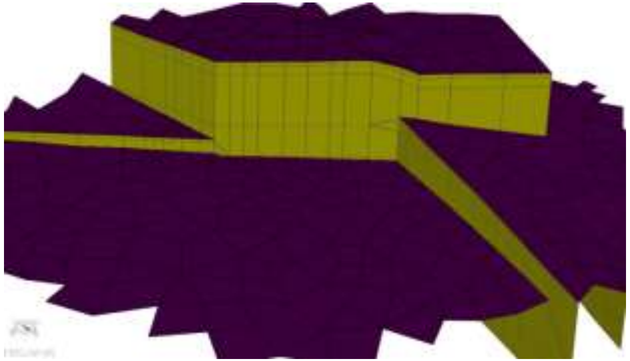


Consideration of Fault Offsets



Consideration of Fault Offsets

- Case 1: Offset at isolated fault



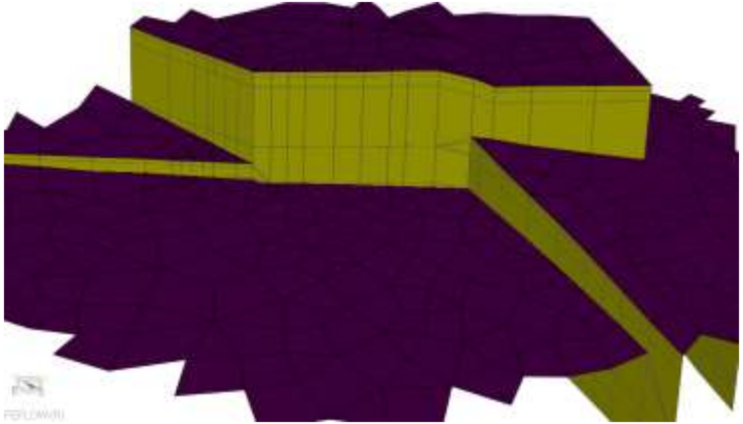
- Solution: Record and sort all elevation data at faults

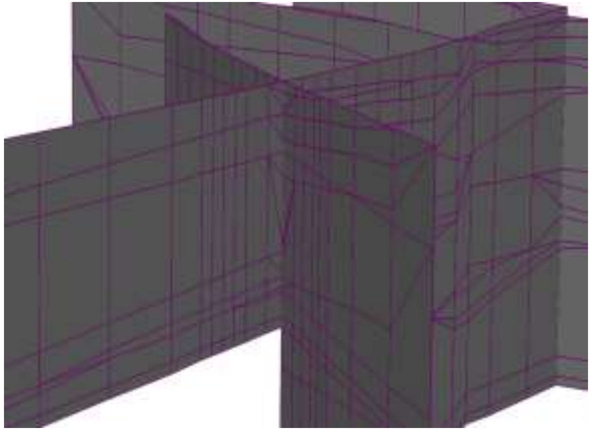
+ applicable for isolated faults

- Not applicable for isolated faults

Consideration of Fault Offsets

- Case 2: Intersecting Faults



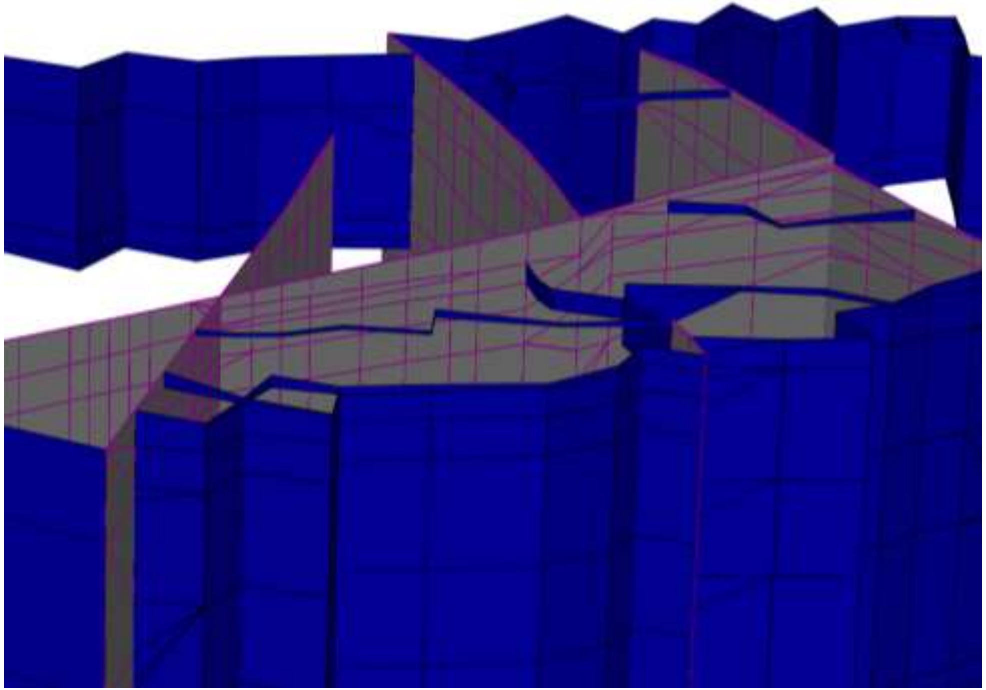


Grouping of elements to sectors

+ can represent more generell complex settings

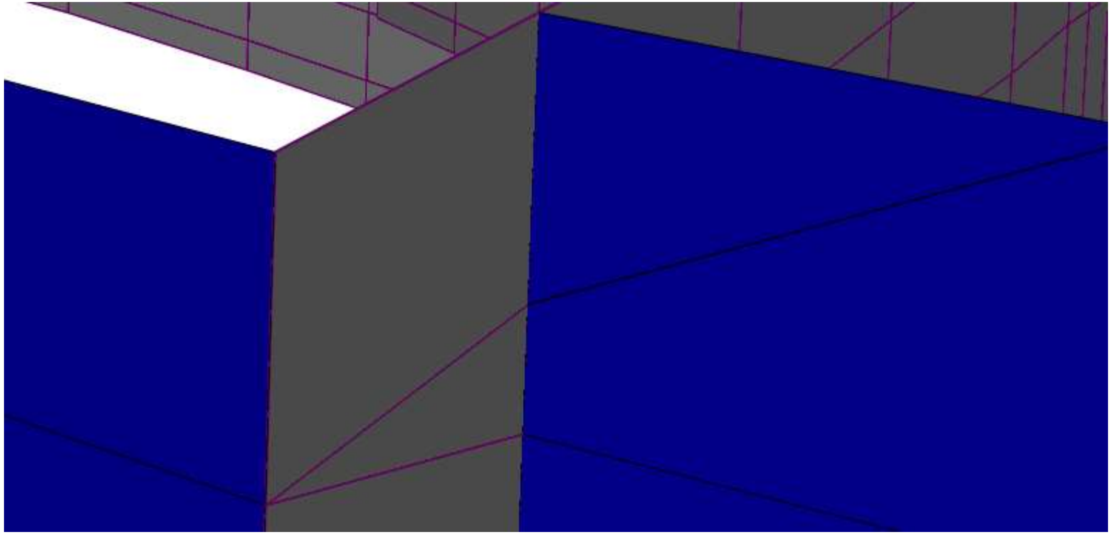
Consideration of Pinchouts

- Pinchouts and outer model hull



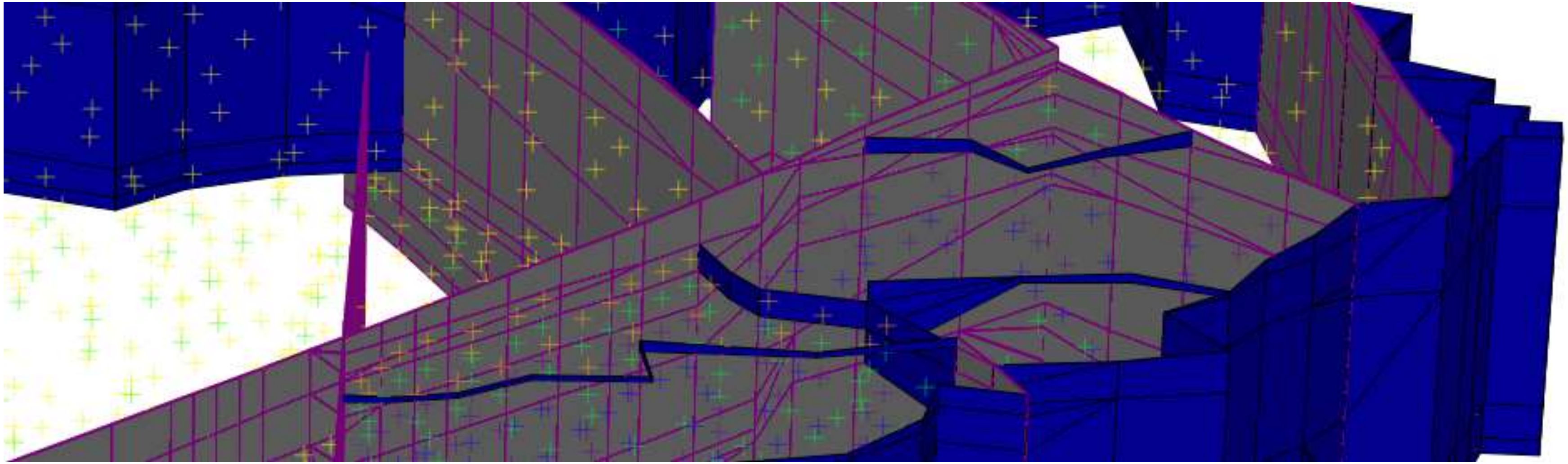
Closing of Remaining Gaps

- Ensure closed volumes



Regional Markers

- Bookkeeping for later numerical model

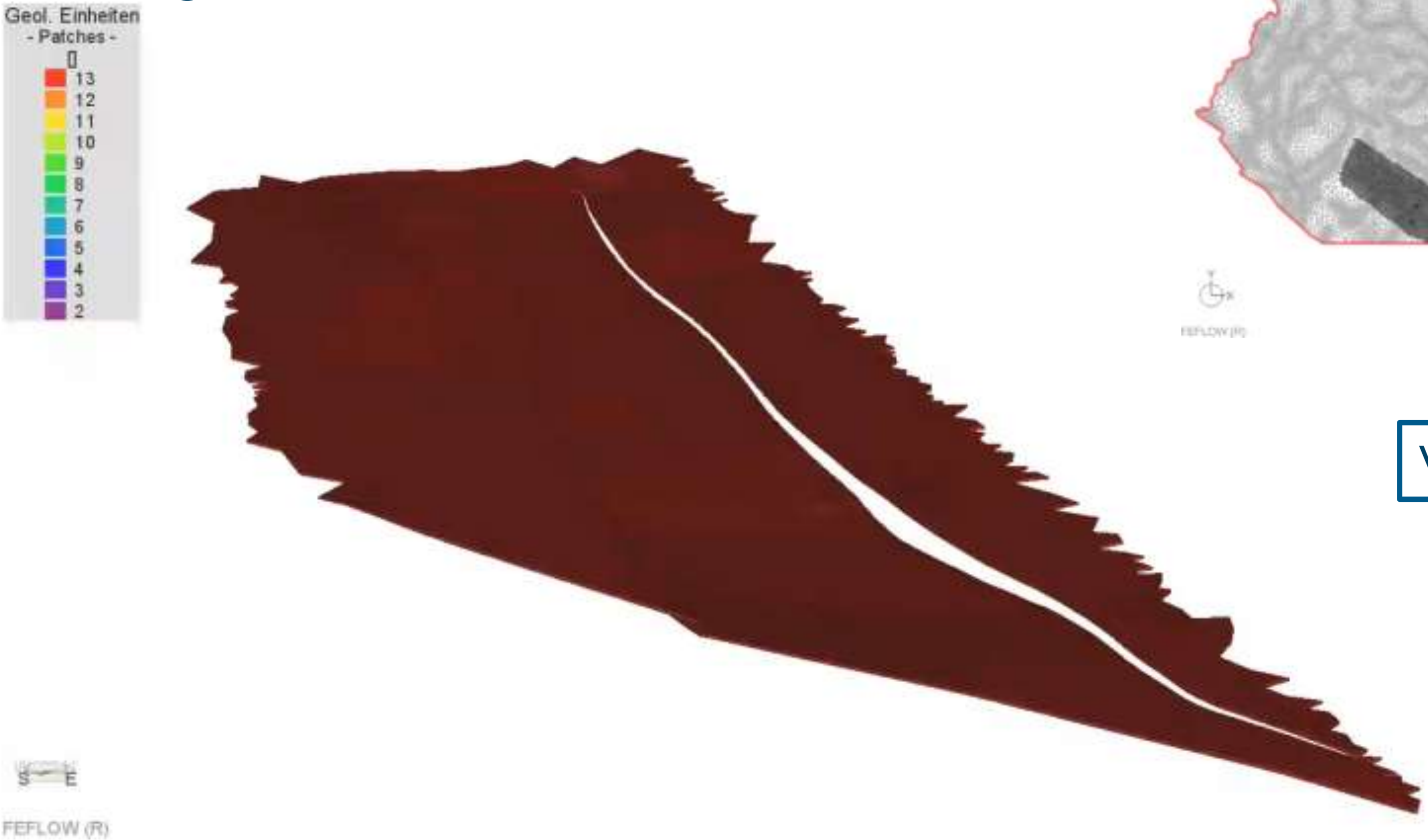


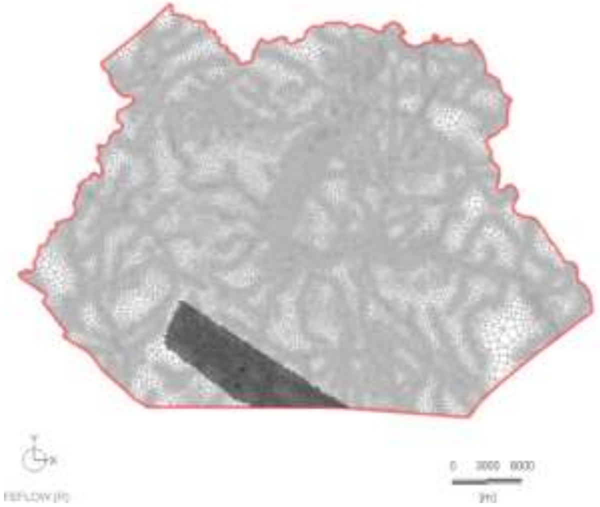
Entwicklung der Methodik

- Result: Set of 3D face objects consistently enclosing all separable geologic volumes

- ~ 700.000 points
- ~ 500.000 faces

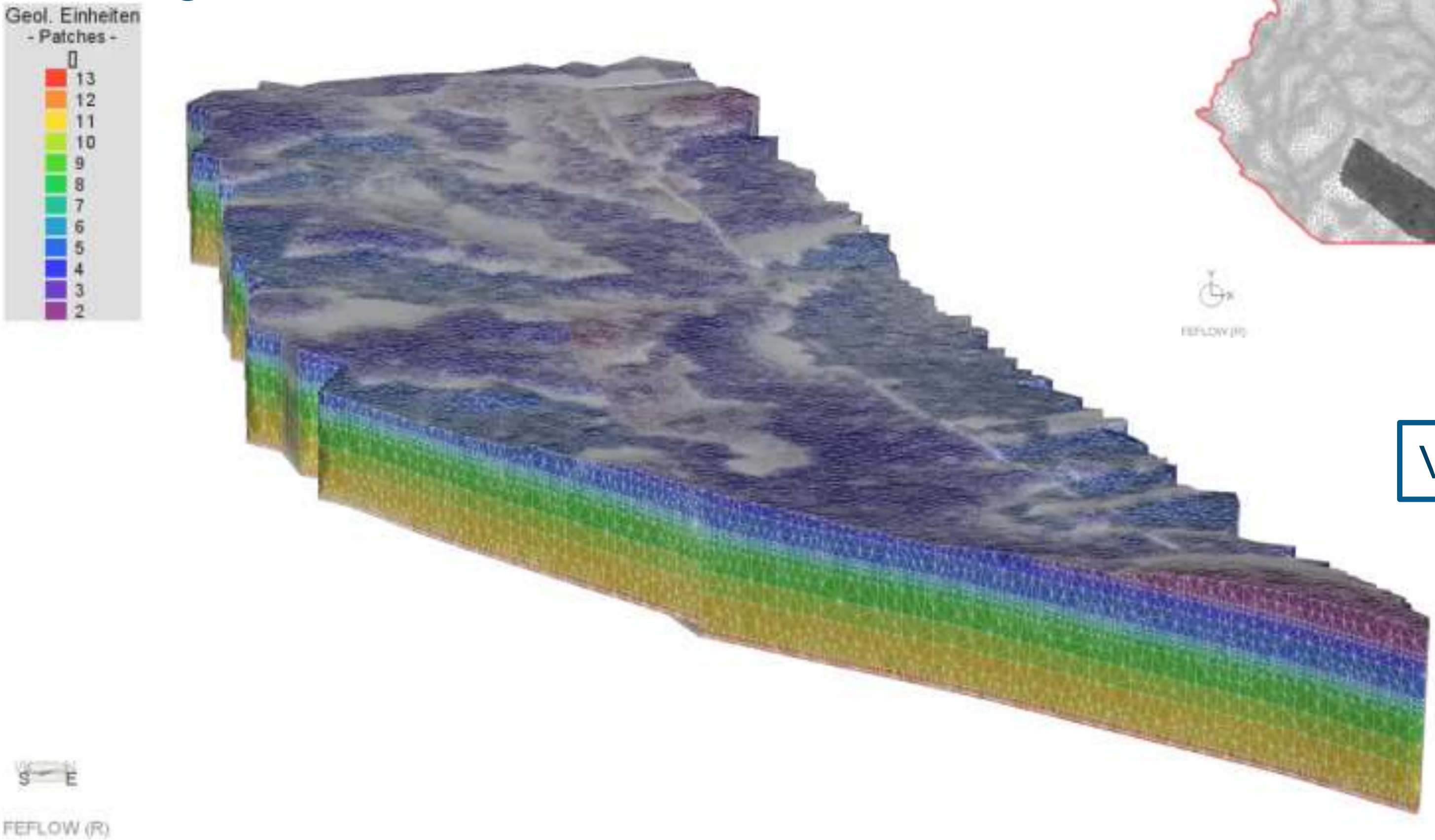
Geologic Units

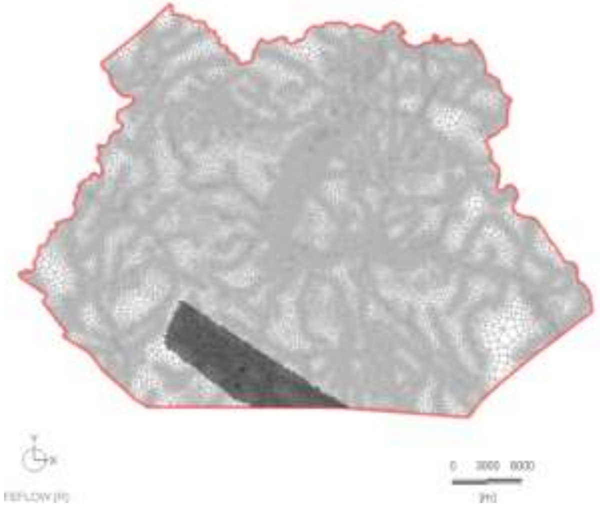




VIDEO

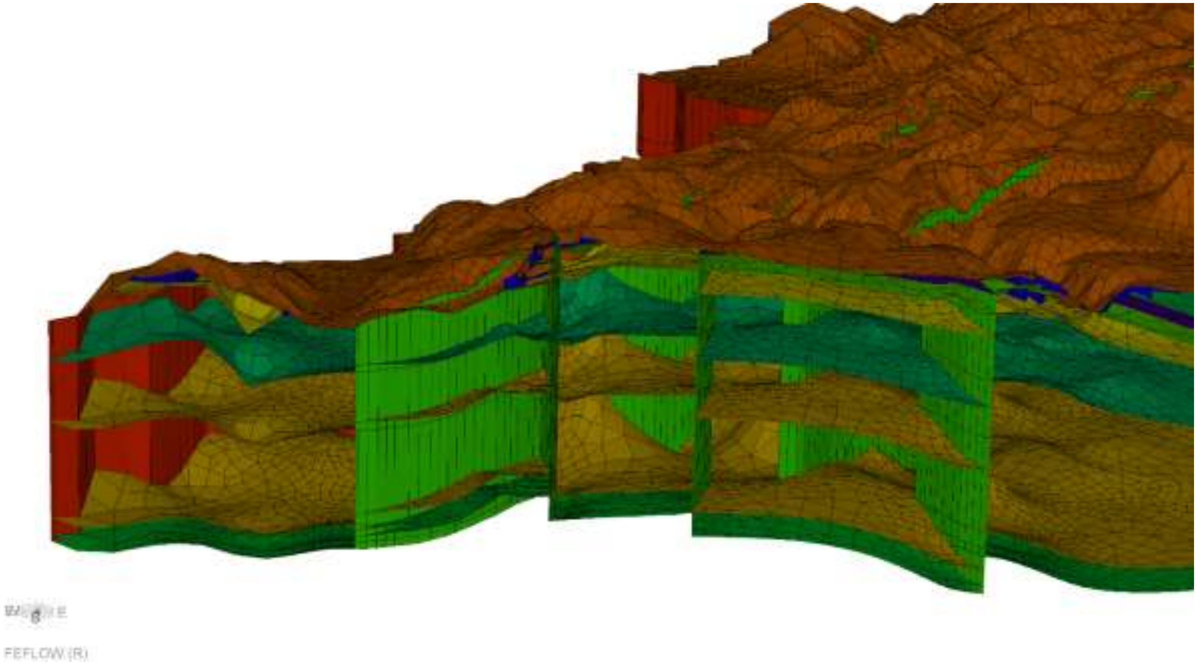
Geologic Units





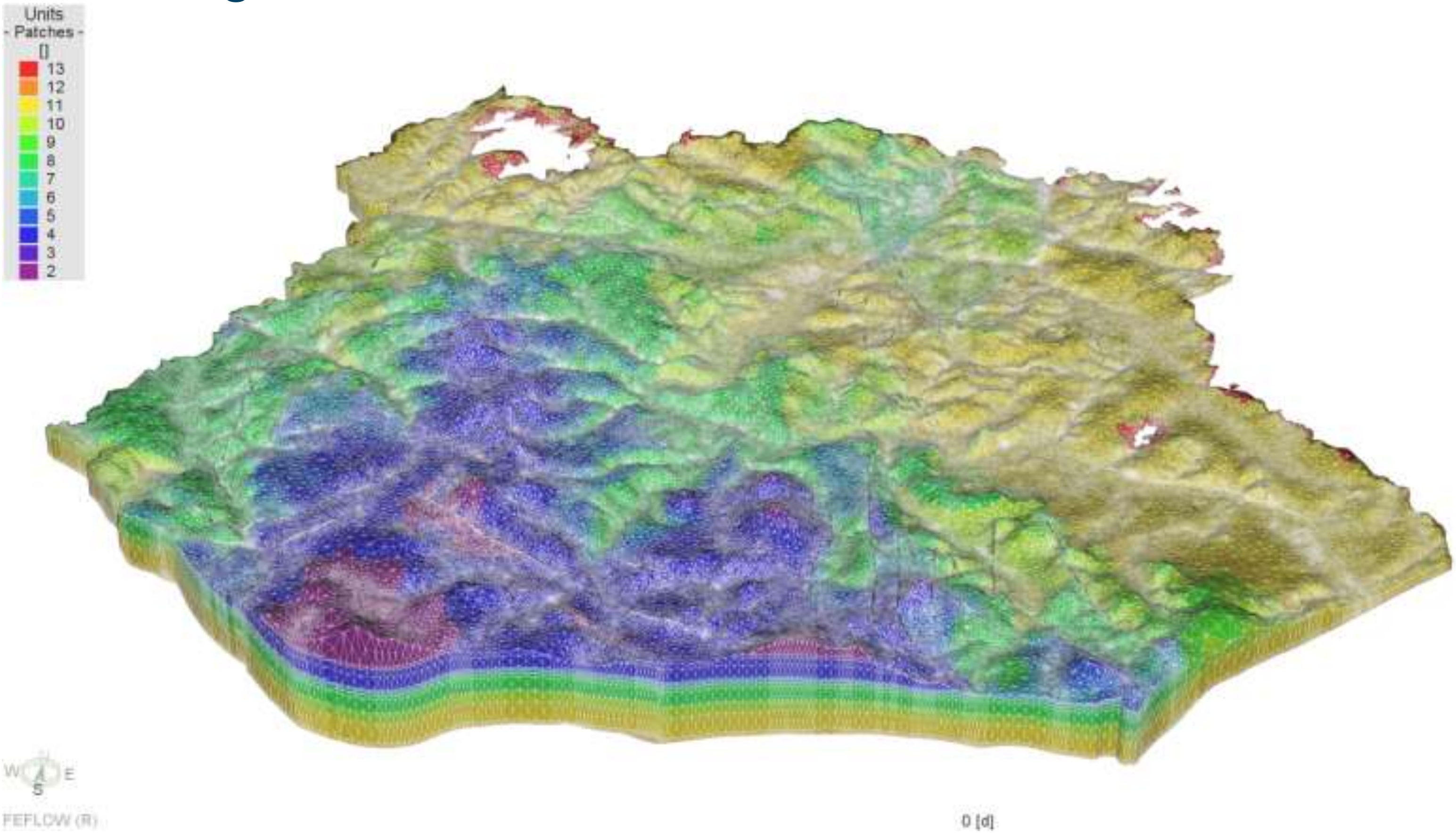
VIDEO

Face Objects

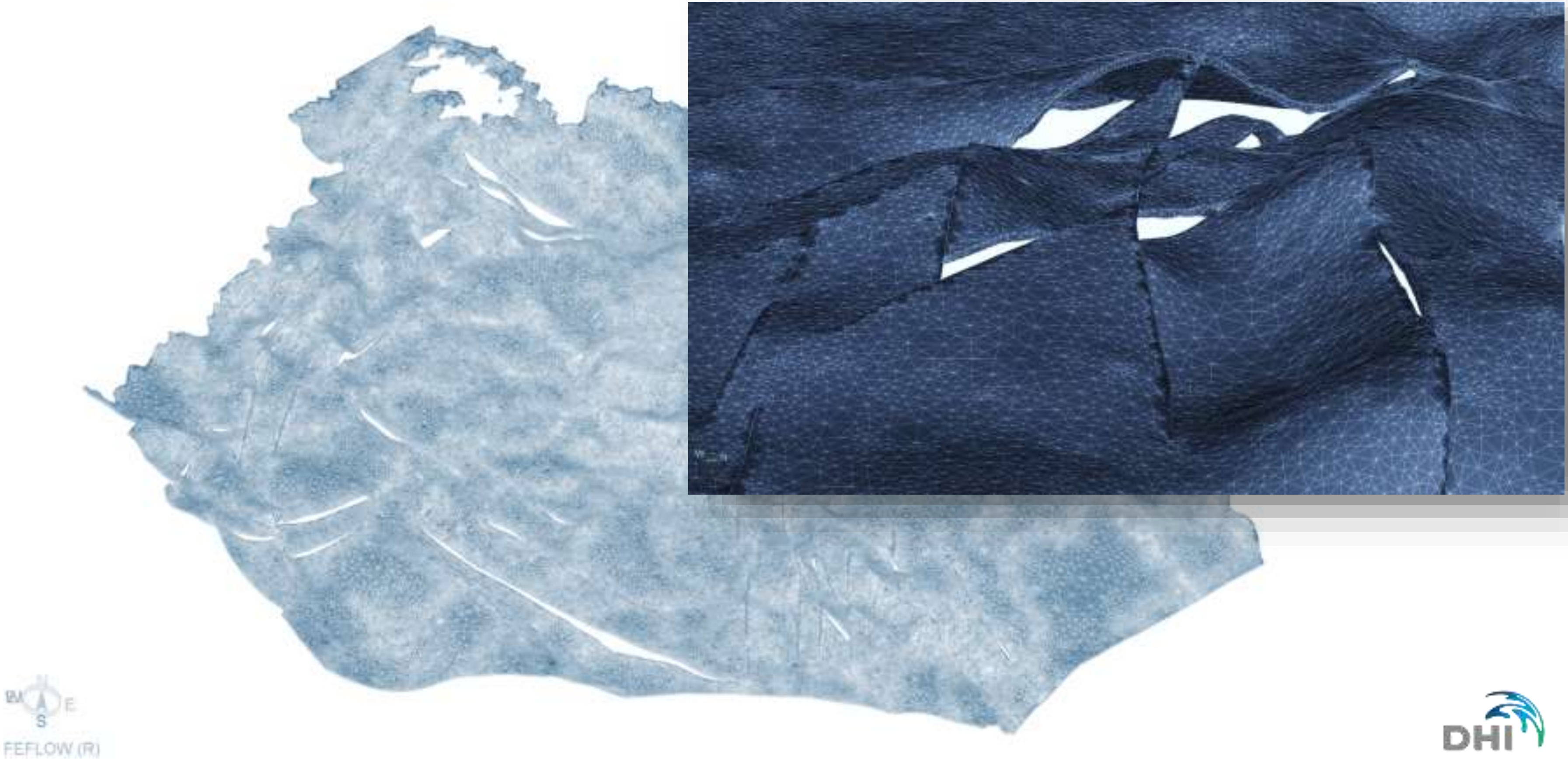


- red: Outer Border
- Light green: Faults
- blue: pinch-outs
- Other colors: geologic contacts

Resulting Mesh



Carbonate Layer at Depth



CGAL Meshing Generator

Computational Geometry Algorithms Library CGAL

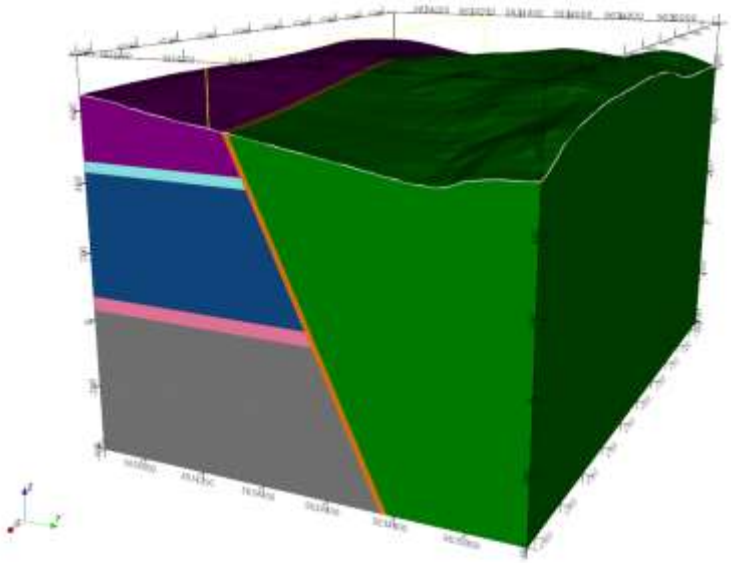
CGAL Library

- Computational Geometry Algorithms Library CGAL

- Open Source (www.cgal.org)

- Integrated in Geomodeller (Intrepid Geophysics)

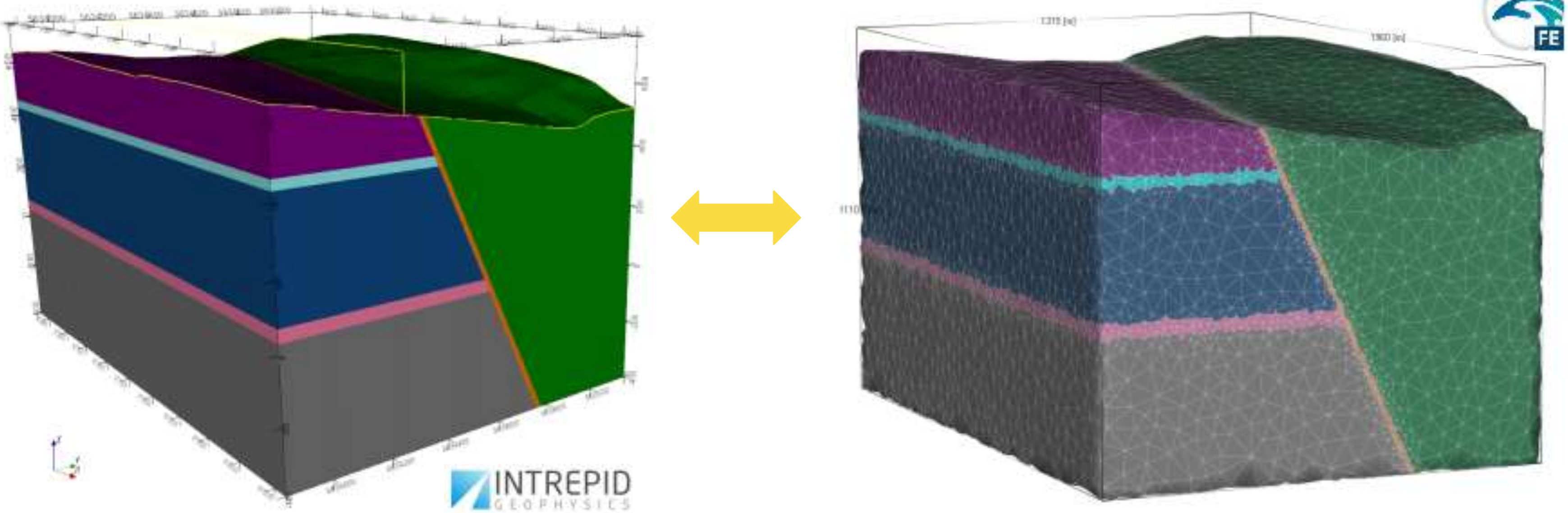
Pilot Model of Lusitian Over-Thrust



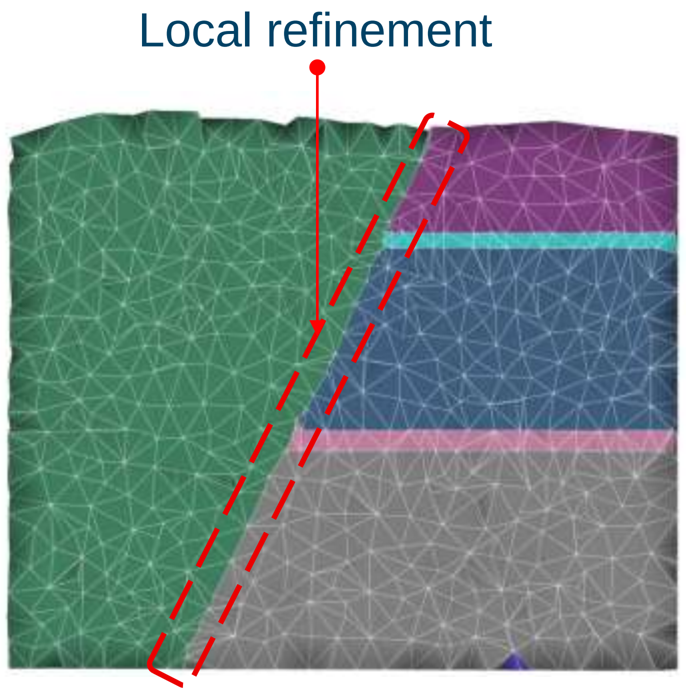
- Geological model created in 3D Geomodeller
- Incl. Major geologic units
- Incl. vertical faults and Lusatian overthrust

Unstructured mesh generated

Tetrahedron mesh created using CGAL



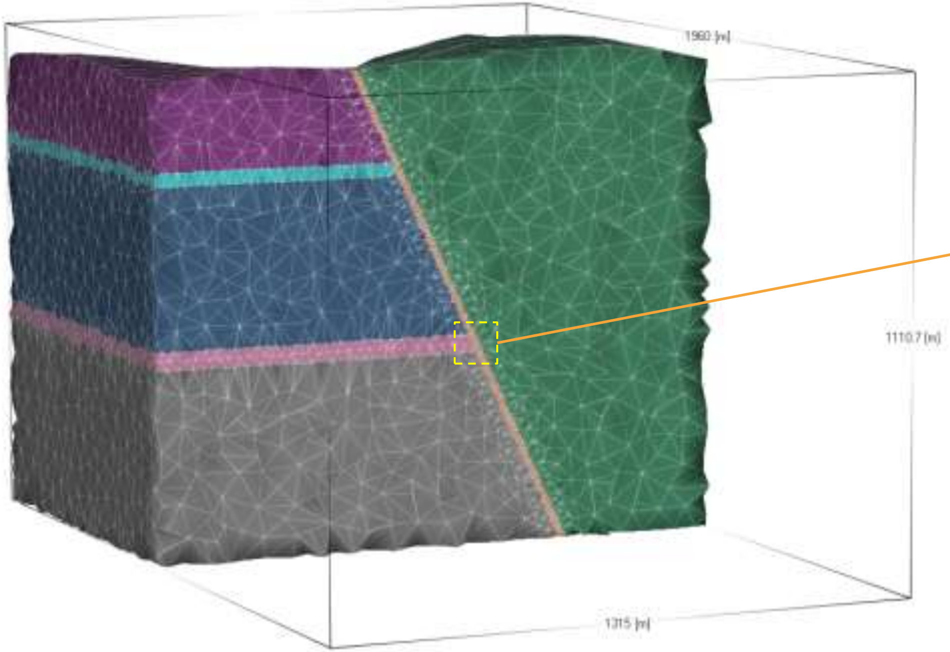
Handling of Faults

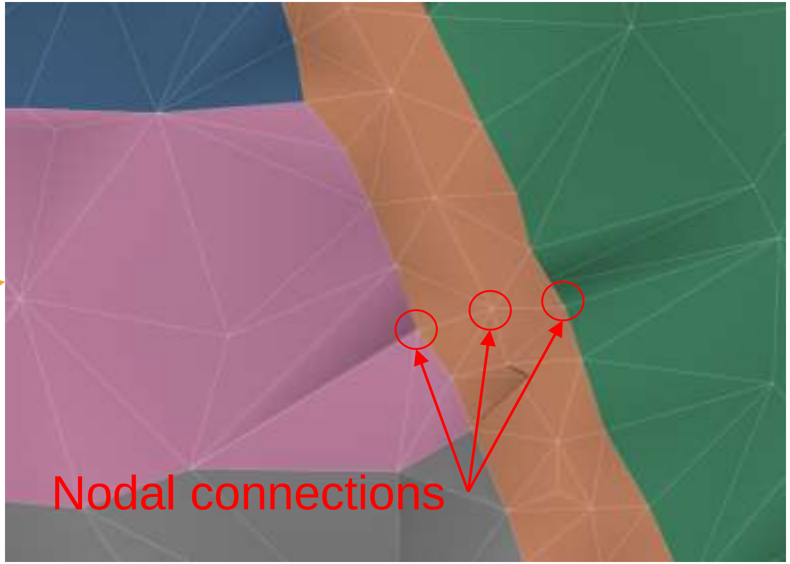


Faults require a finite thickness

- Conduit
- Barrier

Handling of Faults

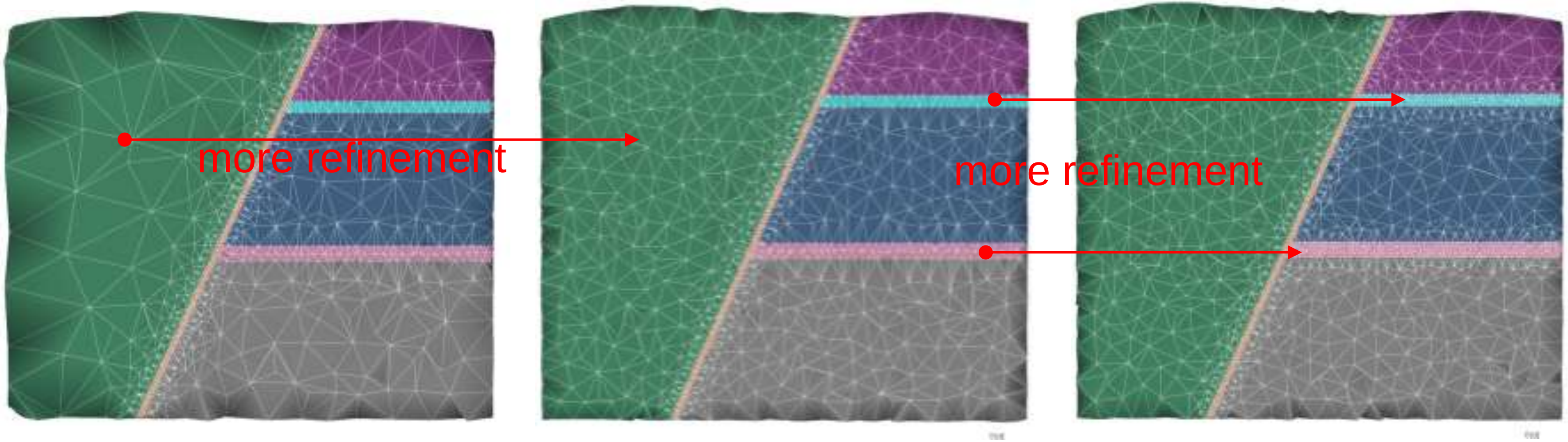




Test24.fem

Mesh Refinement

Accuracy vs. Computational Speed

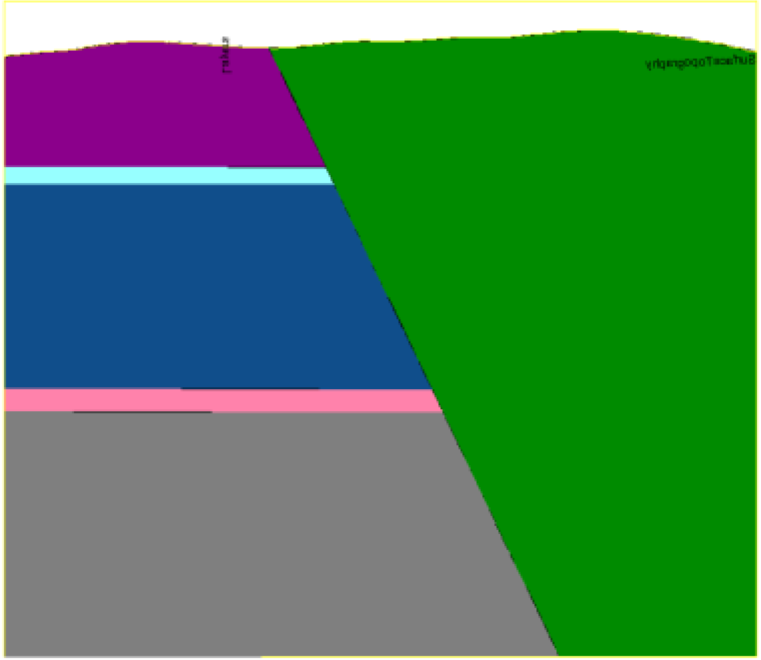


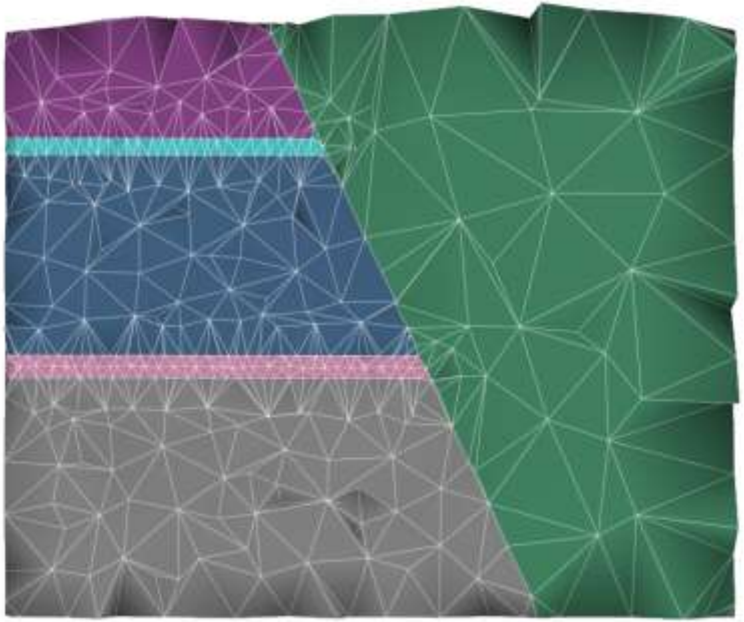
Elements: 669.910
Nodes: 114.274

Elements: 723.628
Nodes: 124.077

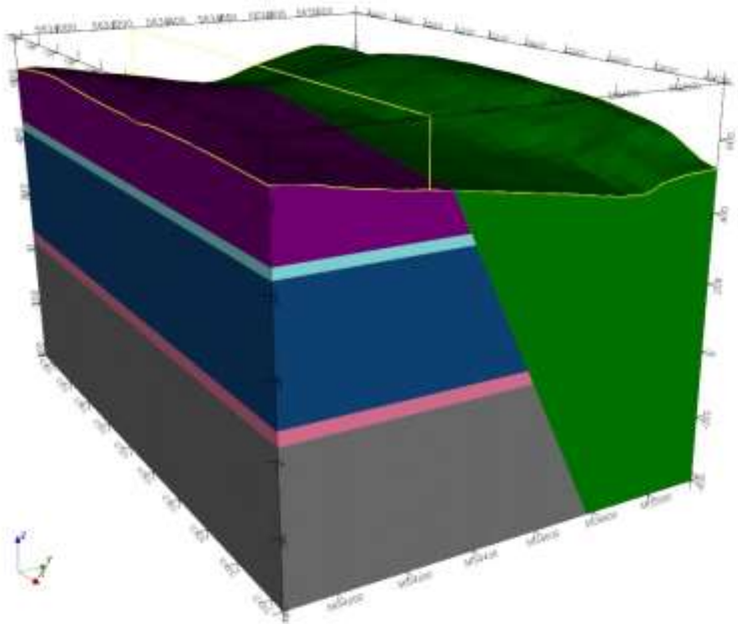
Elements: 1’201.954
Nodes: 201.930

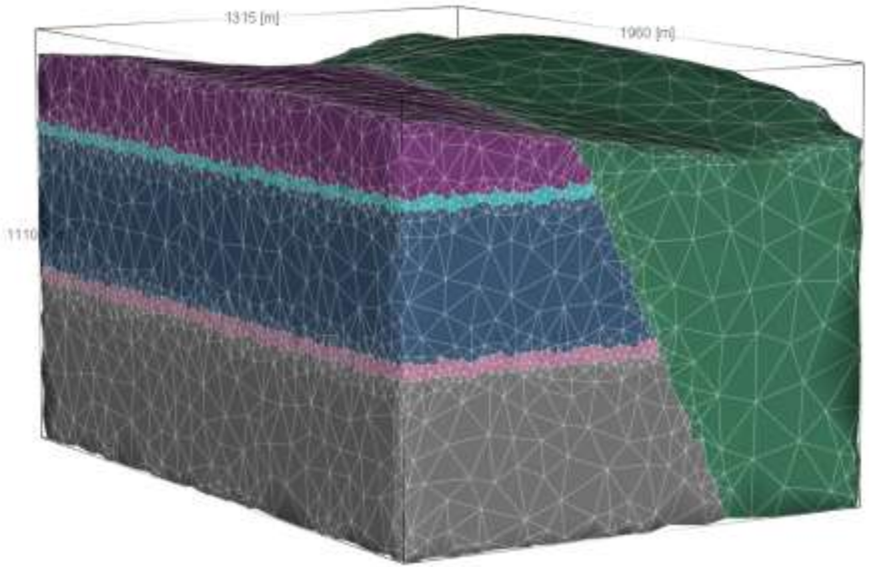
Optimum for Geometric Representation





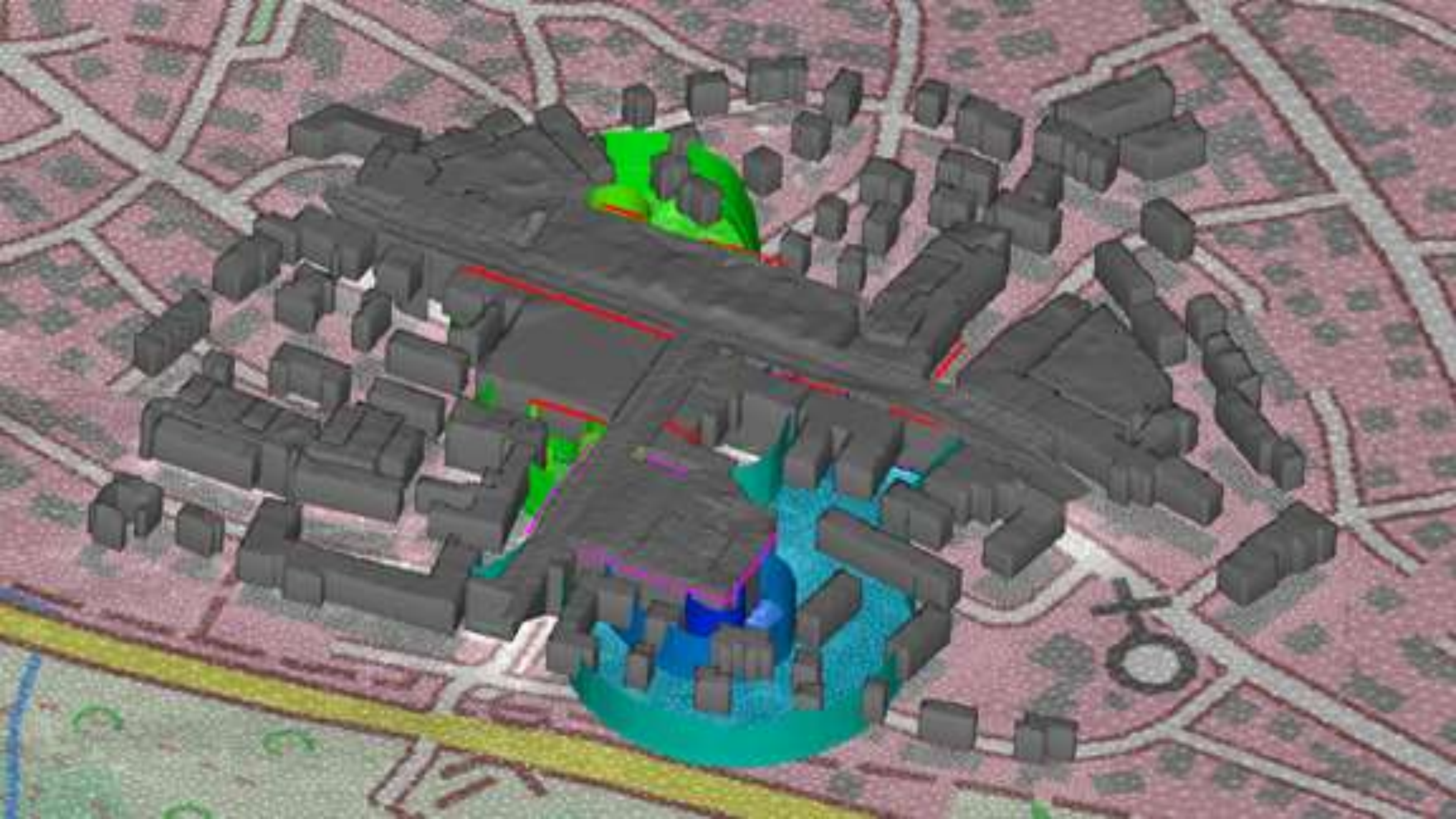
Optimum for Computation

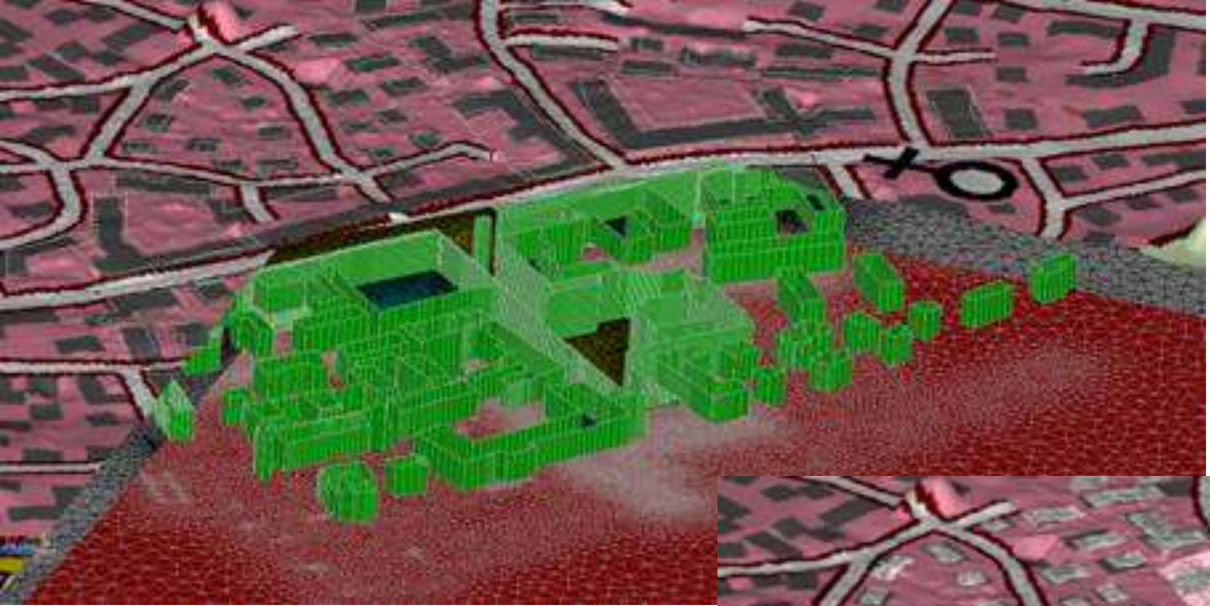


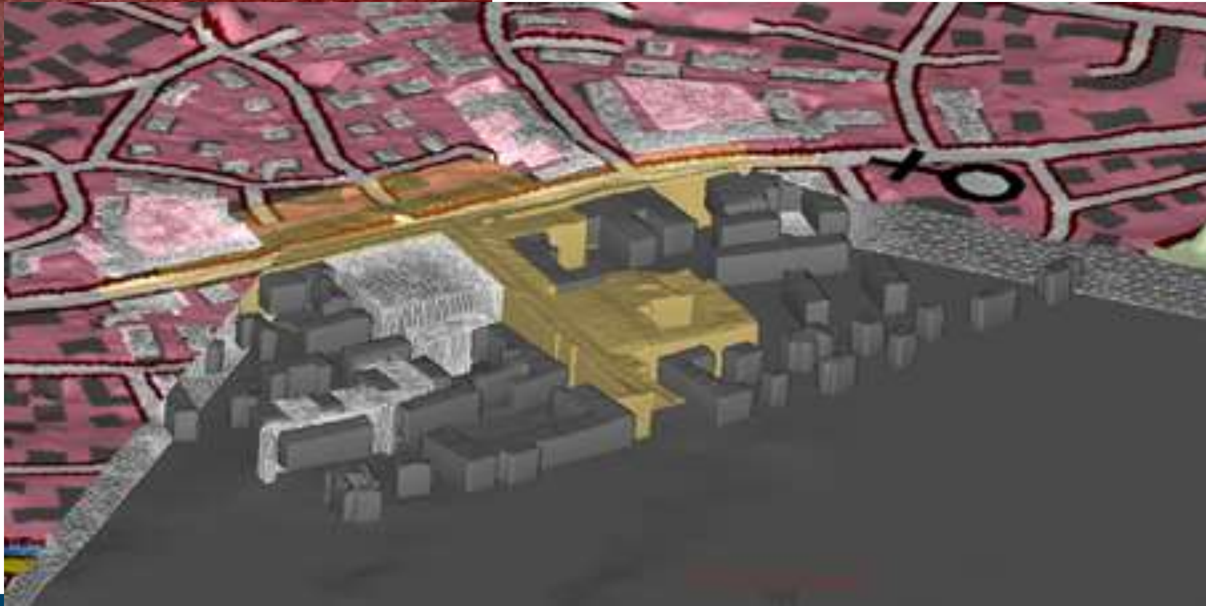


Finally: What are the Benefits?

Flexibility







Thank you!

are@dhigroup.com

About DHI

DHI are the first people you should call when you have a tough challenge to solve in a water environment.

In the world of water, our knowledge is second-to-none, and we strive to make it globally accessible to clients and partners.

So whether you need to save water, share it fairly, improve its quality, quantify its impact or manage its flow, we can help. Our knowledge, combined with our team's expertise and the power of our technology, hold the key to unlocking the right solution.