

Symposium in Honor of Anthony Ingraffea: "Computer Simulation and Physical Testing of Complex Fracturing Processes"

**Non-manifold Geometric Modeling as a Framework
for Computational Mechanics Simulations**

Luiz Fernando Martha, PhD 1989

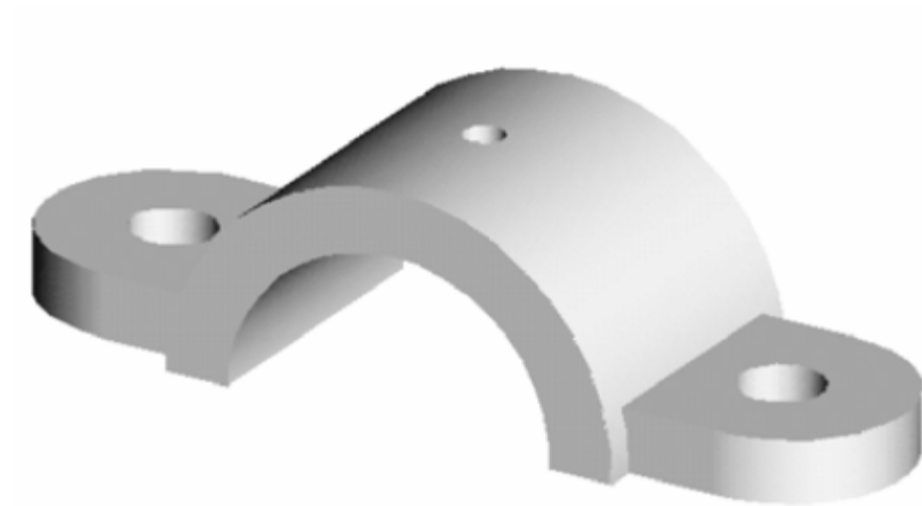
Ithaca, NY
September 27, 2014

Outline

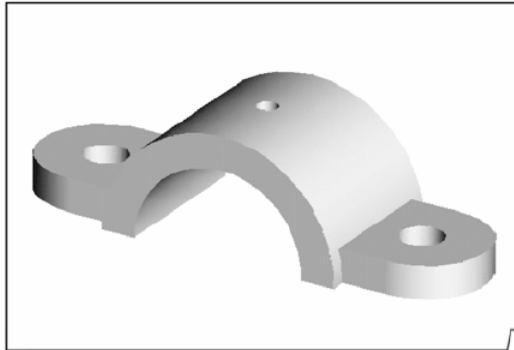
- Solid Modeling
- Modeling in Engineering
- Geometric Modeling
- Applications
- Educational Software for Engineering

Solid Modeling

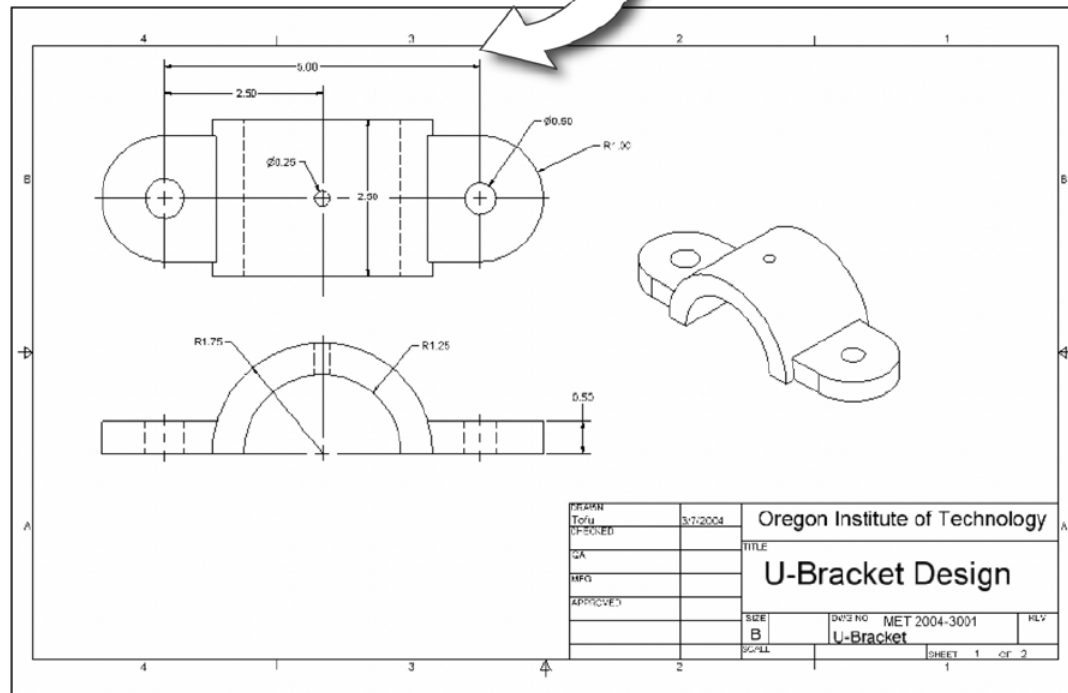
Solid Modeling



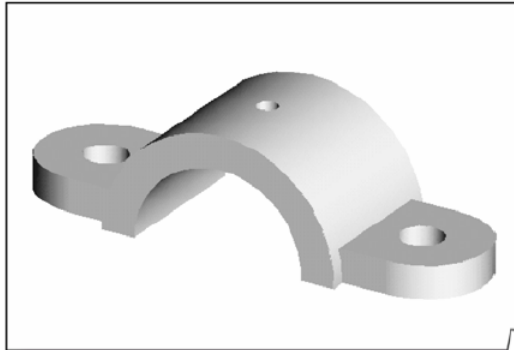
Solid Modeling



The 2D drawings are generated from the 3D model.

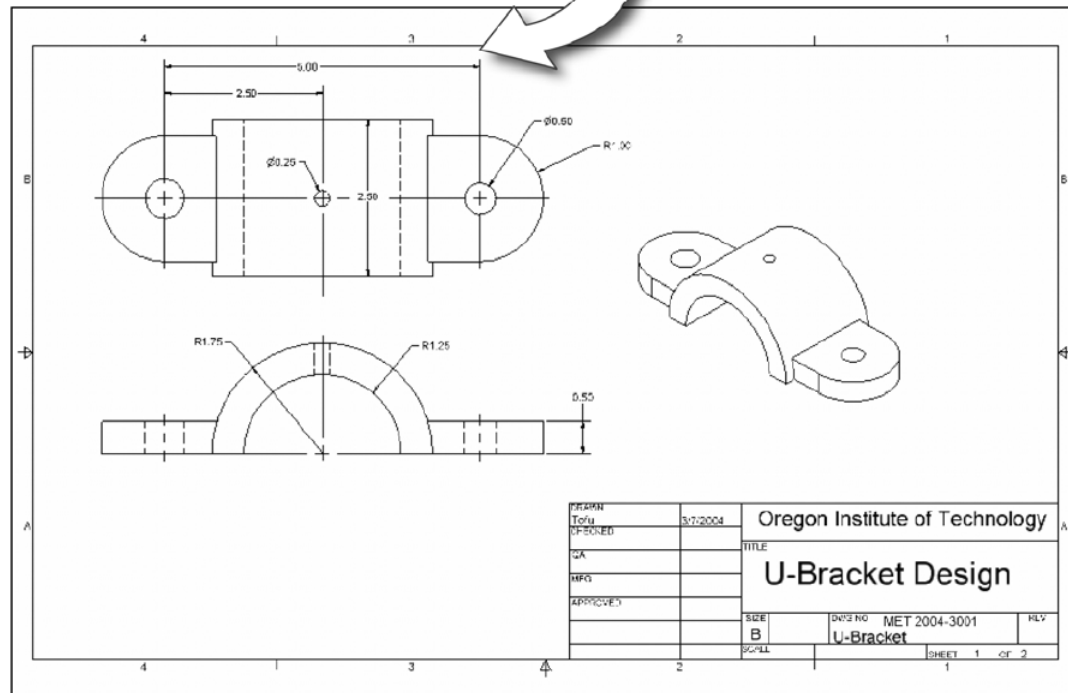


Solid Modeling



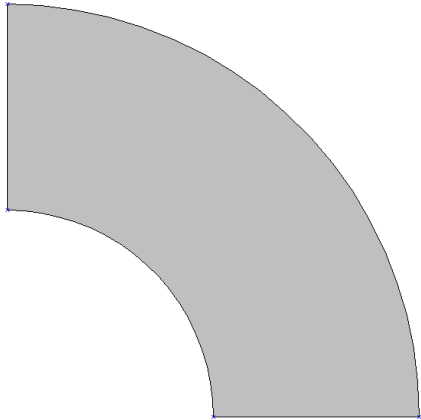
The 2D drawings are generated from the 3D model.

Modifications are automatically updated.

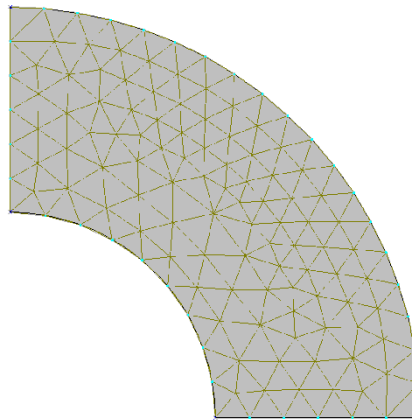


Modeling in Engineering

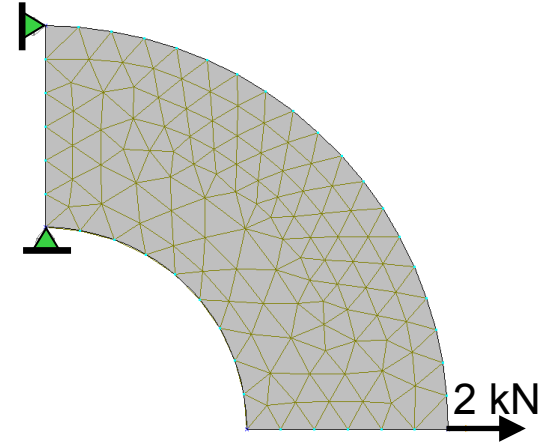
Traditional FE Simulation Process



1. Build geometric model



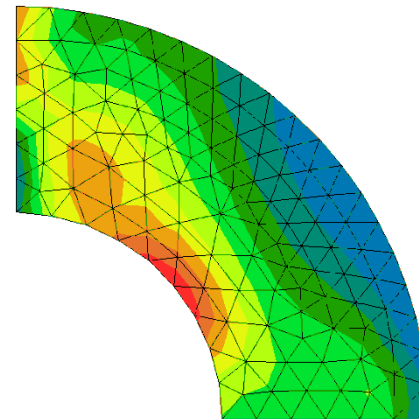
2. Mesh



3. Apply boundary conditions

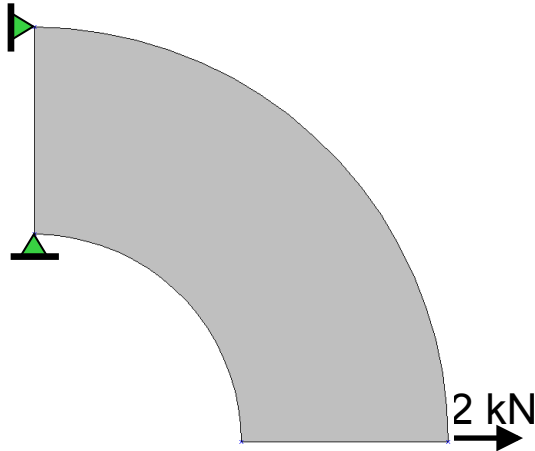


4. Computational analysis

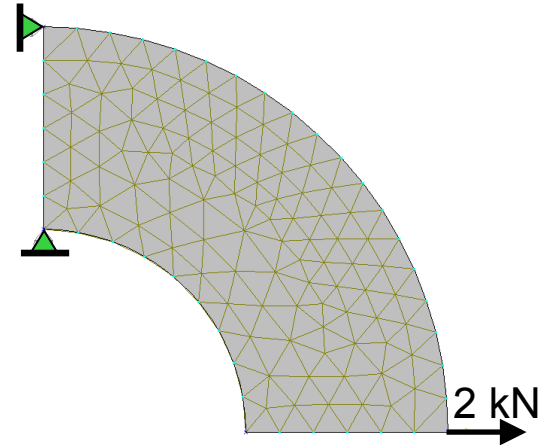


5. Result visualization

Geometry-based Simulation Process



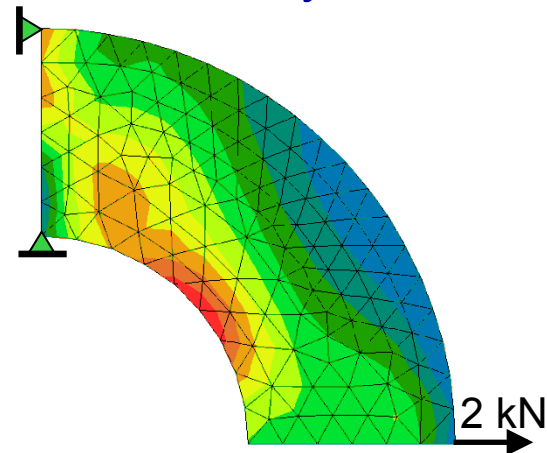
1. Geometric modeling, apply attributes and boundary conditions



2. FE mesh generation, apply boundary conditions



3. Computational analysis



4. Result visualization

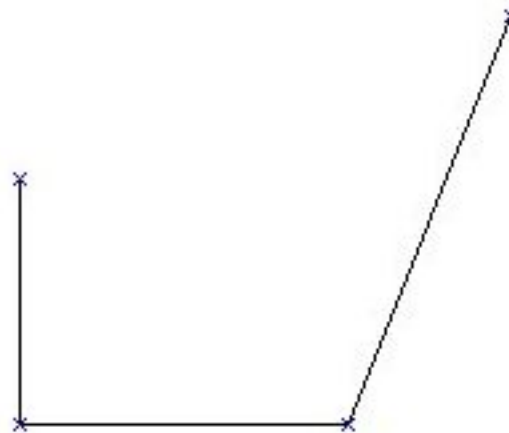
Construction of a Simple FE Model



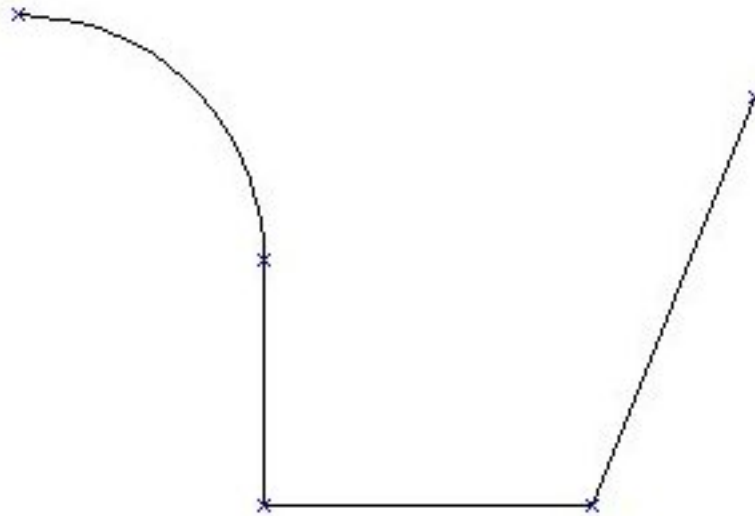
Construction of a Simple FE Model



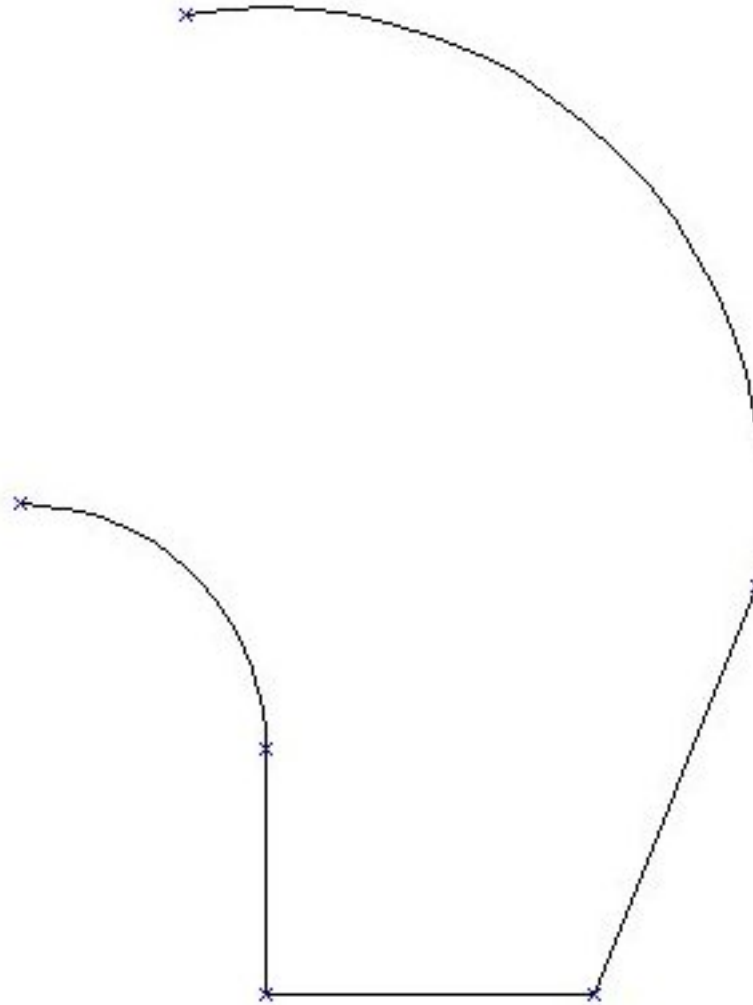
Construction of a Simple FE Model



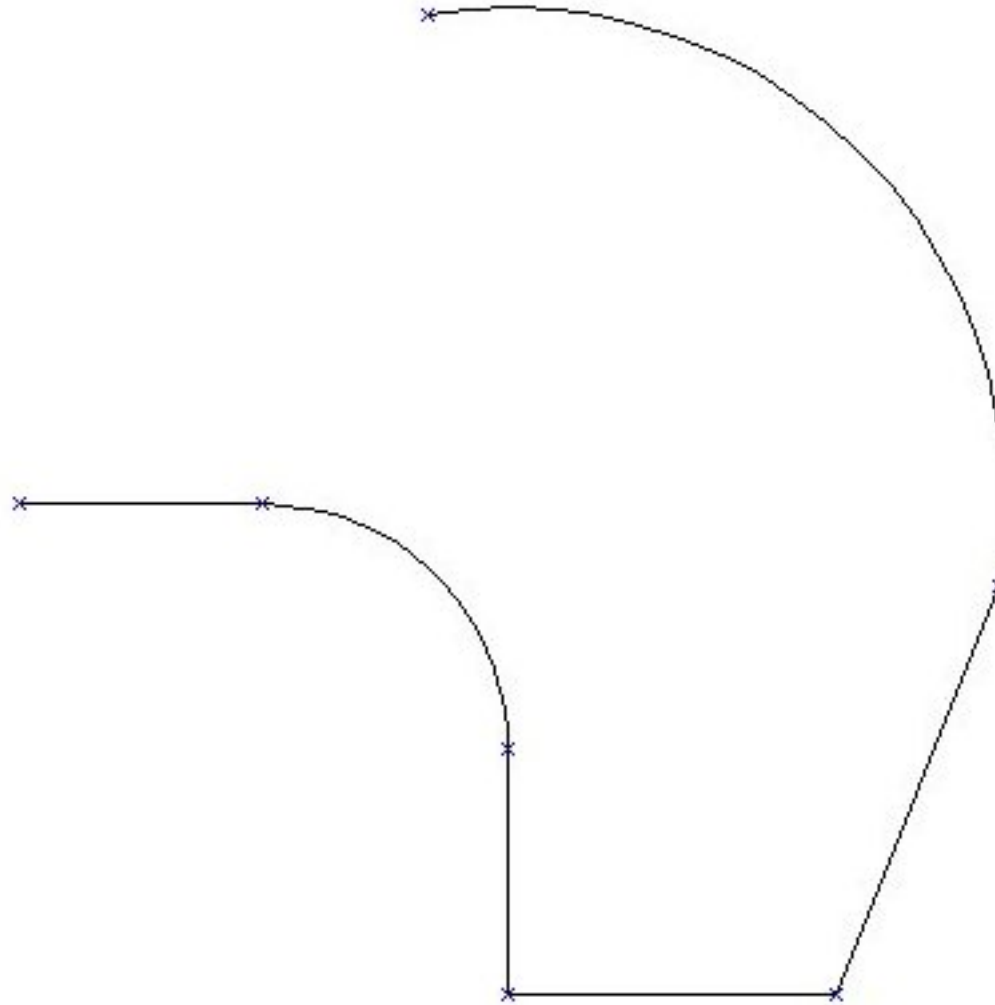
Construction of a Simple FE Model



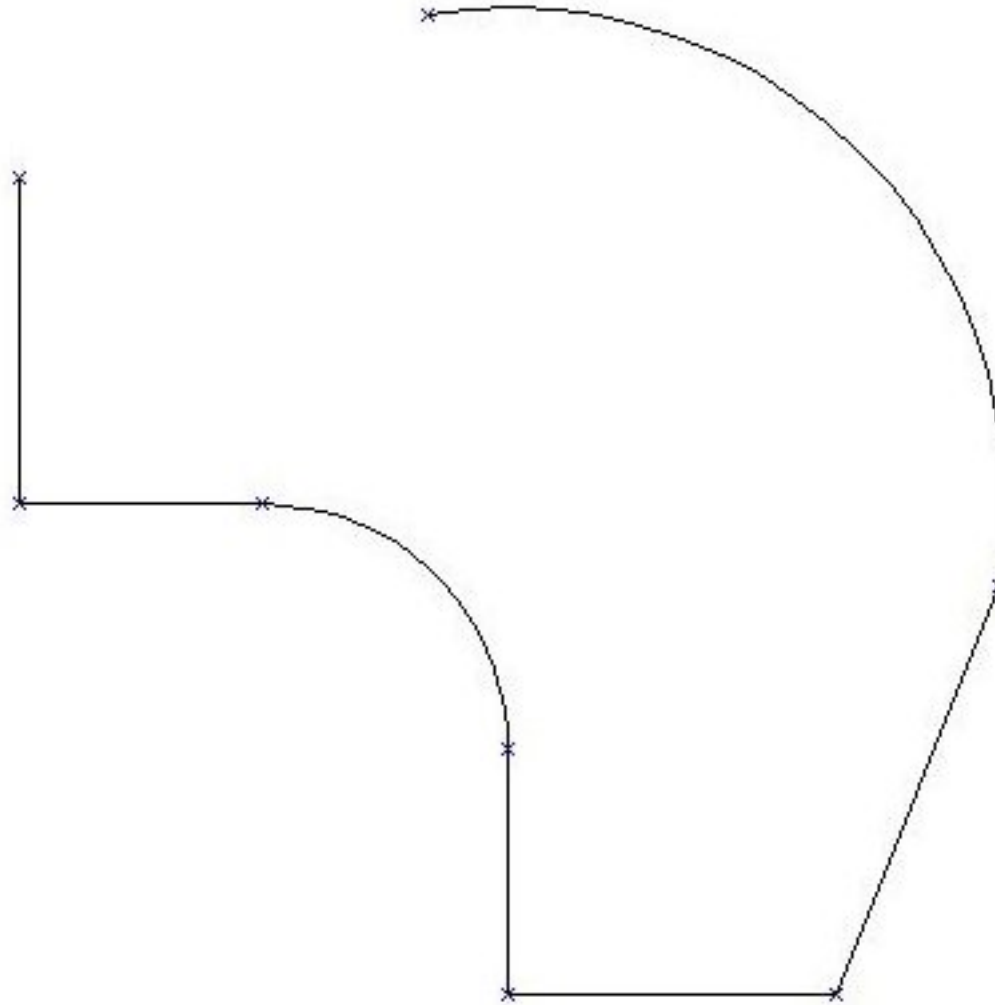
Construction of a Simple FE Model



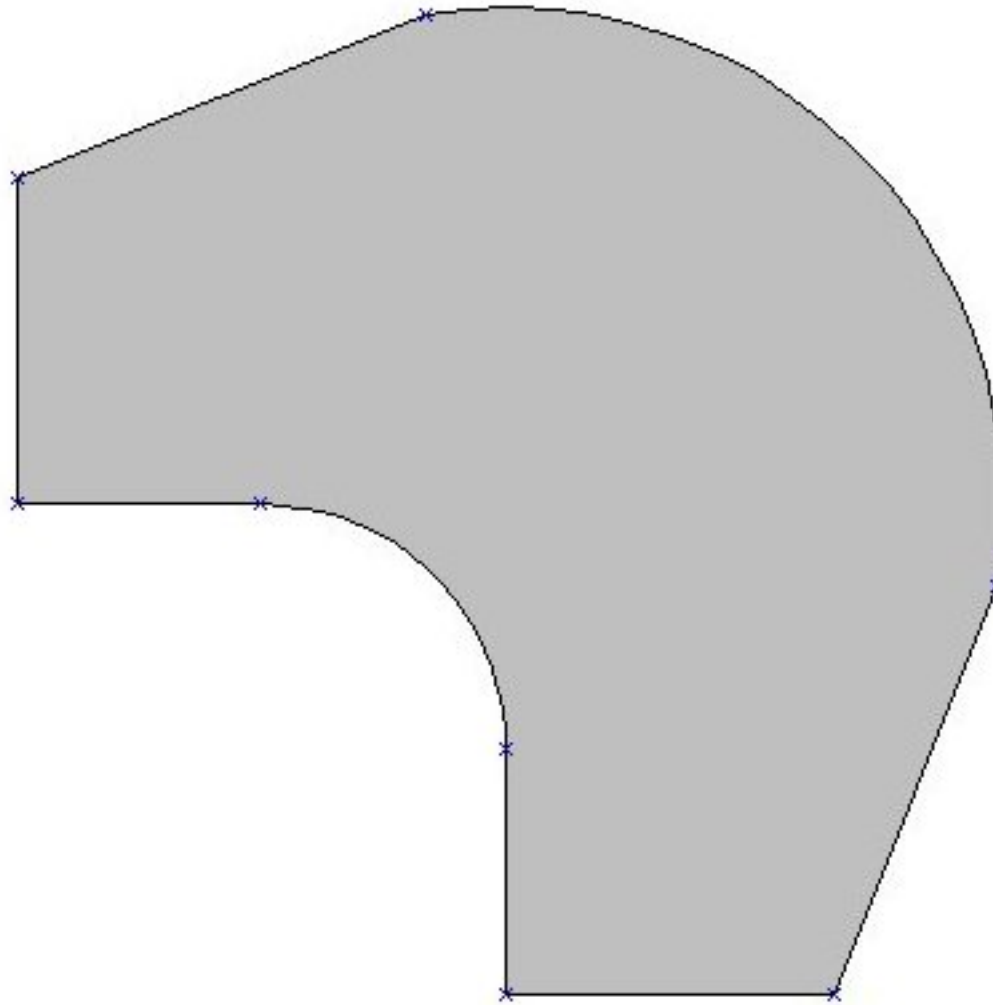
Construction of a Simple FE Model



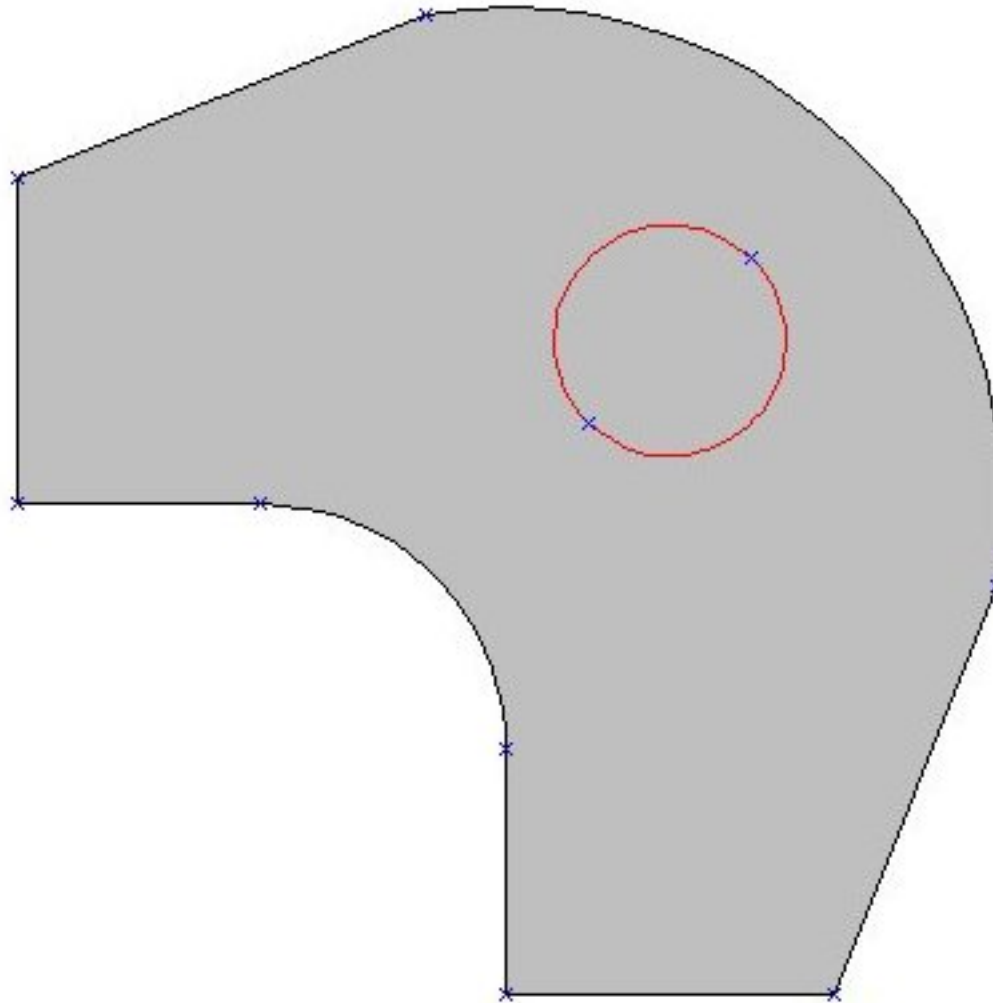
Construction of a Simple FE Model



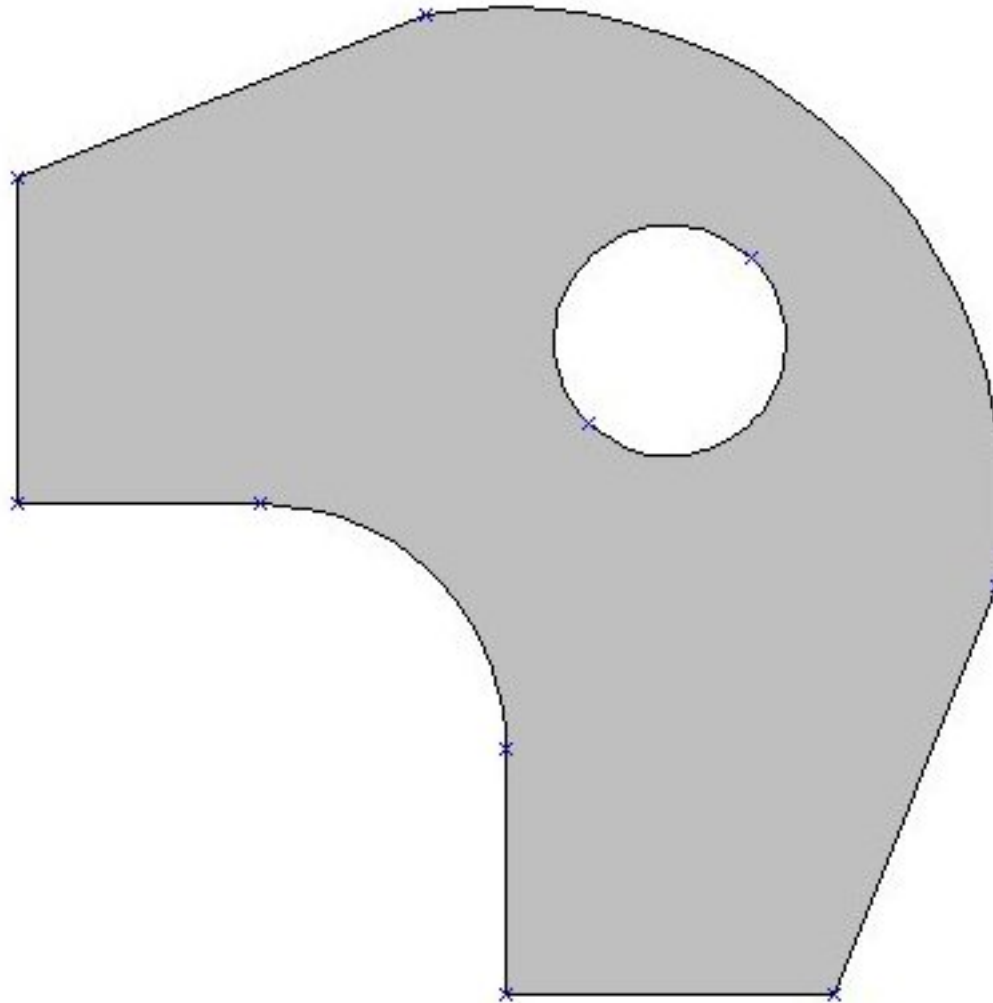
Automatic region recognition



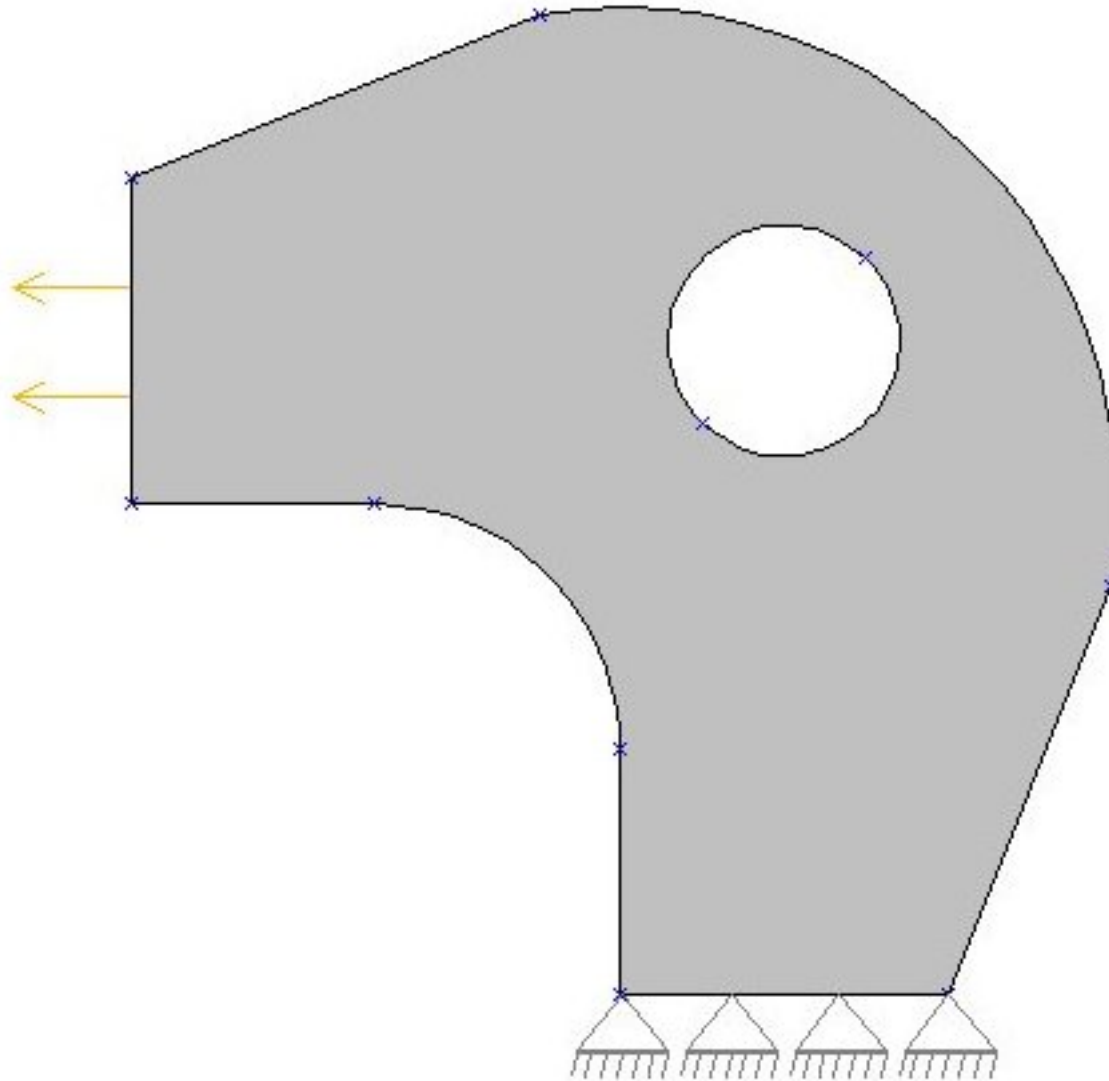
Creating a hole



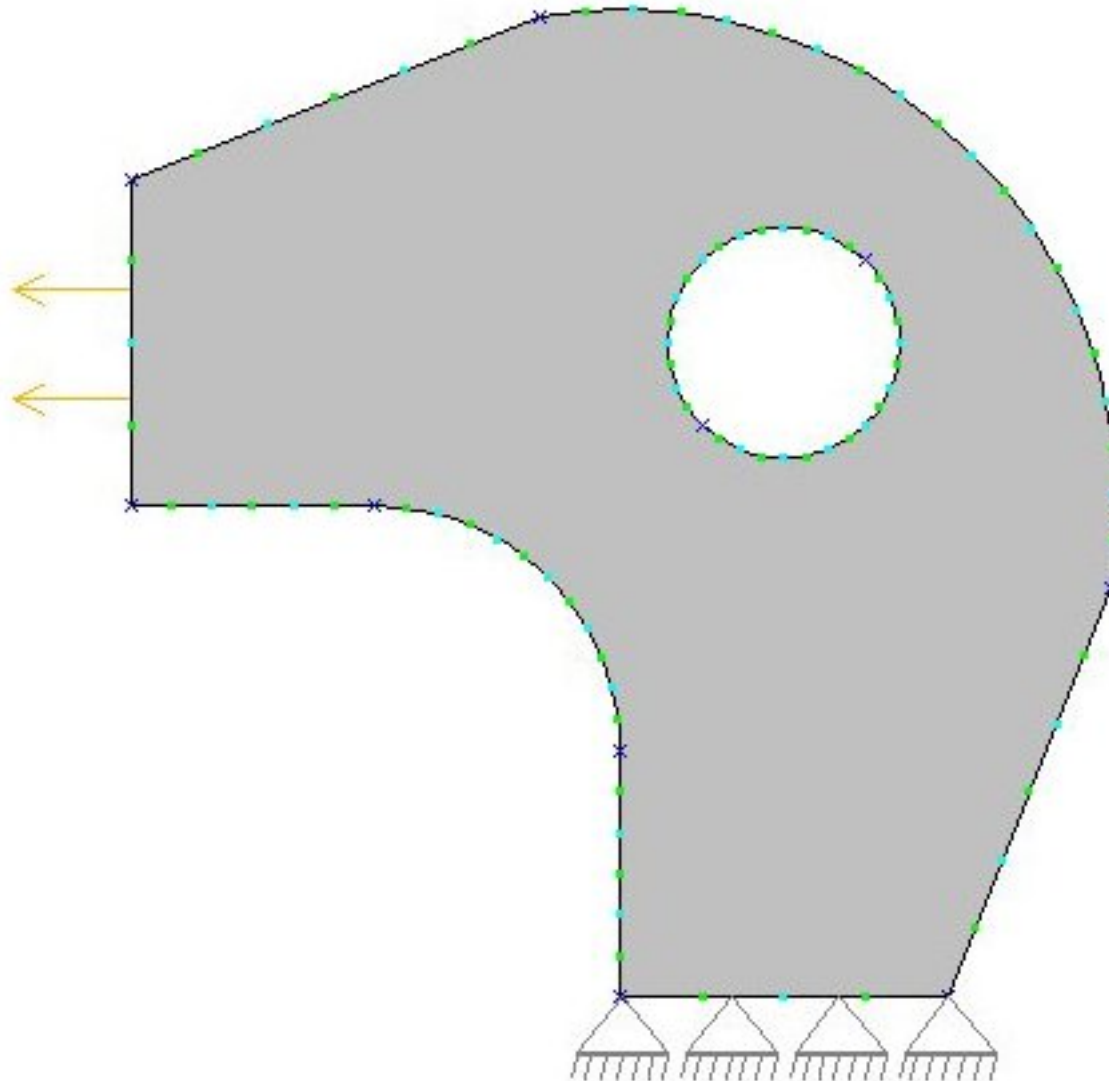
Assigning hole attribute



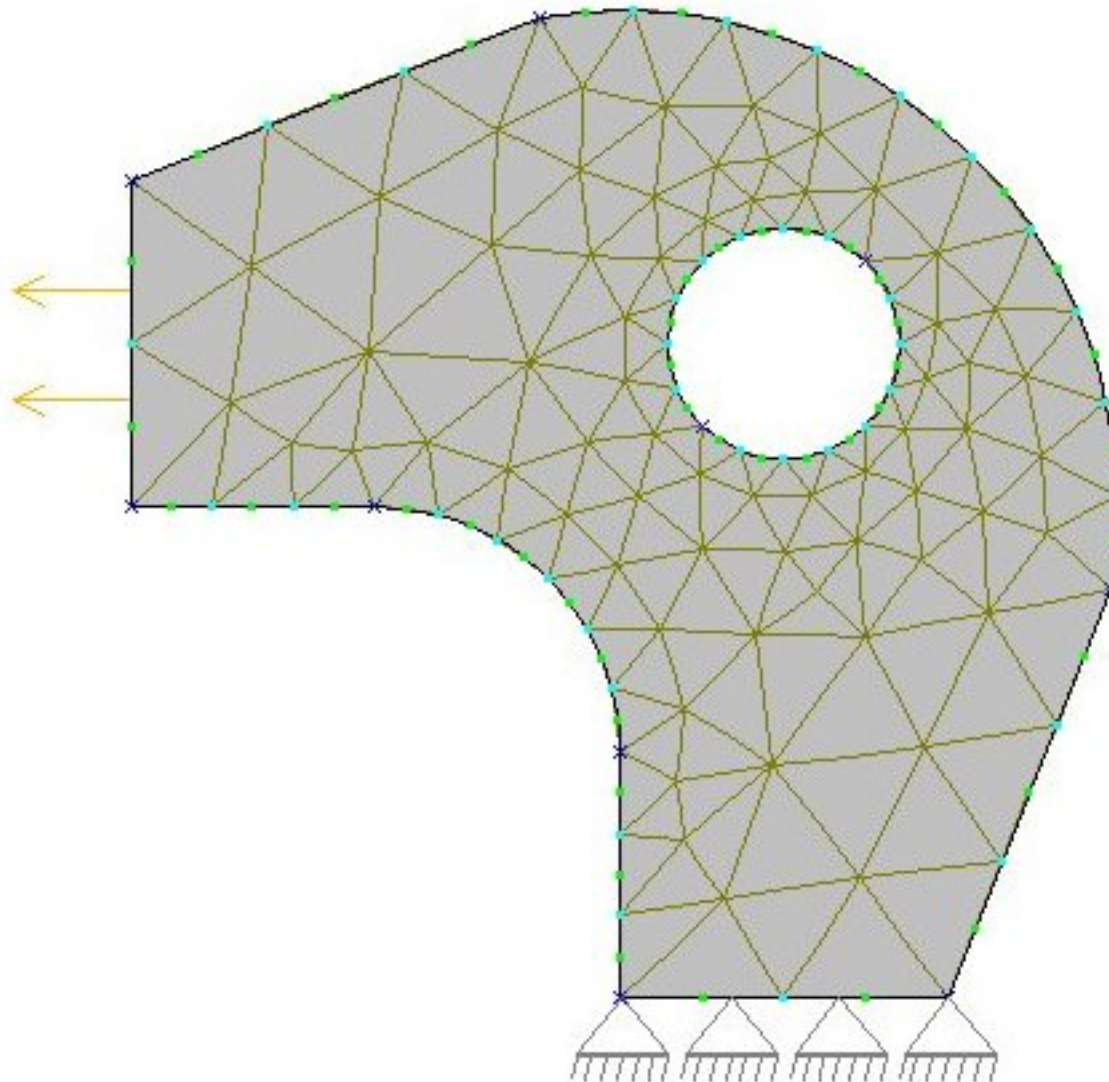
Applying attributes to geometry



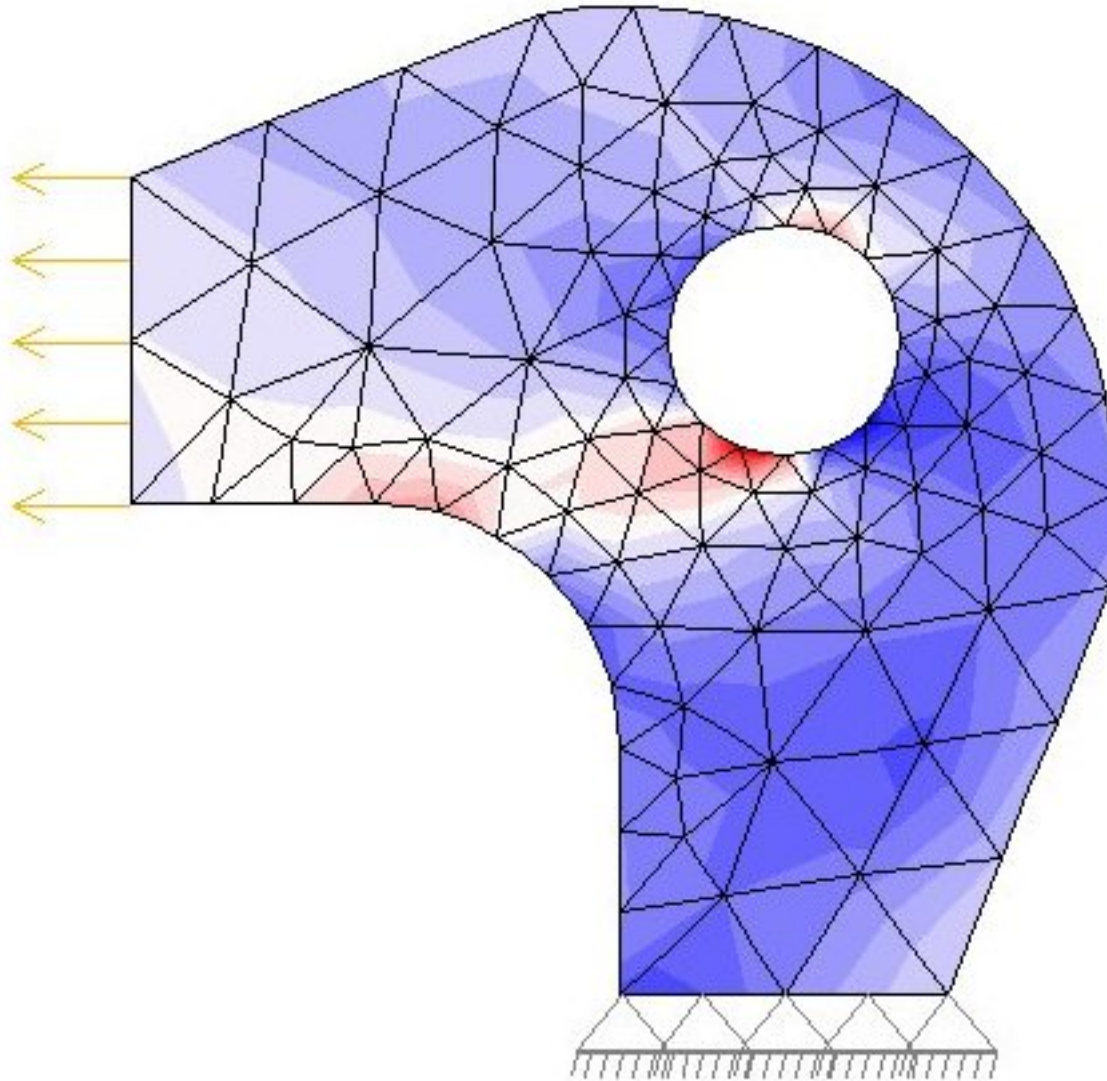
*Defining meshing refinement parameters:
boundary subdivision*



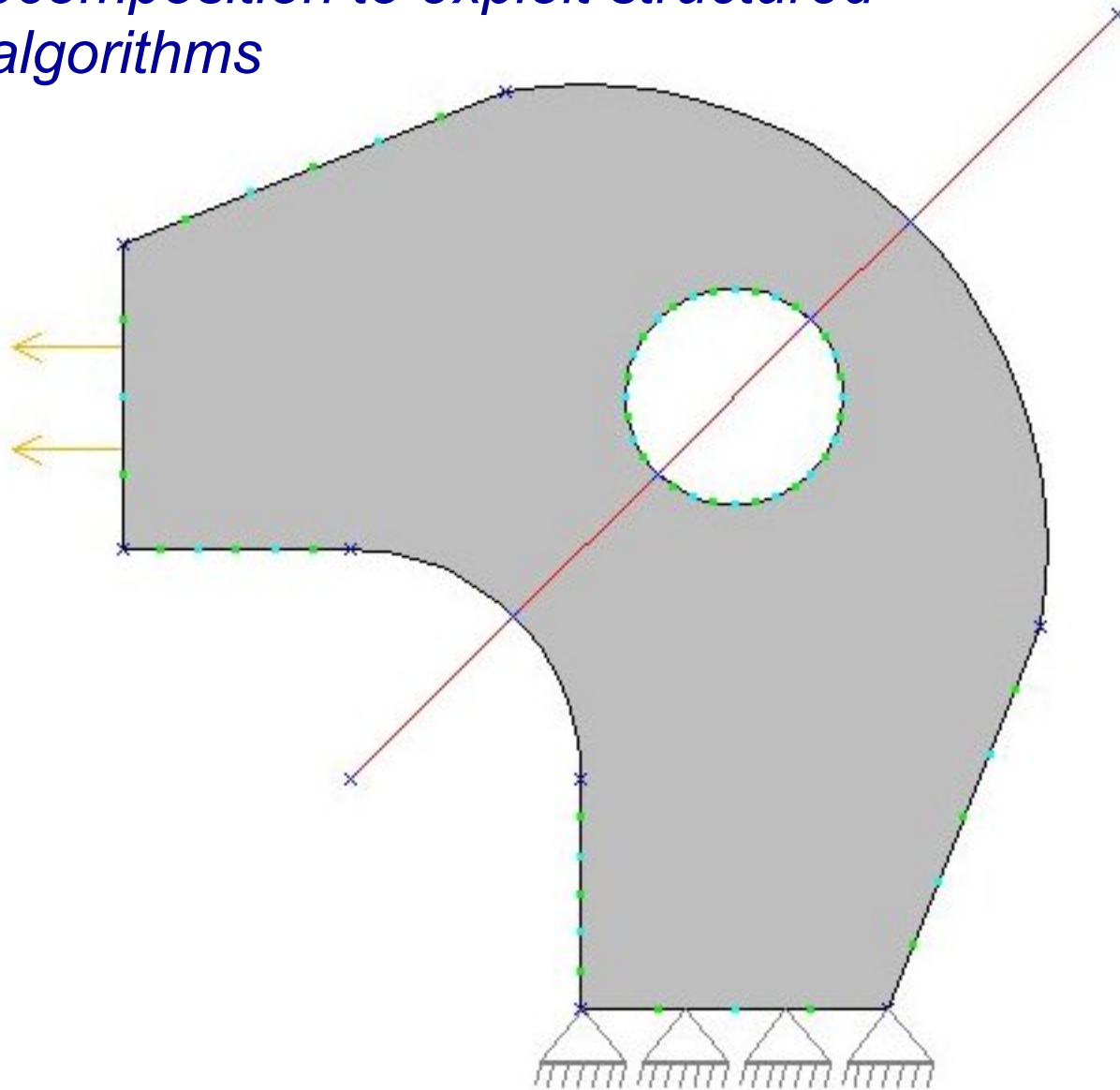
Automatic unstructured mesh generation



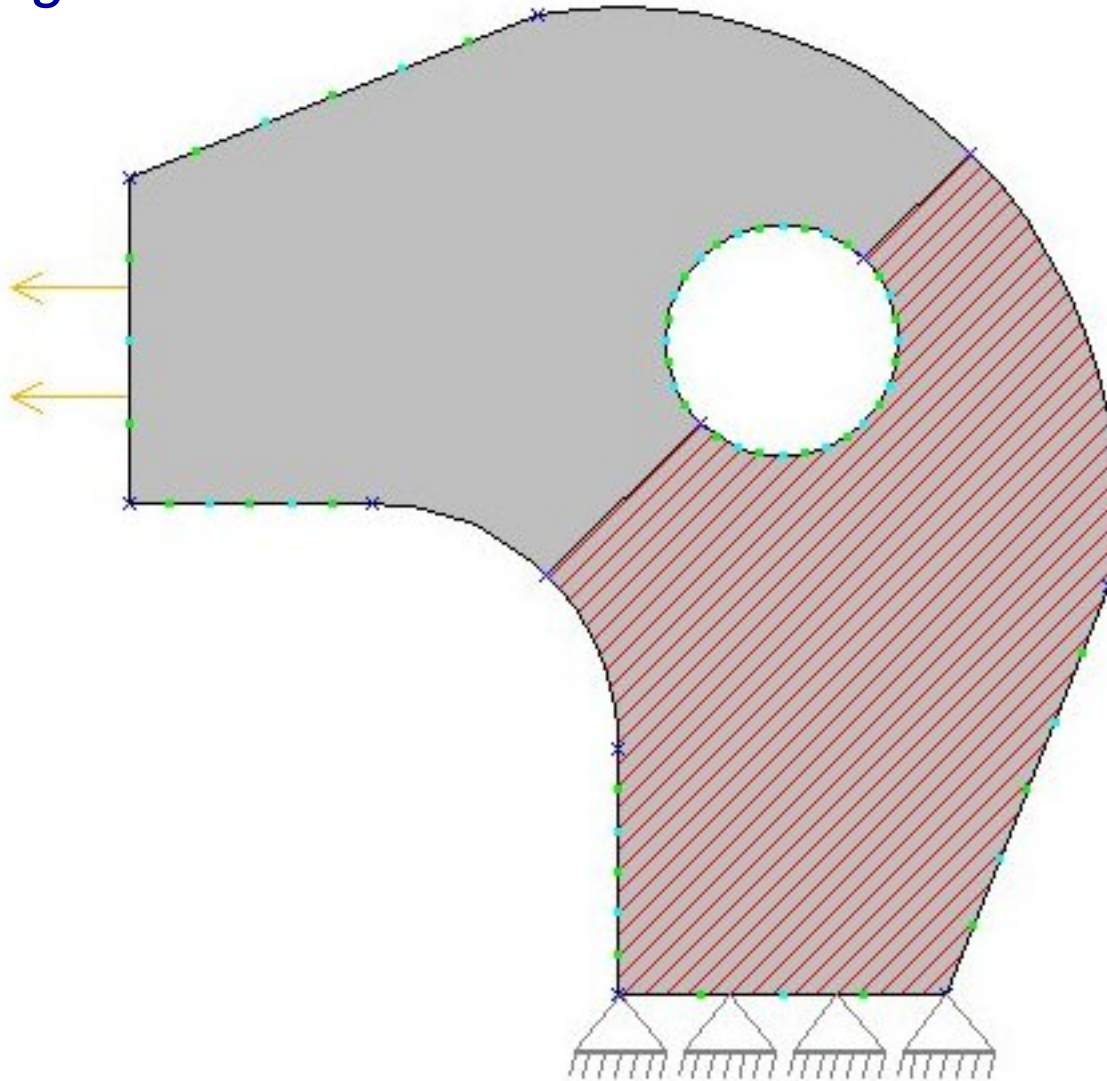
Attributes automatically assigned to mesh entities



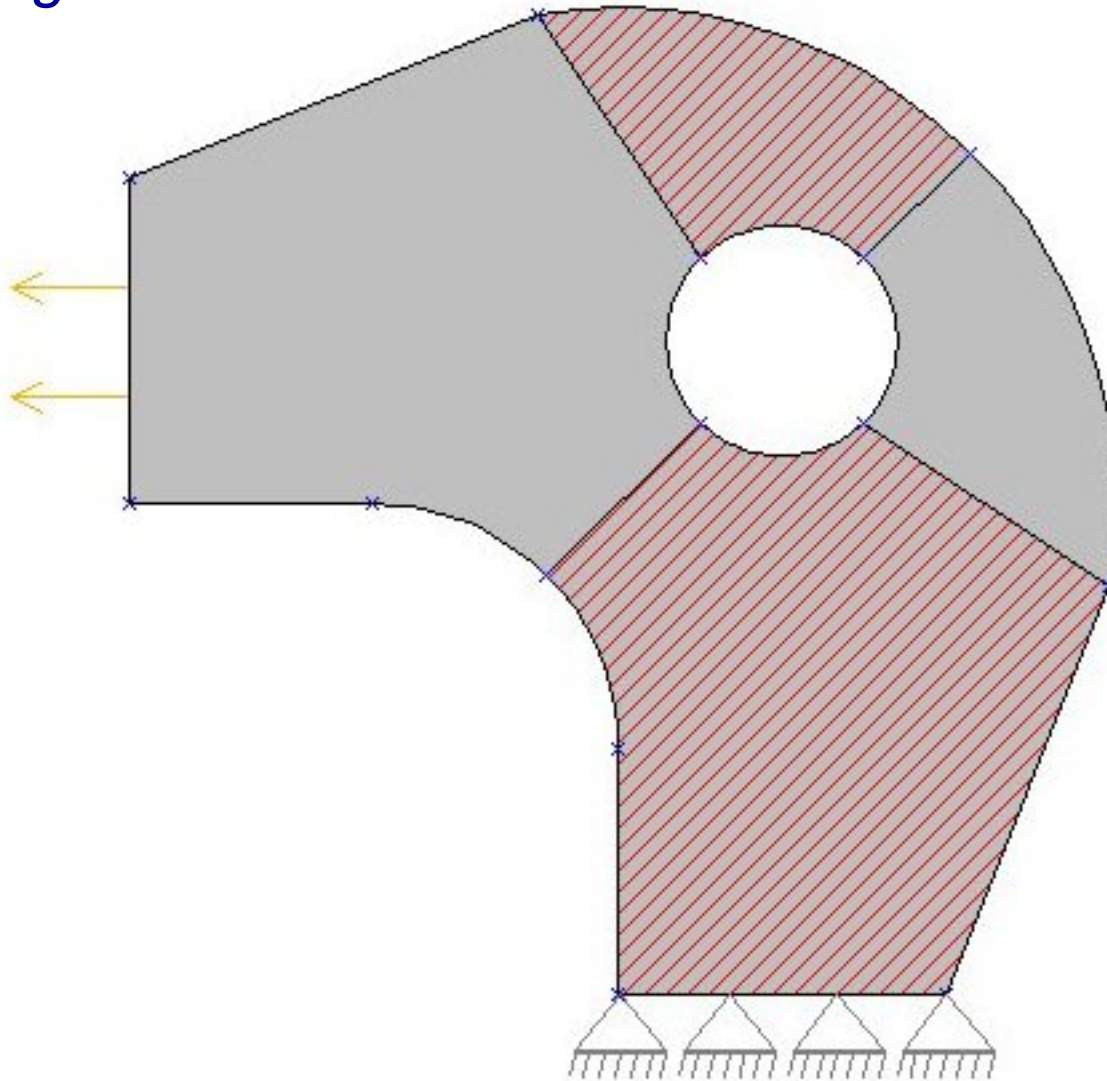
*Region decomposition to exploit structured
meshing algorithms*



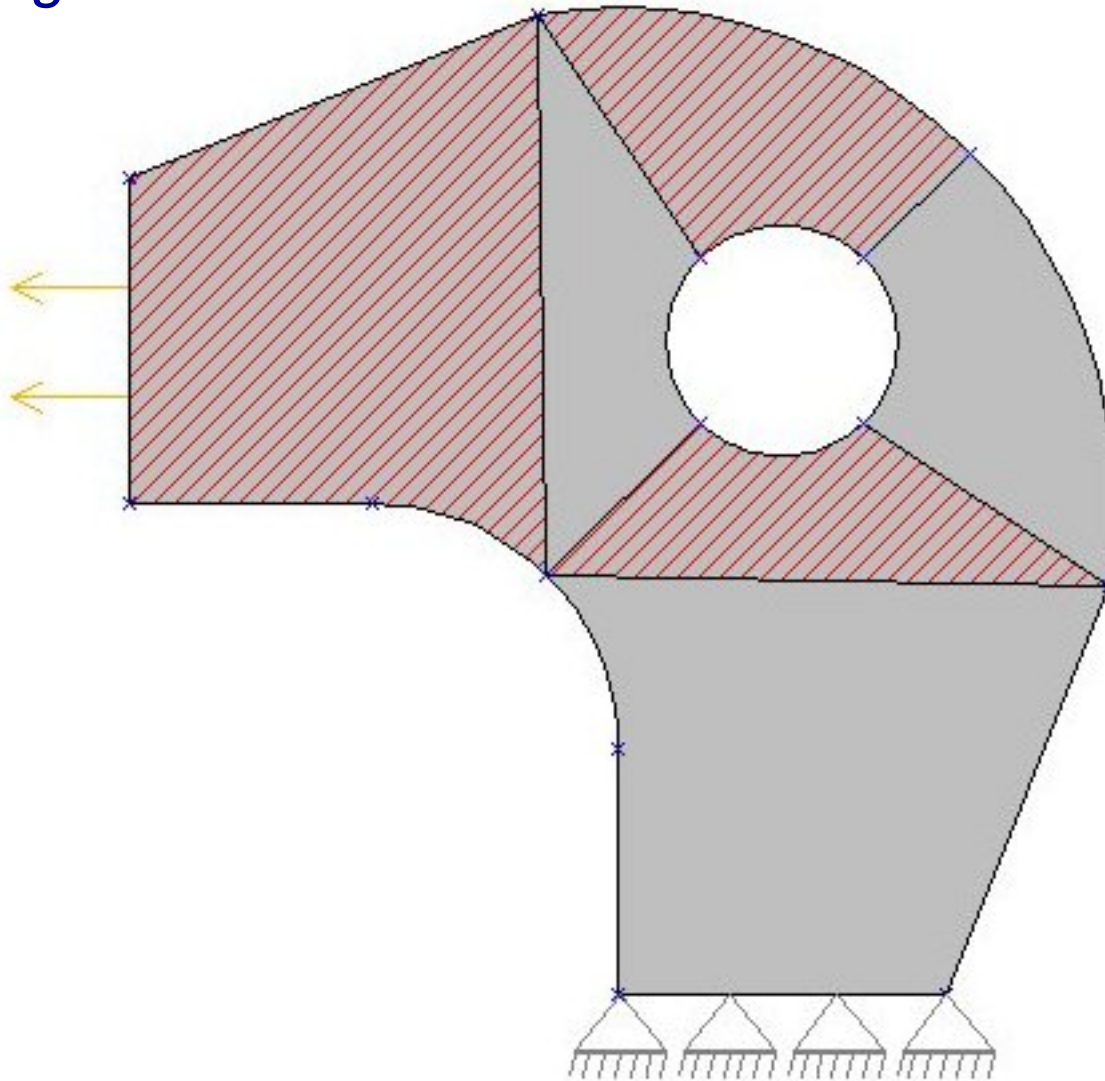
*Region decomposition to exploit structured
meshing algorithms*



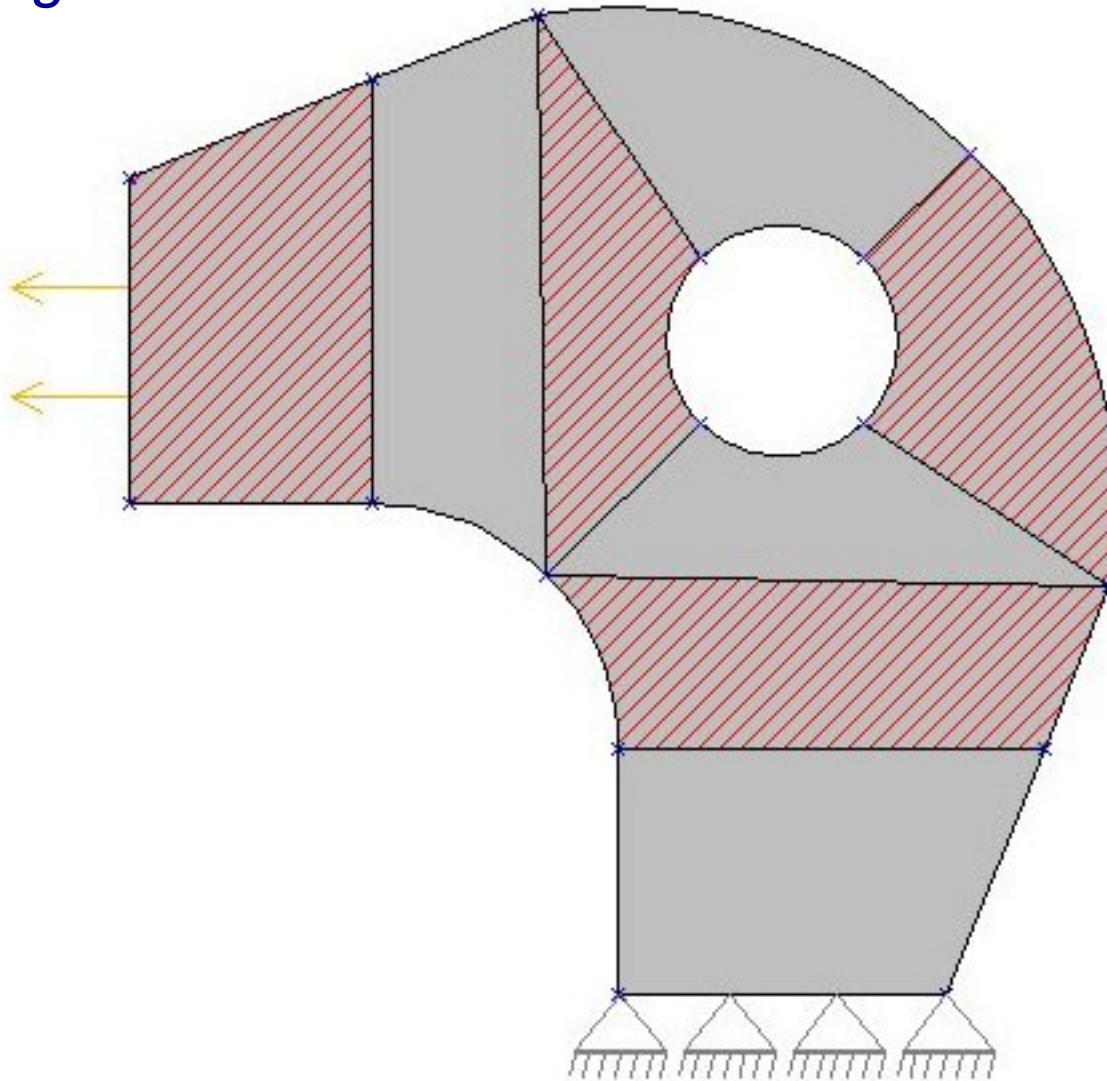
*Region decomposition to exploit structured
meshing algorithms*



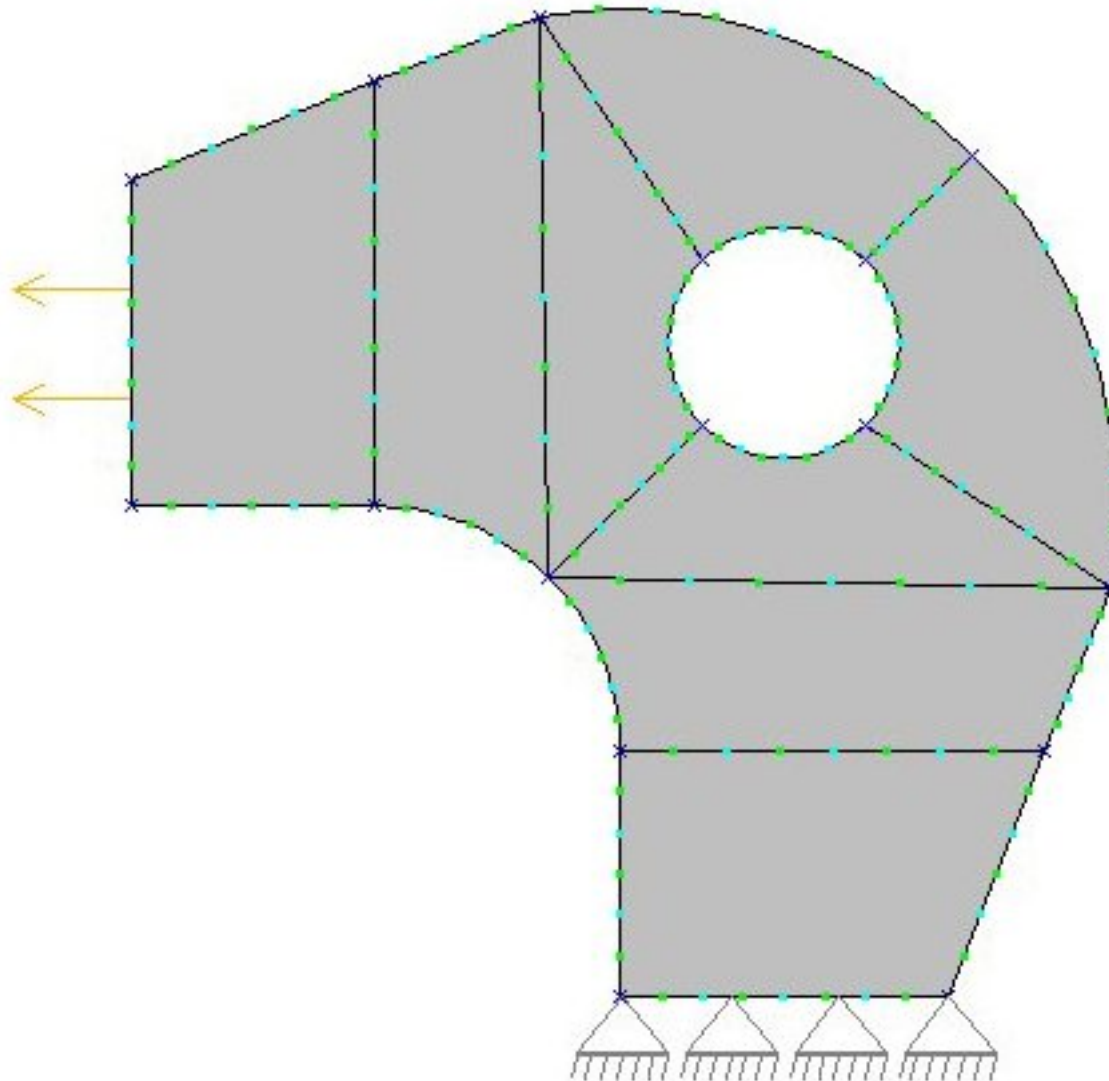
*Region decomposition to exploit structured
meshing algorithms*



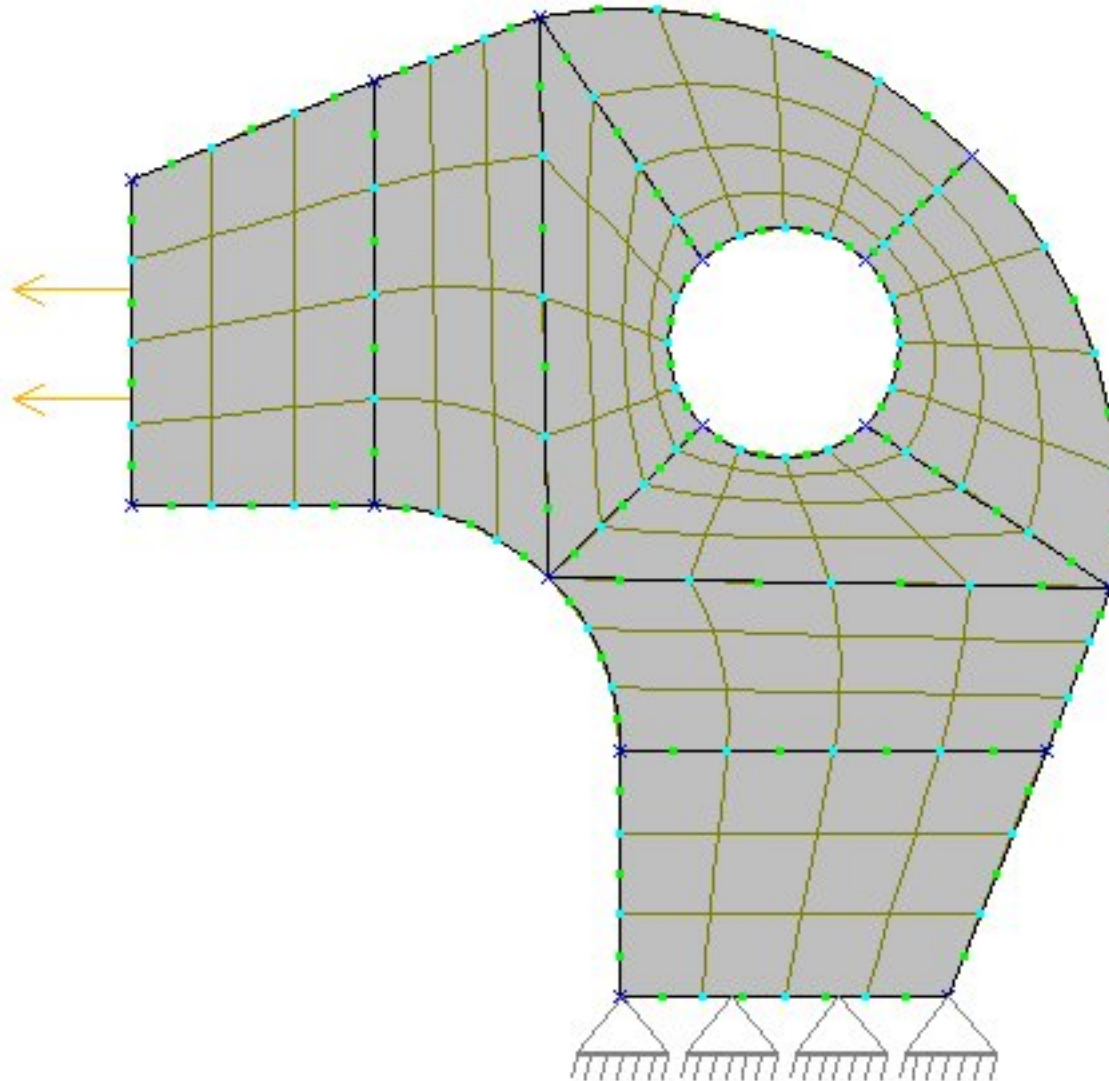
Region decomposition to exploit structured meshing algorithms



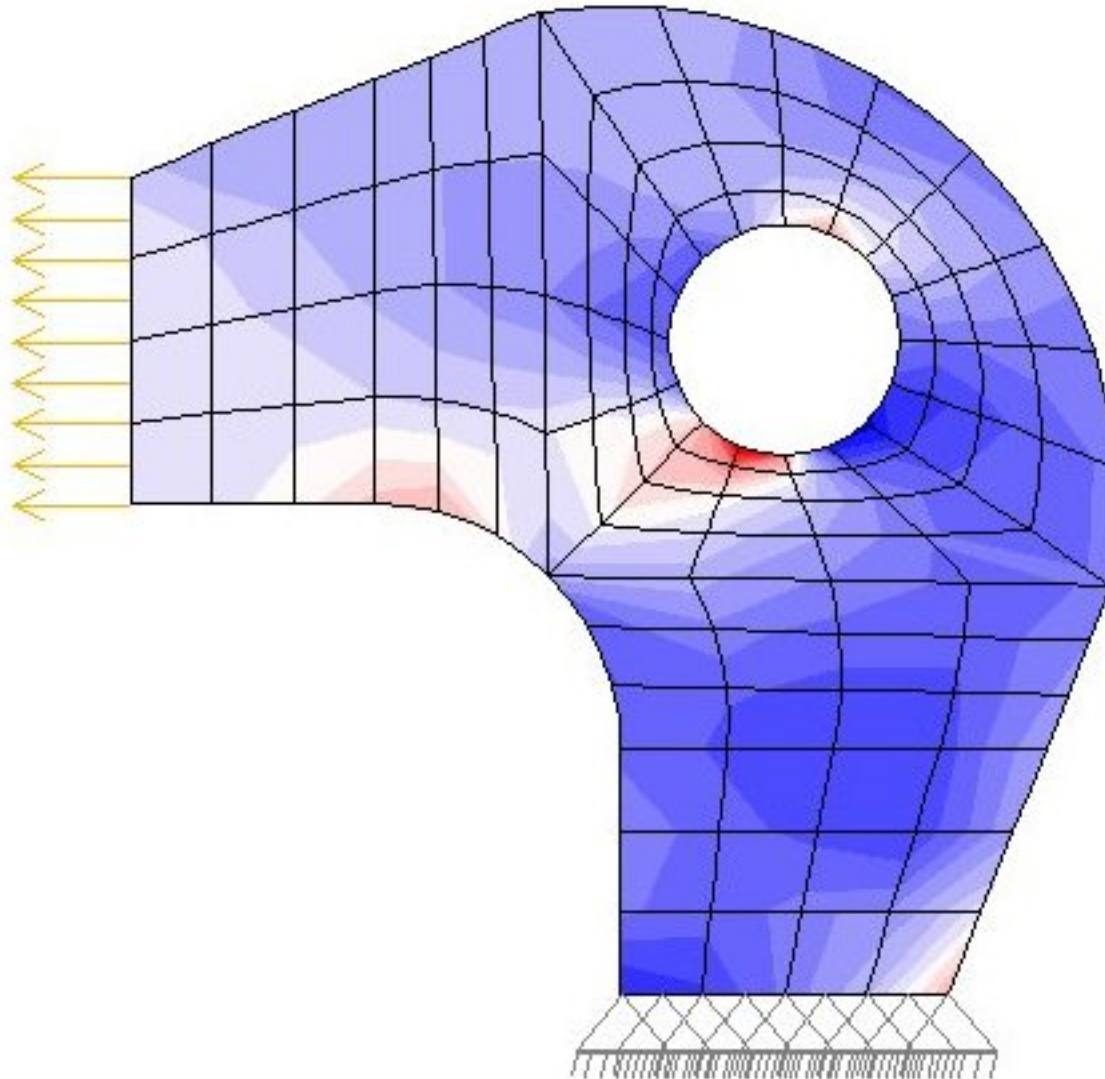
*Defining meshing refinement parameters:
boundary subdivision*



Automatic unstructured mesh generation

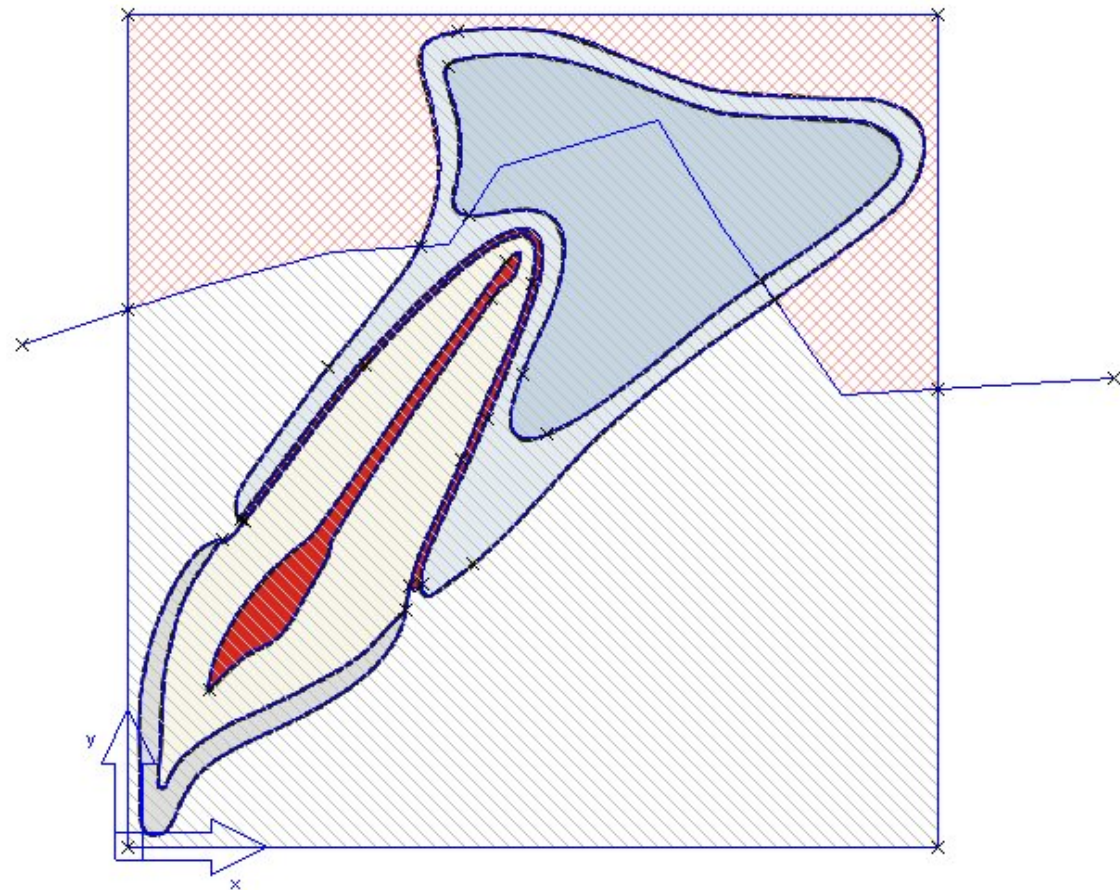


What is the technology behind this?
What issues we have to address?



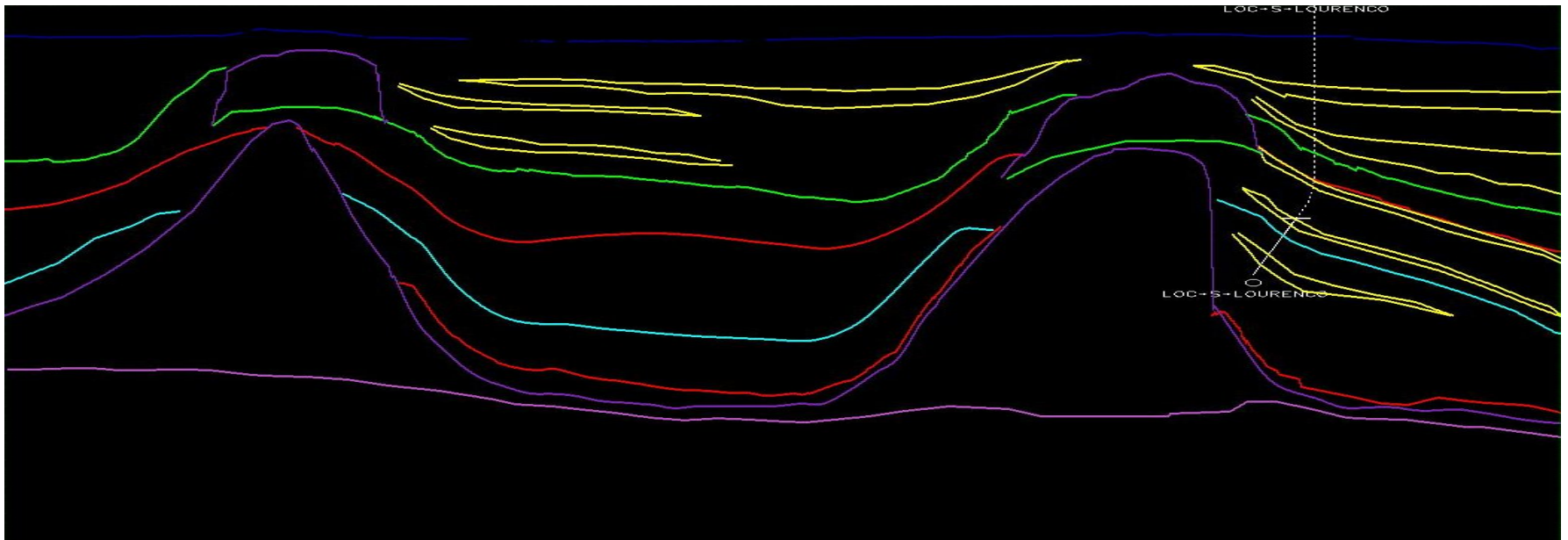
Generic Space Subdivision: Many Applications

*An environment in which curves and surfaces are inserted randomly.
Automatic region recognition and full adjacency information.*



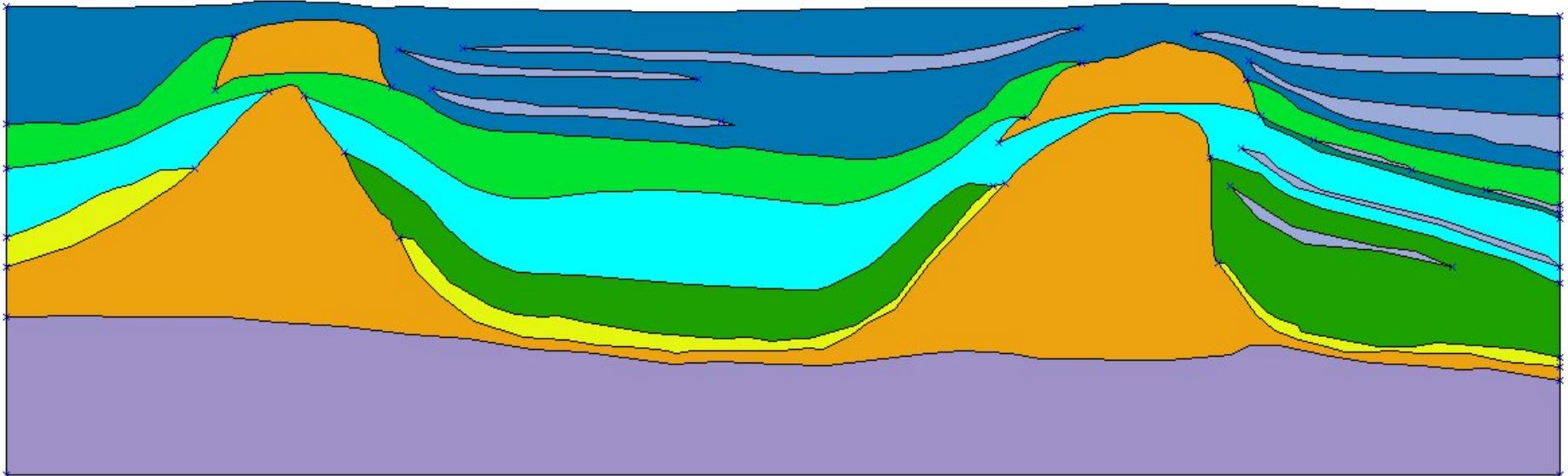
2D Subsurface Simulation Modeling

Geological cross-section



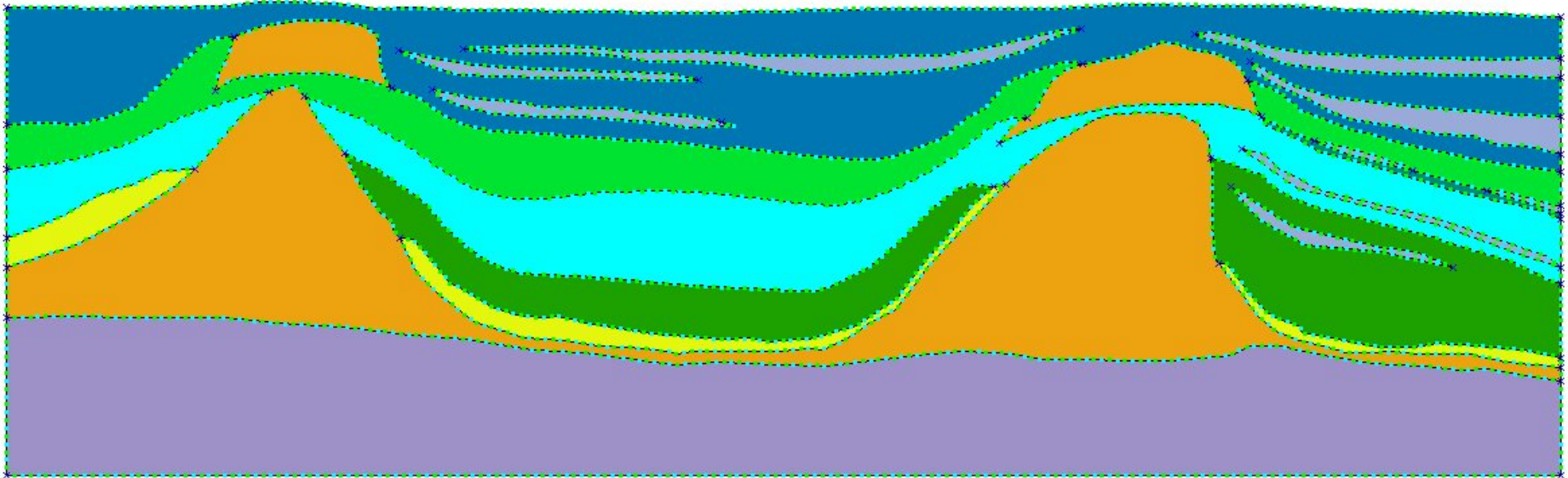
2D Subsurface Simulation Modeling

Curve digitalization



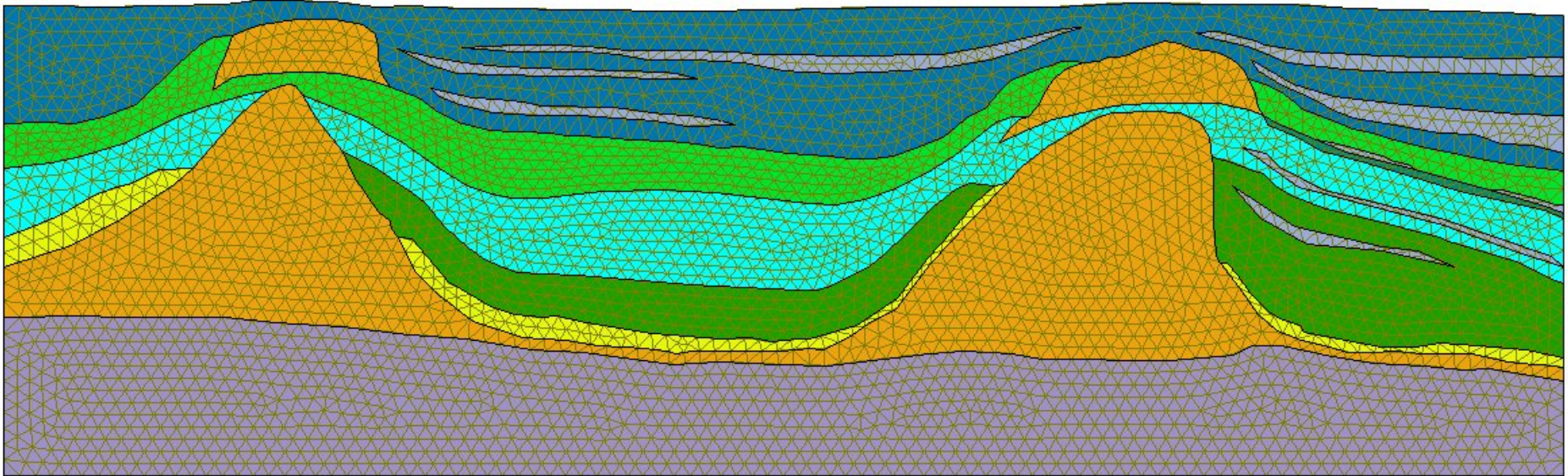
2D Subsurface Simulation Modeling

Curve subdivision



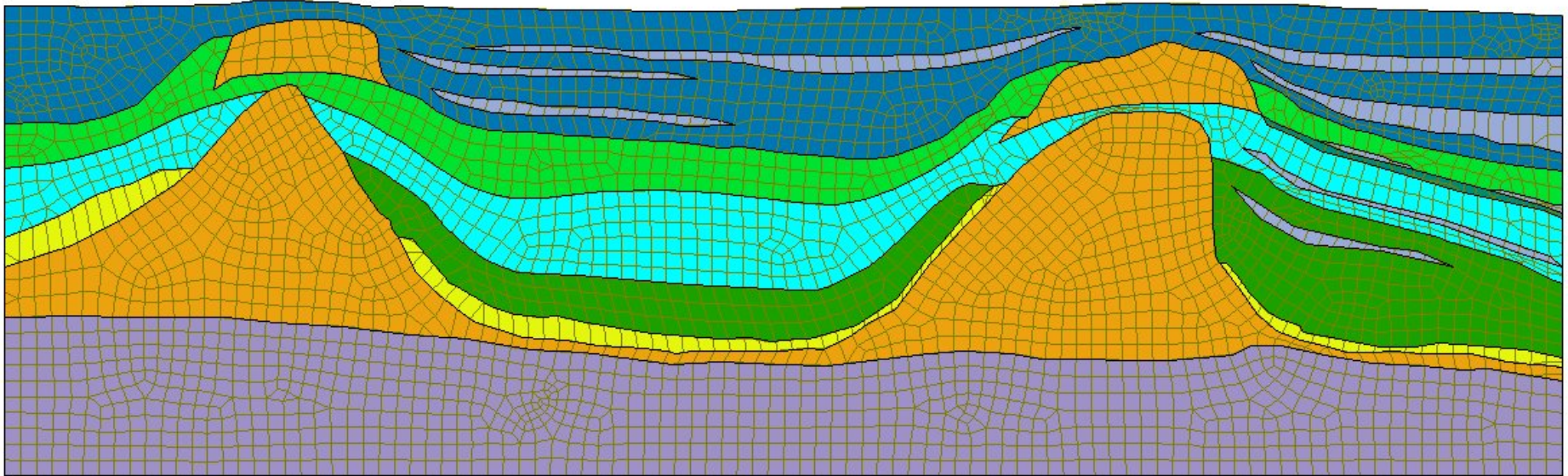
2D Subsurface Simulation Modeling

Mesh generation: triangular elements



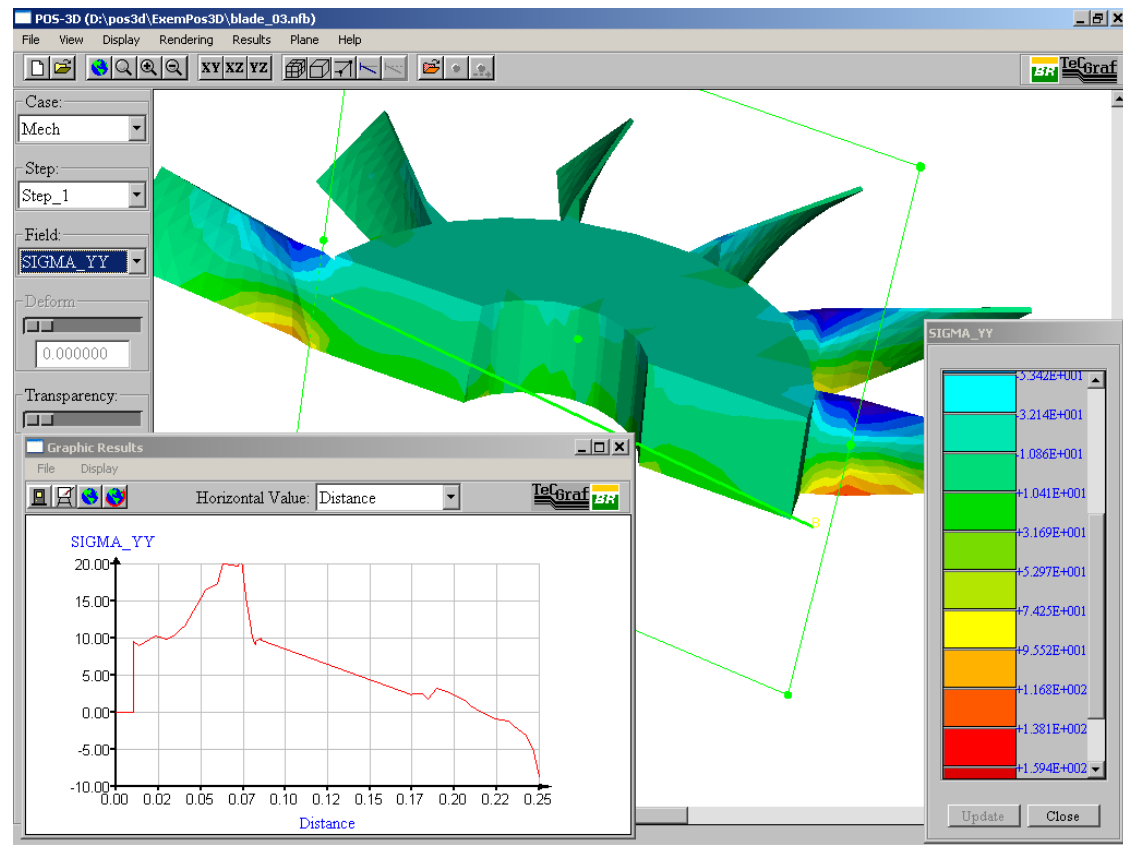
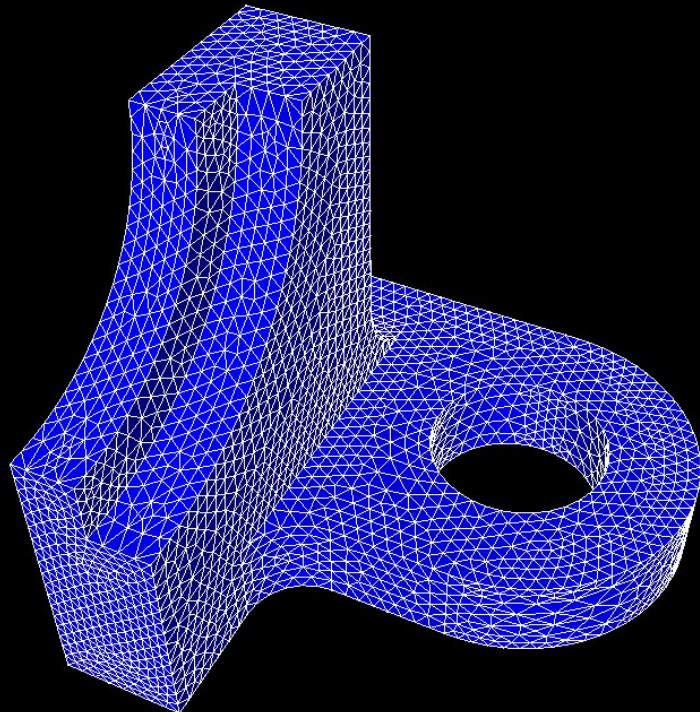
2D Subsurface Simulation Modeling

Mesh generation: quadrilateral elements



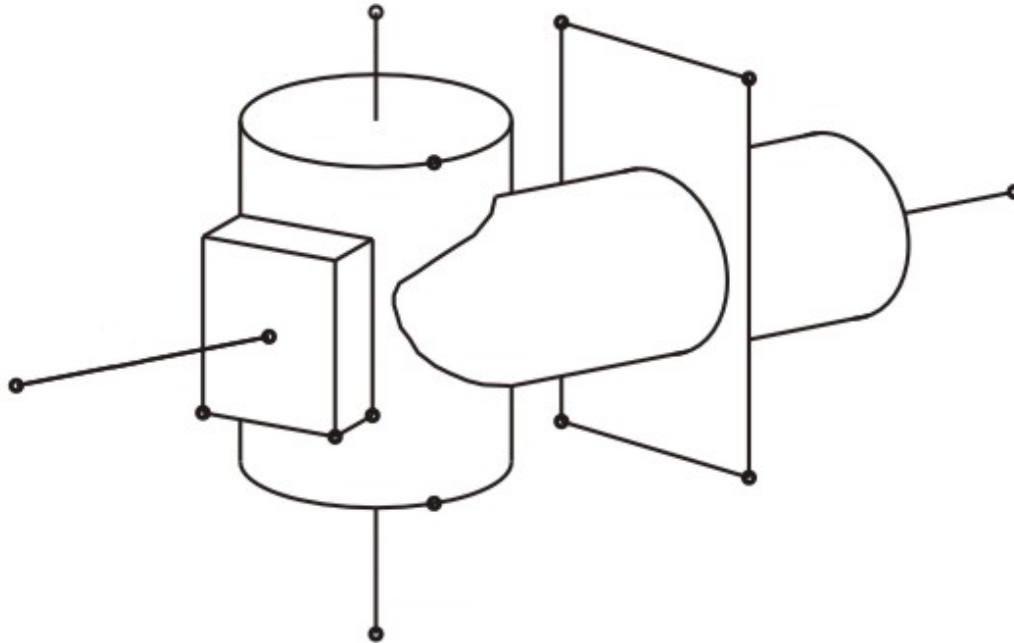
Requirements for Underlying Data Representation

- *The data structures must provide a natural navigation across all phases of a simulation: pre-processing (model creation), numerical analysis, and post-processing (model results visualization).*



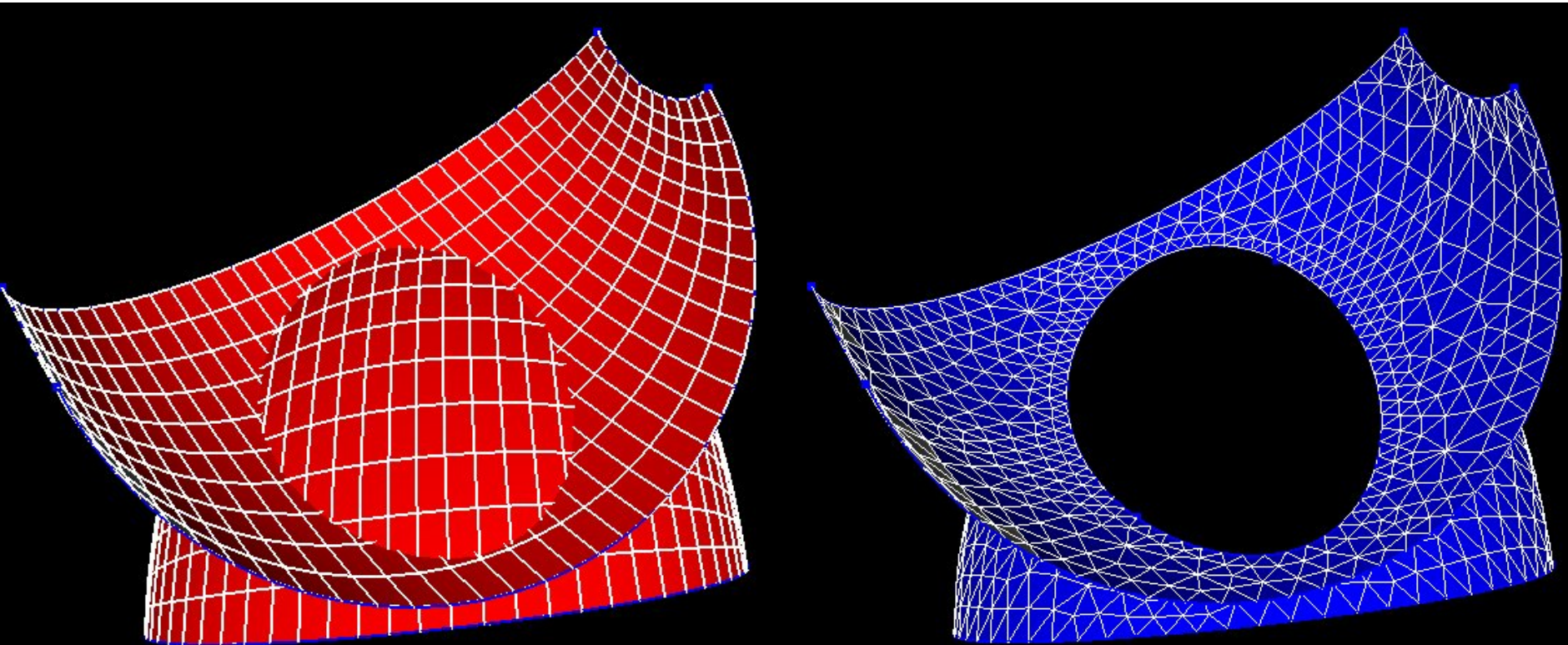
Requirements for Underlying Data Representation

- *The data structures must take into account that the simulation may induce, at least temporarily during model creation, geometric objects (curves and surfaces) that are inconsistent with the target final model. This requires a non-manifold topology representation capability.*



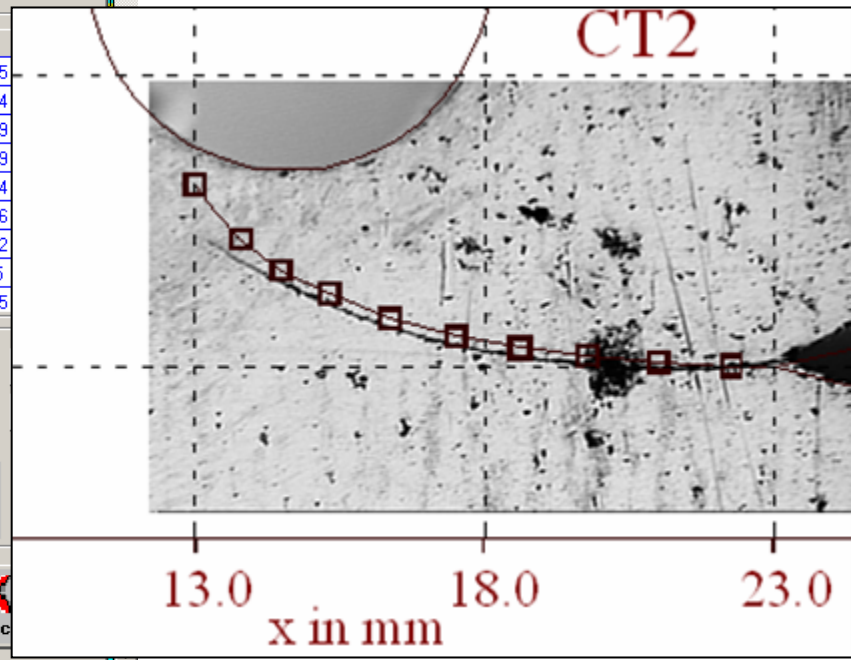
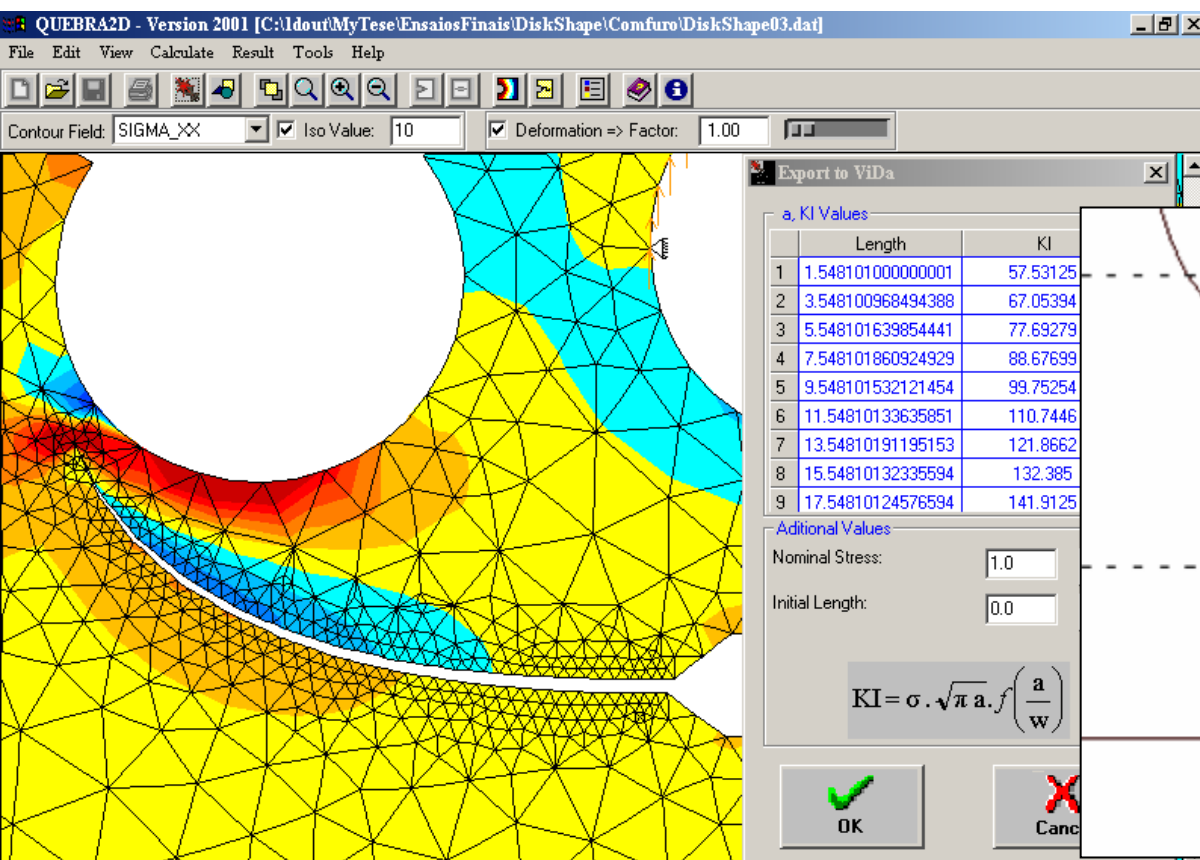
Requirements for Underlying Data Representation

- *The data structure should aid in key aspects of geometric modeling, such as surface intersection and automatic region recognition, as well as in surface and solid finite element mesh generation in arbitrary domains.*



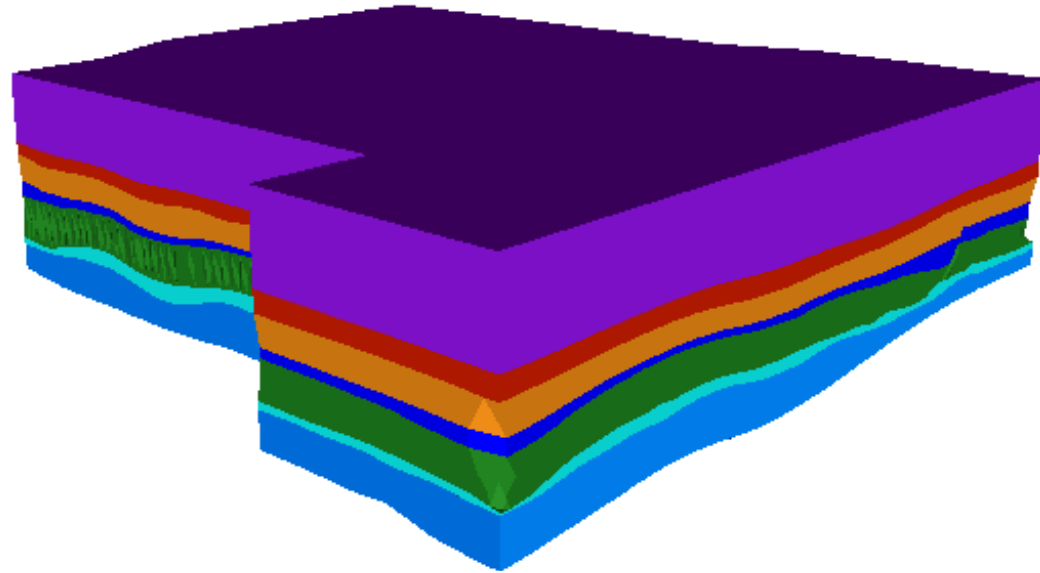
Requirements for Underlying Data Representation

- *The data structure must provide for efficient geometric operators, including automatic intersection detection and processing.*
- *This is necessary in simulations with evolving topology and geometry.*

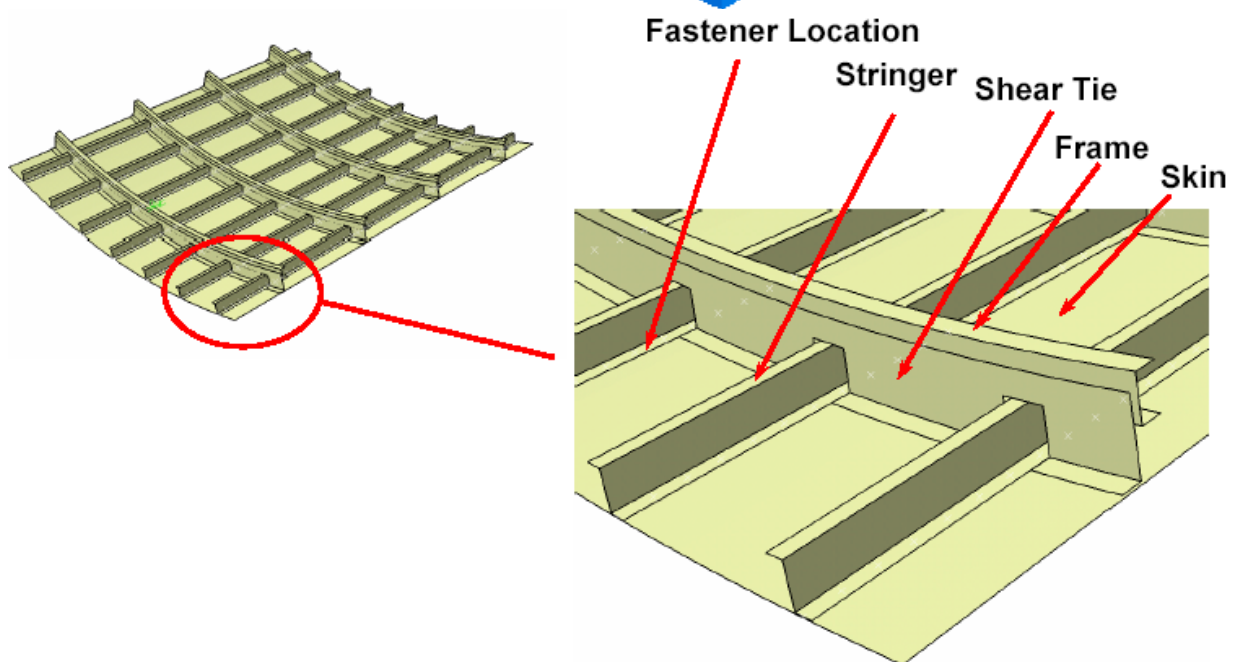


The need for non-manifold modeling

Multi-region modeling

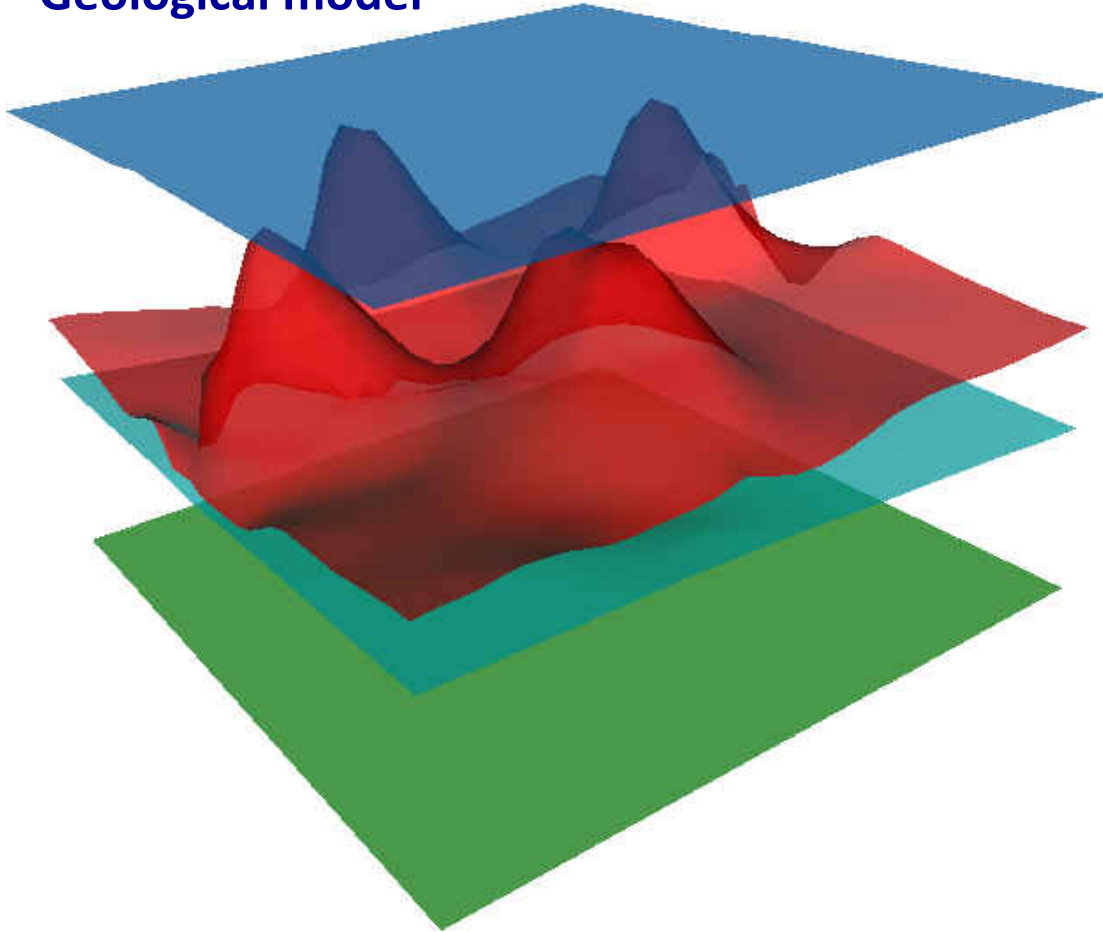


Degenerated structures

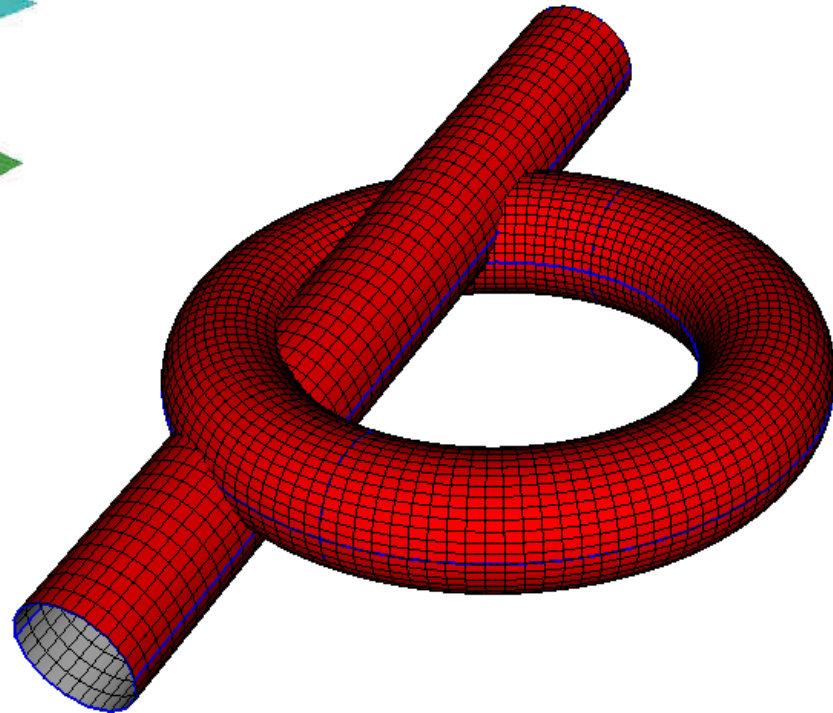


Natural Modeling: surface patches as primitives

Geological model

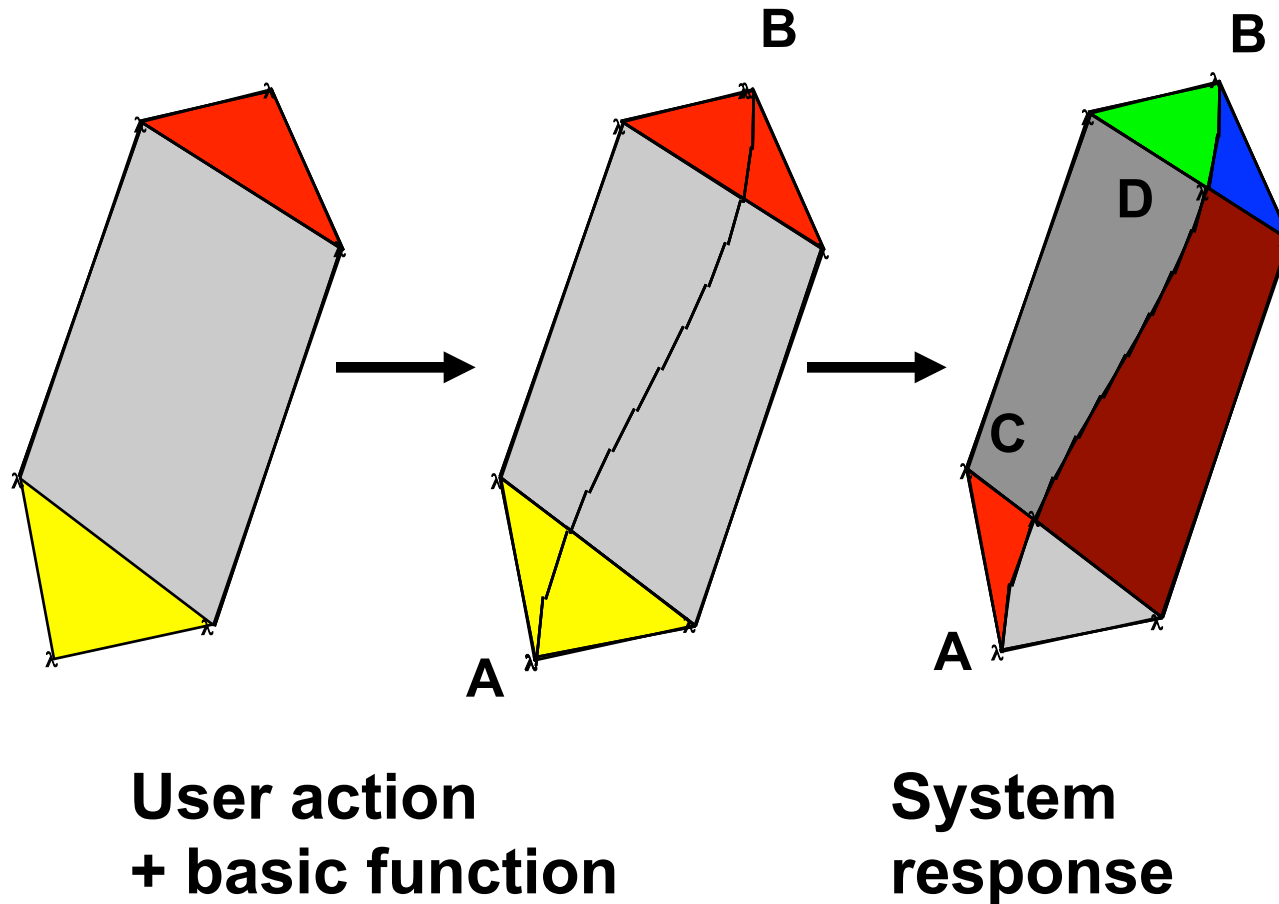


Manufactured model

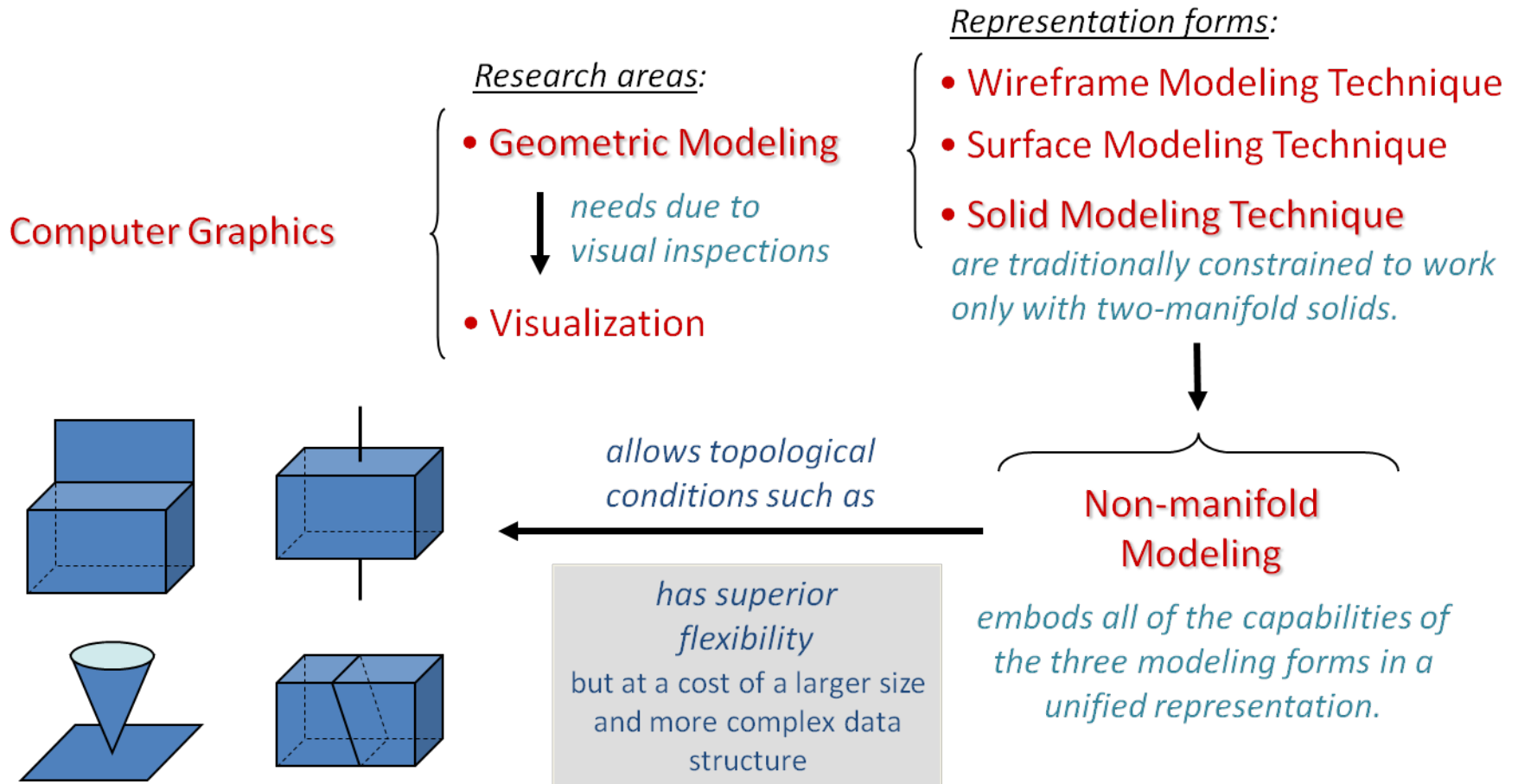


Ideal Environment: complete space subdivision

Space subdivision in 2D: high level operations



Modeling in Engineering



Modeling in Engineering

Computer Graphics

Research areas:

- Geometric Modeling

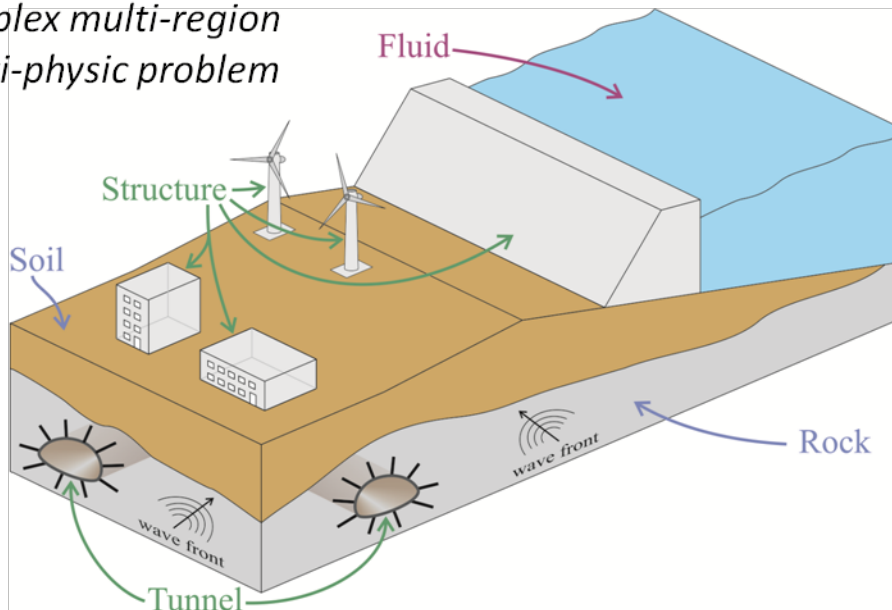
↓ *needs due to
visual inspections*

- Visualization

Representation forms:

- Wireframe Modeling Technique
- Surface Modeling Technique
- Solid Modeling Technique
*are traditionally constrained to work
only with two-manifold solids.*

*complex multi-region
multi-physic problem*



↓
**Non-manifold
Modeling**

*embods all of the capabilities of
the three modeling forms in a
unified representation.*

Geometric Modeling

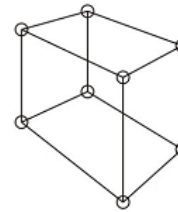
Geometric Modeling

- Creation, manipulation, maintenance and analysis of representations of geometric forms of two and three dimensional objects.
- Application in several fields, such as movie production, design of industrial mechanical parts, scientific visualization and reproduction of objects for analysis in engineering.

Geometric Modeling

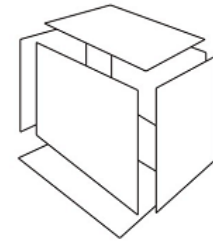
- **Historic Evolution:**

a) Wire Modeling



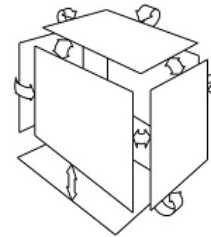
(a)

b) Surface Modeling



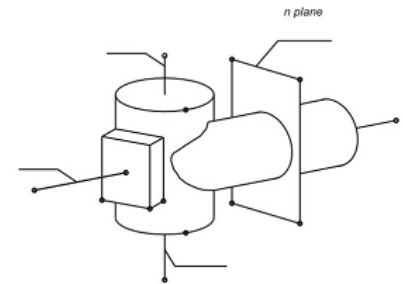
(b)

c) Solid Modeling



(c)

d) Non-manifold Modeling



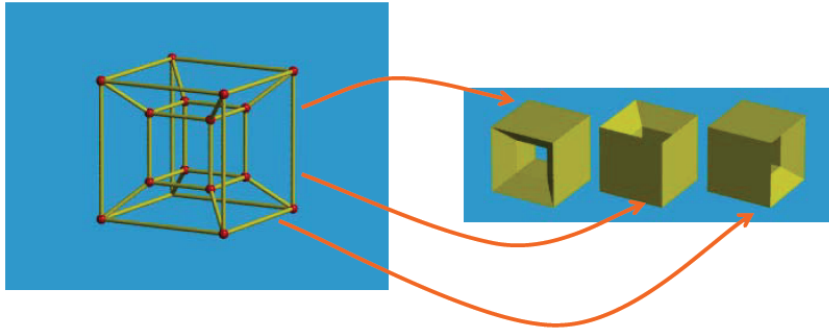
(d)

Geometric Modeling

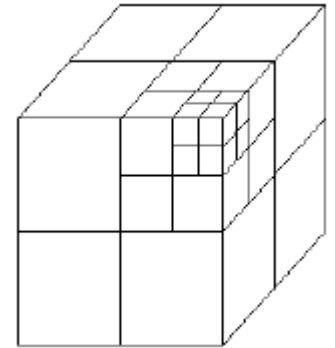
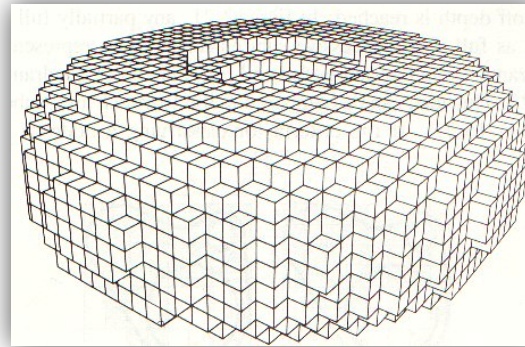
- **Strategies for Representing Solids**
 - Decomposition Models
 - B-Rep Models
 - Constructive Models (CSG)
 - Hybrid Models

Geometric Modeling

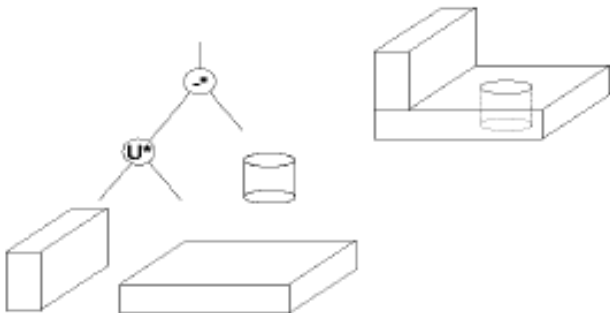
Wire Frame



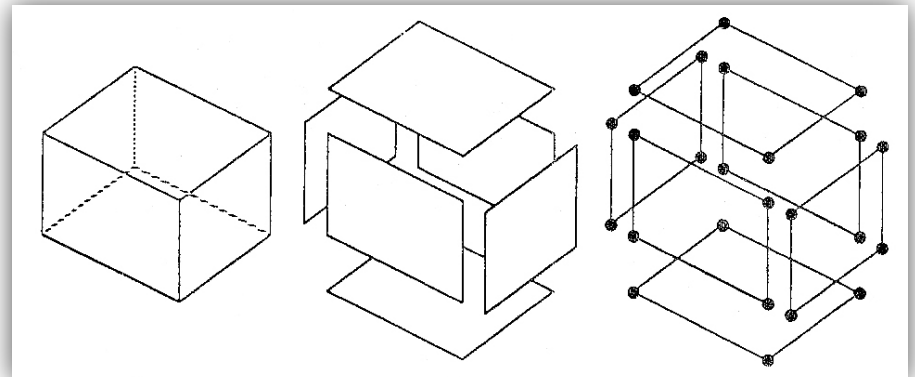
Cell Decomposition / Space Enumeration



Constructive Solid Geometry (CSG)

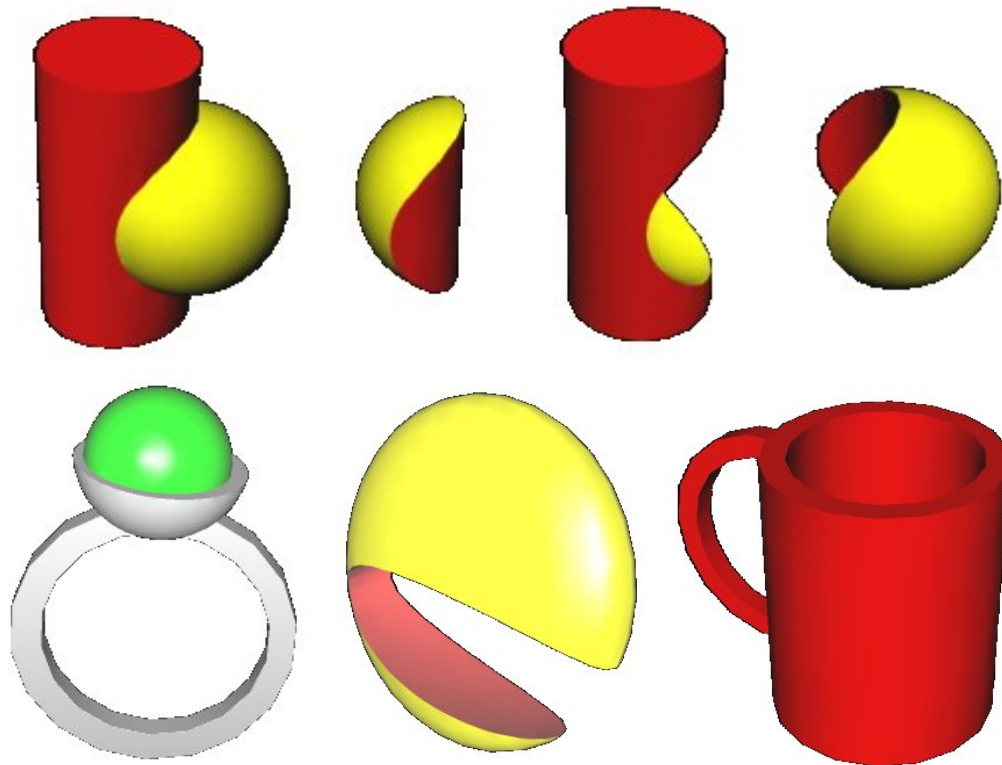


Boundary Representation (B-Rep)



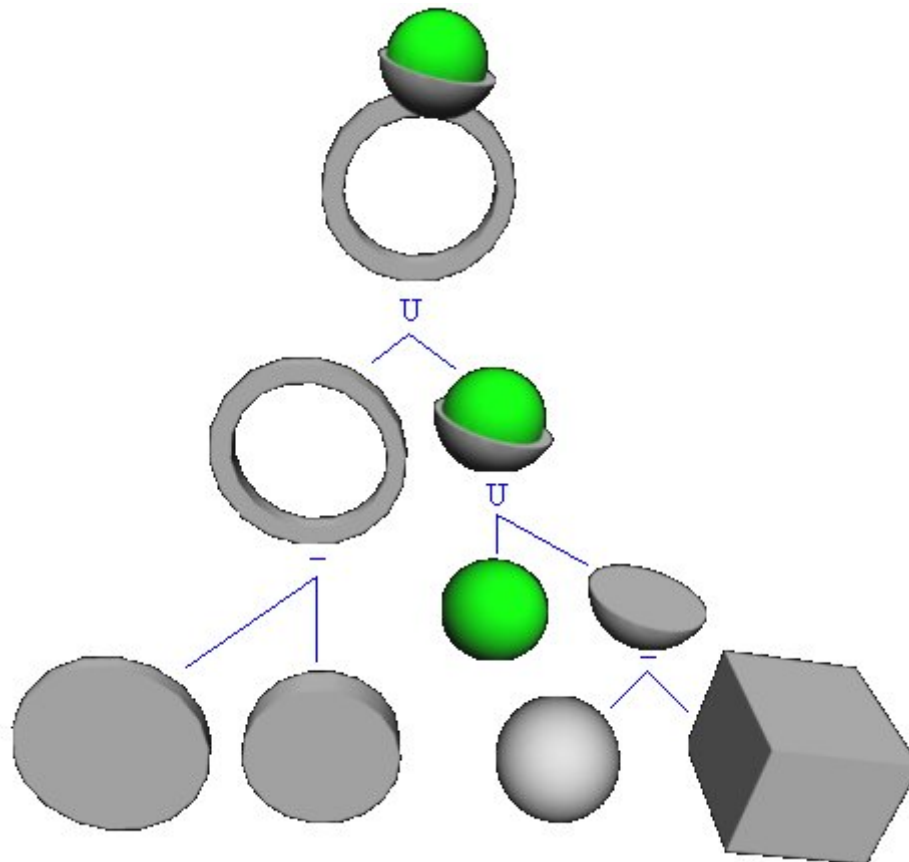
Geometric Modeling

- The Constructive Solid Geometry (CSG) uses Boolean operations and rigid body motions into simple primitives to build more complex solid objects.



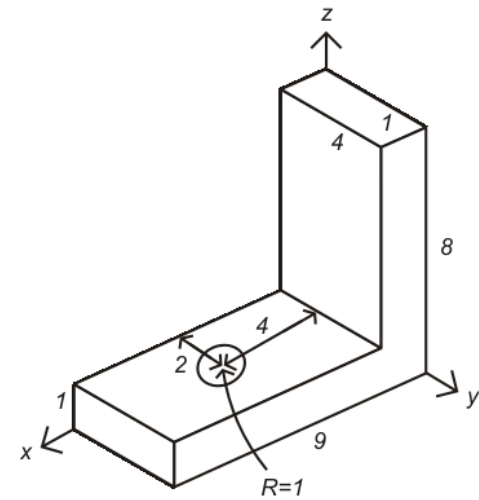
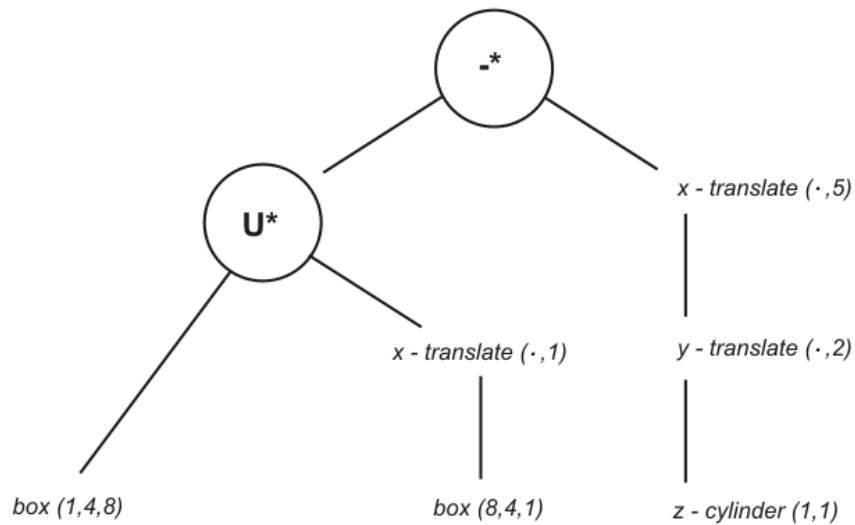
Geometric Modeling

- CSG Tree



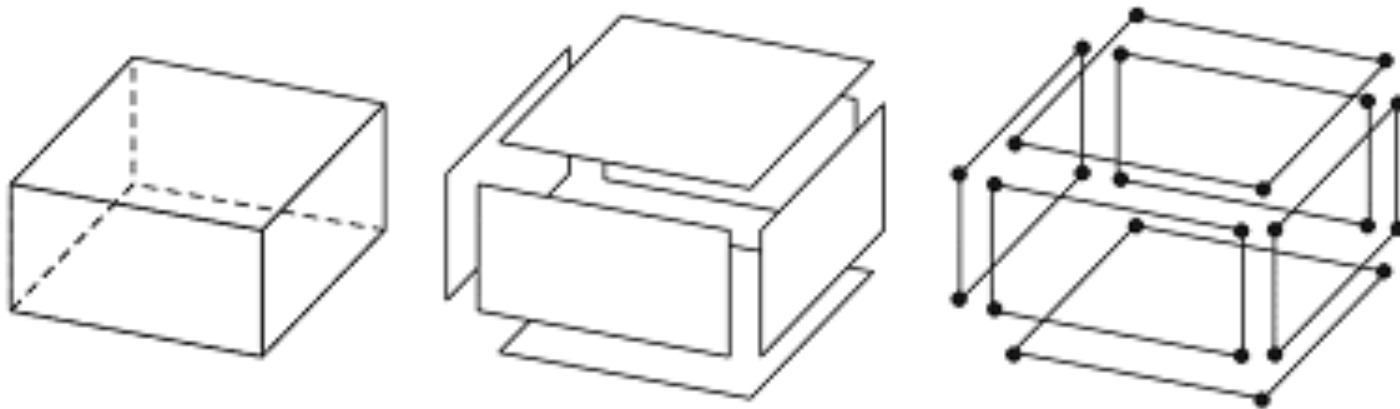
Geometric Modeling

- CSG Tree



Geometric Modeling

- B-Rep models explicitly use the adjacency relations among the topological elements (vertices, edges and faces) to define the topological boundary of the objects.

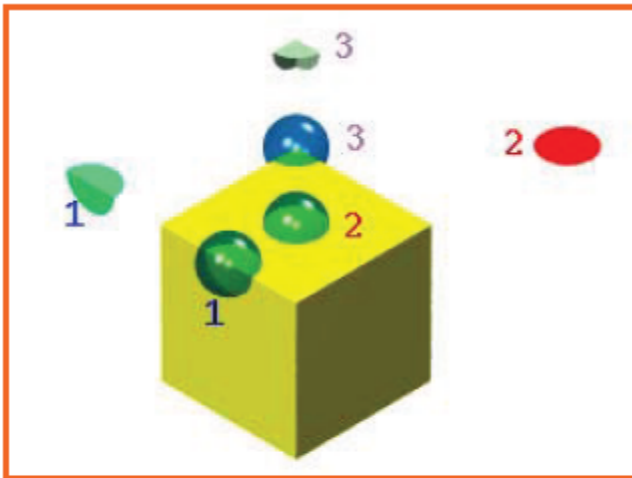


Geometric Modeling

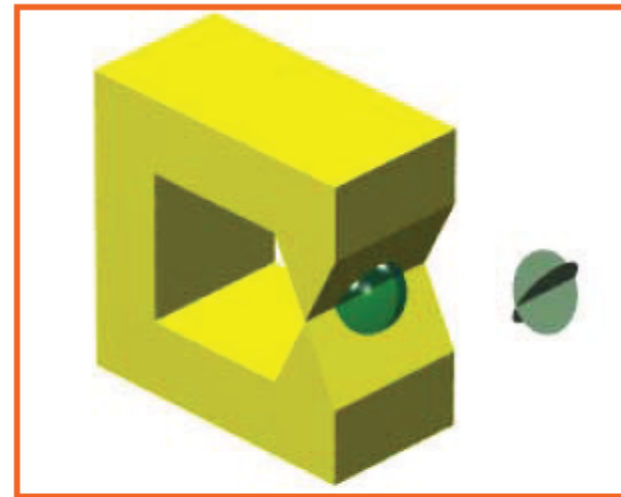
- **Non-manifold Modeling**
 - Aggregates all the capabilities of the previous three types of modeling.
 - Removes restrictions to the domain of the analyzed models.
 - Allows the representation of internal or dangling structures of lower dimensions.

Geometric Modeling

Manifold



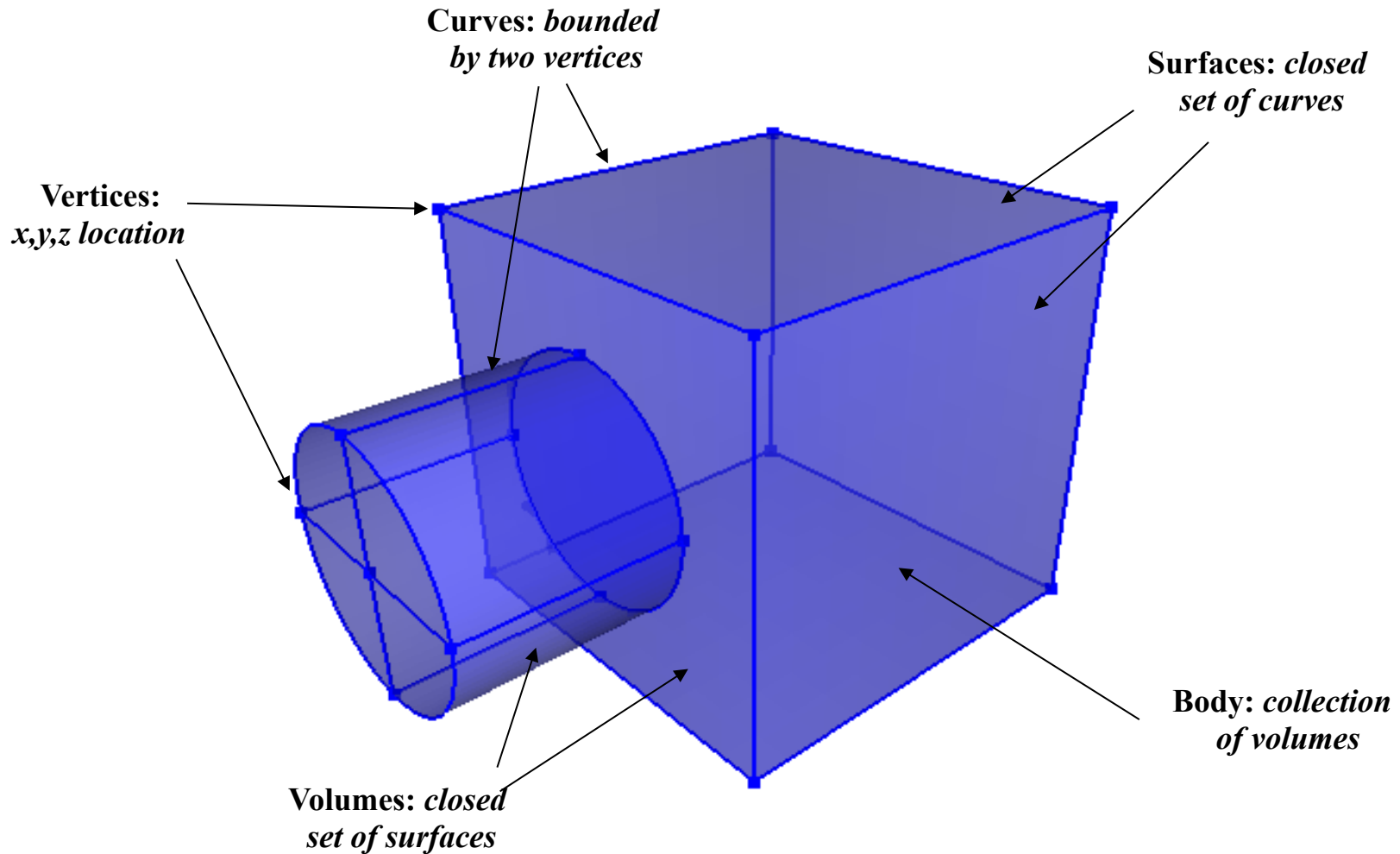
Non-manifold



Geometric Modeling

- **Topology and Geometry**
 - **Geometry** – set of complete and essential information to define the shape and spatial location of objects.
 - **Topology** – subset of information obtained from the geometry of the object. Invariant after applying geometric transformations to the object.

Geometric and Topological Entities



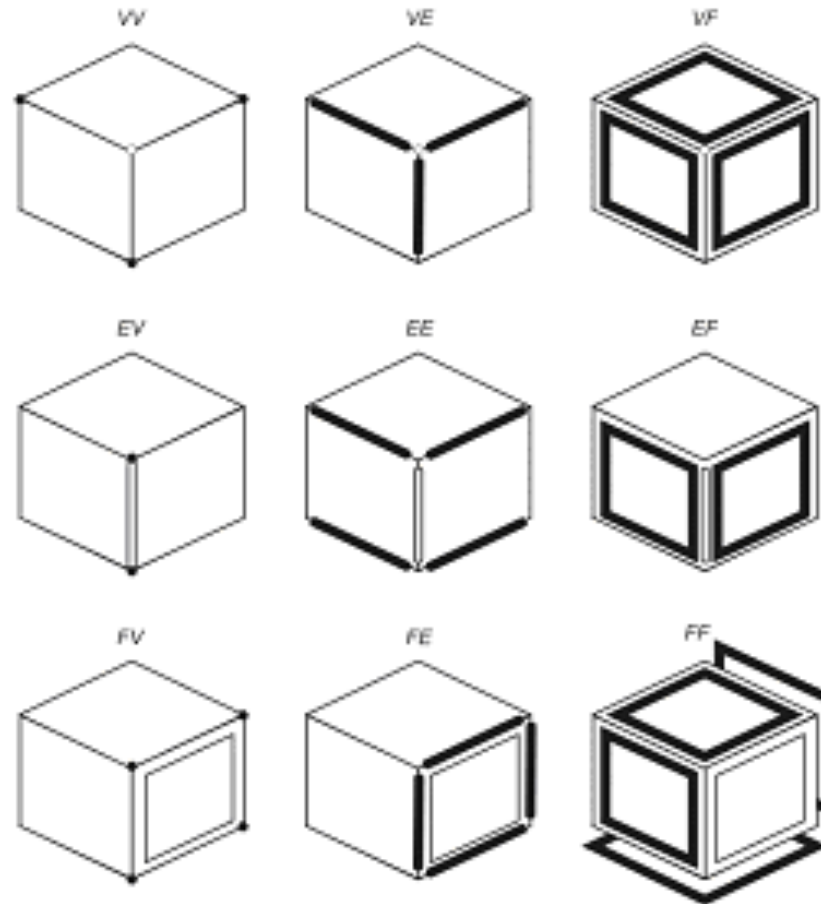
Geometric Modeling

- **Using the topology as basis for a modeling system:**
 - 1) System stability
 - 2) Avoiding numerical errors
 - 3) Separation of geometric and topological information

Geometric Modeling

- **Adjacency Relationships**
 - Connectivity among the topological elements
 - Extracted from the geometric information of the model
 - Use as a base of modeling framework, ensuring the implementation of algorithms simpler and more efficient
 - Determination of a minimal set of sufficient adjacency relationships

Geometric Modeling



Adjacency relation among vertices, edges and faces

Geometric Modeling

- **Topological Data Structures**

- Systematization and organization of topological information of a model from the storage of a sufficient set of adjacency relations.
- Main topological elements: vertices, edges and faces.
- Additional topological elements: loops, shells, regions, vertex uses, half-edges, edge uses, loop uses, face uses.

Geometric Modeling

- **Topological Data Structures**

- Examples of data structures established in *manifold* modeling:

- *Winged-edge*
 - *Half-edge*

- Data structures established in *non-manifold* modeling:

- *Radial Edge*

***Winged-Edge* Topological Data Structure**

Winged-Edge (Baumgart, 1972)

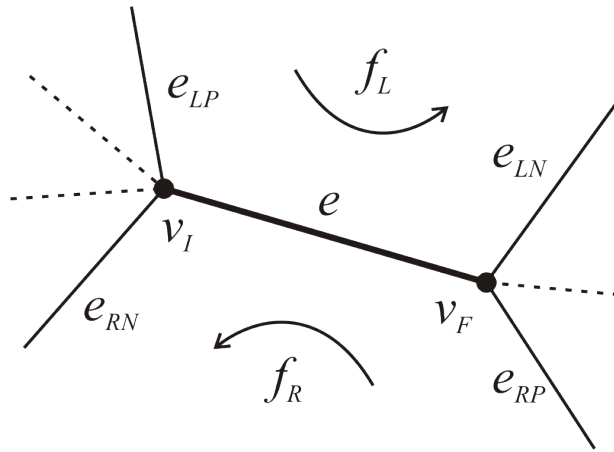


Table of Vertexes

v	x	y	z	e_I

Table of Faces

f	e_I

Table of Edges

e	v_I	v_F	f_L	f_R	e_{LP}	e_{LN}	e_{RP}	e_{RN}

Topological Data Structure - Planar Subdivision

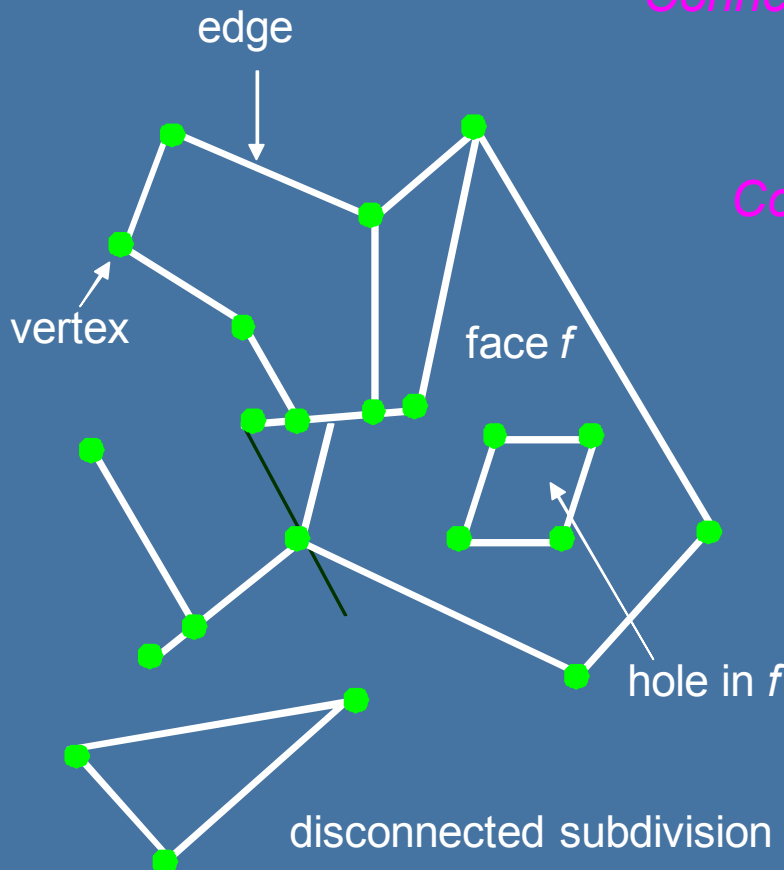
Induced by planar embedding of a graph.

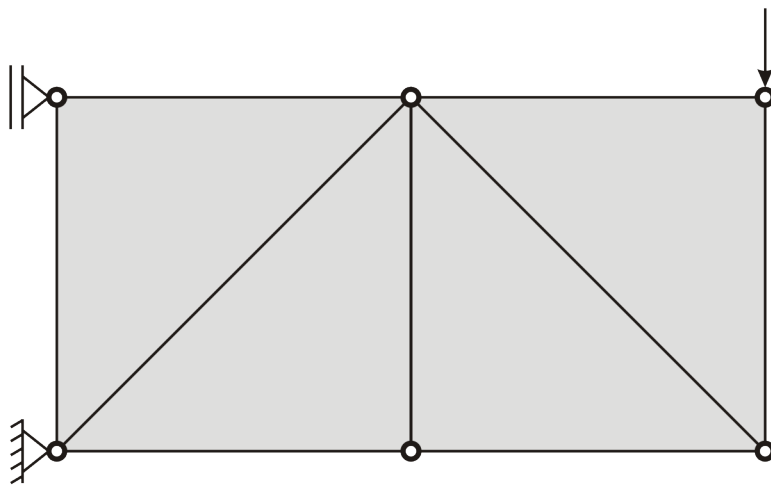
Connected if the underlying graph is.

$$\text{Complexity} = \# \text{vertices} + \# \text{edges} + \# \text{faces}$$

Typical operations:

- ✦ Walk around a face.
- ✦ Access one face from an adjacent one via a common edge.
- ✦ Visit all the edges adjacent to a vertex.





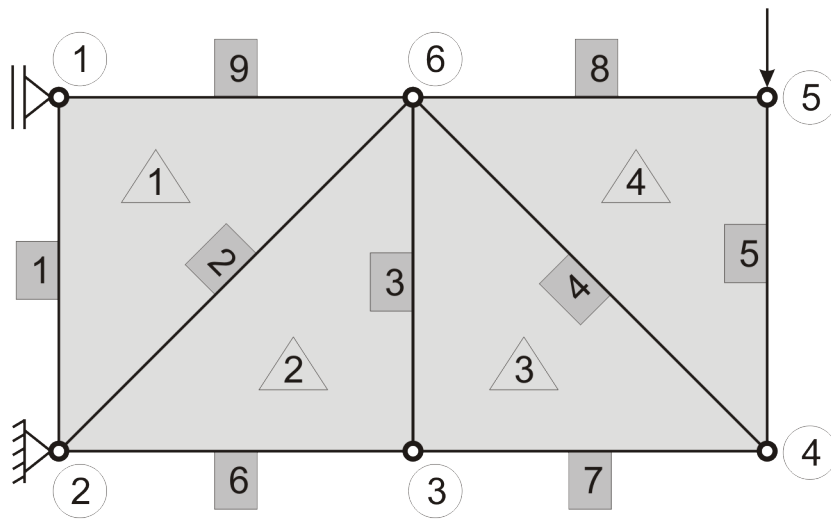
Legend:

geometry

point

curve

surface



Legend:

mesh

node 

element 1d 

element 2d 

geometry

point

curve

surface

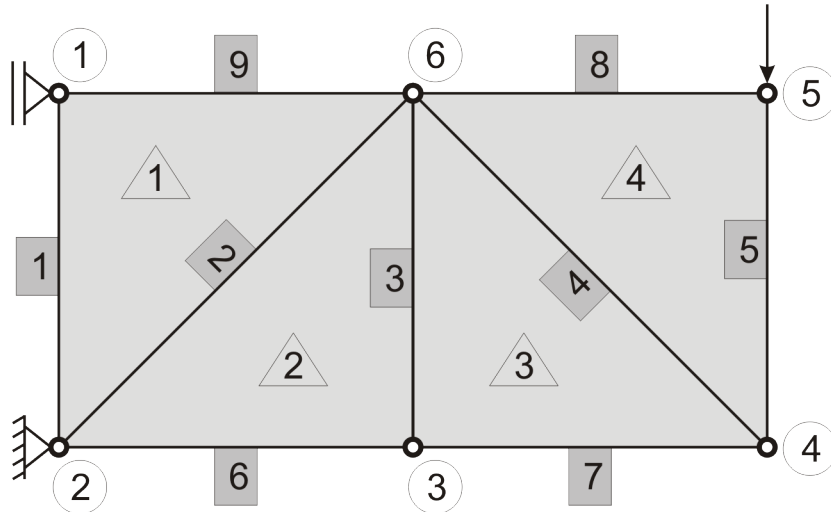
Table of nodes

N	x	y	z
1	0	1	0
2	0	0	0
3	1	0	0
4	2	0	0
5	2	1	0
6	1	1	0

Table of Incidences

E	N_1	N_2	N_3
1	1	2	6
2	2	3	6
3	6	3	4
4	4	5	6

E	N_1	N_2
1	1	2
2	2	6
3	6	3
4	6	4
5	4	5
6	2	3
7	3	4
8	5	6
9	6	1



Legend:

mesh	topology	geometry
node	5	vertex
element 1d	5	edge
element 2d	5	face

Table of nodes

N	x	y	z
1	0	1	0
2	0	0	0
3	1	0	0
4	2	0	0
5	2	1	0
6	1	1	0

Table of Incidences

E	N_1	N_2	N_3
1	1	2	6
2	2	3	6
3	6	3	4
4	4	5	6

E	N_1	N_2
1	1	2
2	2	6
3	6	3
4	6	4
5	4	5
6	2	3
7	3	4
8	5	6
9	6	1

Table of vertexes

v	x	y	z	e_I
1	0	1	0	1
2	0	0	0	6
3	1	0	0	7
4	2	0	0	4
5	2	1	0	8
6	1	1	0	2

Table of faces

f	e_I
0	1
1	2
2	6
3	4
4	4

Table of edges

e	v_I	v_F	f_L	f_R	e_{LP}	e_{LN}	e_{RP}	e_{RN}
1	1	2	1	0	9	2	6	9
2	2	6	1	2	1	9	3	6
3	6	3	3	2	4	7	6	2
4	6	4	4	3	8	5	7	3
5	4	5	4	0	4	8	8	7
6	2	3	2	0	2	3	7	1
7	3	4	3	0	3	4	5	6
8	5	6	4	0	5	4	9	5
9	6	1	1	0	2	1	1	8

Euler Operators

From a topological viewpoint, the simplest solids are those that have a closed orientable surface and no holes or interior voids. We assume that each face is bounded by a single loop of adjacent vertices; that is, the face is homeomorphic to a closed disk. Then the number of vertices V , edges E , and faces F of the solid satisfy the *Euler* formula:

$$V - E + F - 2 = 0$$

This fact is easily proved by induction on the surface structure. Extensions to this formula have been made that account for faces not being homeomorphic to closed disks, the solid surface not being without holes, and the solid having interior voids, as reviewed next.

We consider the possibility that the solid has holes, but that it remains bounded by a single, connected surface. Moreover, each face is assumed to be homeomorphic to disk. For example, the torus has one hole, and the object in Figure **A** has two. It is a well-known fact that such solids are topologically equivalent, i.e., *homeomorphic*, to a sphere with zero or more handles. For example, the object of Figure **A** is homeomorphic to a sphere with two handles, the latter shown in Figure **B**. The number of handles is called the *genus* of the surface. In general, with a genus G , the numbers of vertices, edges, and faces obey the *Euler–Poincaré* formula:

$$V - E + F - 2(1 - G) = 0 \quad \text{[HOFFMANN1992]}$$

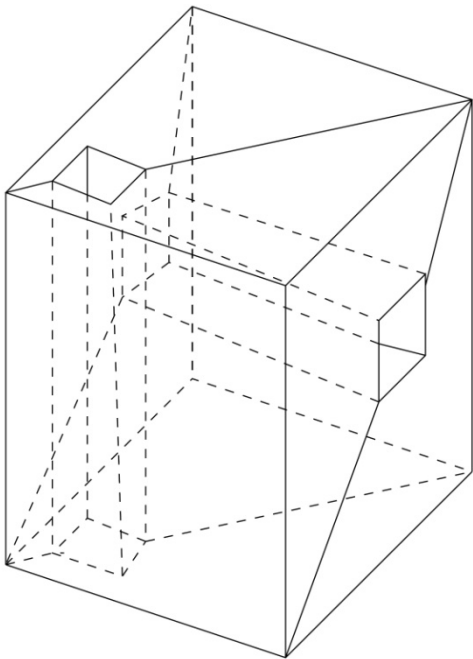


Figure A An Object with Two Holes and with Faces Homeomorphic to Disks

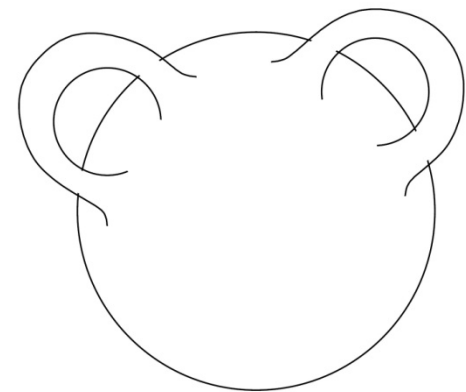


Figure B A Surface of Genus 2

Next, we further generalize by adding the possibility of internal voids. These voids are bounded by separate closed manifold surfaces, called *shells*. The number of shells will be denoted by S . Finally, we relax the requirement that a face is bounded by a single loop of vertices, but require that each face can be mapped to the plane. Thus, a sphere missing at least one point can be a face. In Figure **C**, a face is shown with four bounding loops. Note that one of these loops consists of a single vertex, and another one of two vertices connected by an edge. To account for faces of this complexity, we must count, for each face, the number of bounding vertex loops. For the face in Figure **C**, this number is four. With L the total number of loops, the relationship among the number of faces, edges, vertices, loops, and shells, and the sum G of each shell's genus, is then

$$V - E + F - (L - F) - 2(S - G) = 0$$

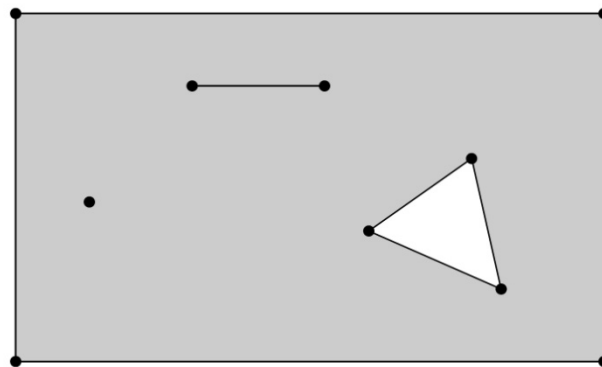


Figure C A Face with Four Bounding Loops

[HOFFMANN1992]

An example solid illustrating this relationship is shown in Figure **D**.

We may think of the quantities V , E , F , L , S , and G as existing in an abstract six-dimensional space. The relationship among them is then the equation of a hyperplane. Since the values of the variables must be non-negative integers, we might view the relation as defining a lattice on this hyperplane. For each solid with a given topological structure, there corresponds a point in this lattice.

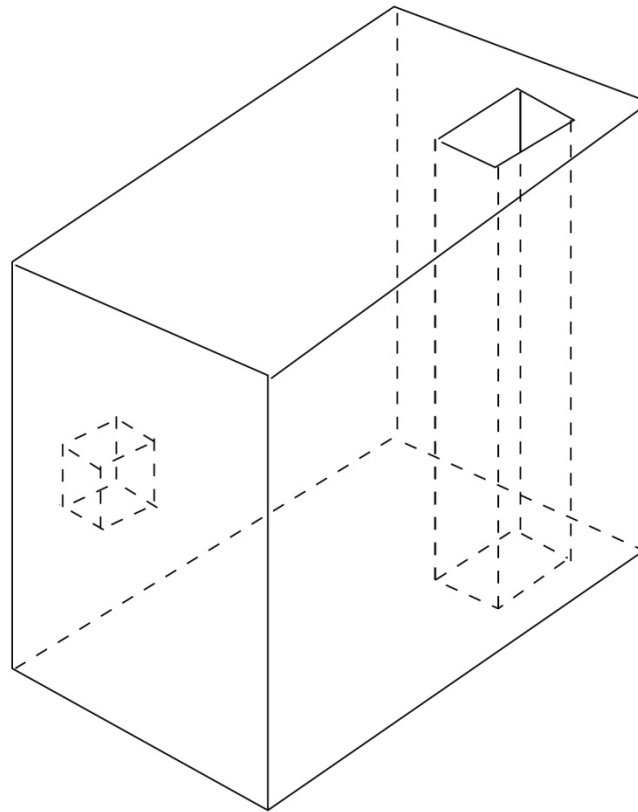


Figure D Solid with 24 Vertices, 36 Edges, 16 Faces, 18 Loops, 2 Shells, and Genus Sum 1

[HOFFMANN1992]

Euler Operators

Operator Name	Meaning	V	E	F	L	S	G
MEV	Make an edge and a vertex	+1	+1				
MFE	Make a face and an edge		+1	+1	+1		
MSFV	Make a shell, a face and a vertex	+1		+1	+1	+1	
MSG	Make a shell and a hole					+1	+1
MEKL	Make an edge and kill a loop		+1		-1		

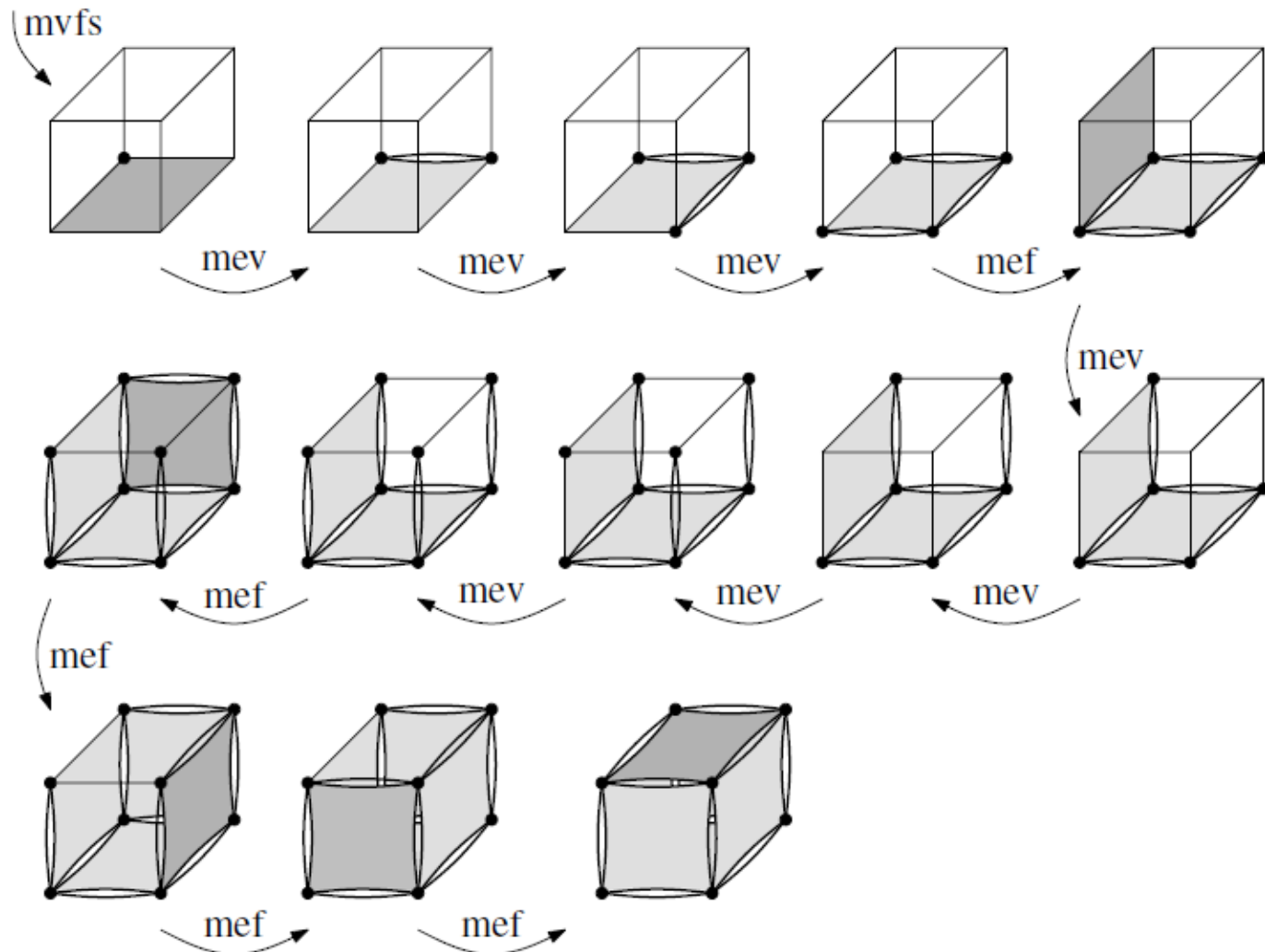
$$V - E + F - (L - F) - 2(S - G) = 0$$

Euler Operators

Operator Name	Meaning	V	E	F	L	S	G
MEV	Make an edge and a vertex	+1	+1				
MFE	Make a face and an edge		+1	+1	+1		
MSFV	Make a shell, a face and a vertex	+1		+1	+1	+1	
MSG	Make a shell and a hole					+1	+1
MEKL	Make an edge and kill a loop		+1		-1		

<i>Operator Name</i>	<i>Meaning</i>	<i>V</i>	<i>E</i>	<i>F</i>	<i>L</i>	<i>S</i>	<i>G</i>	<i>Result</i>
MSFV	Make a shell, a face and a vertex	+1		+1	+1	+1		
MEV	Make an edge and a vertex	+1	+1					
MEV	Make an edge and a vertex	+1	+1					
MEV	Make an edge and a vertex	+1	+1					
MFE	Make a face and an edge		+1	+1		+1		
MFE	Make a face and an edge		+1	+1		+1		
MFE	Make a face and an edge		+1	+1		+1		

Using Euler Operators to Construct a Solid



***Half-Edge* Topological Data Structure**

Half-Edge (Mäntylä, 1988)

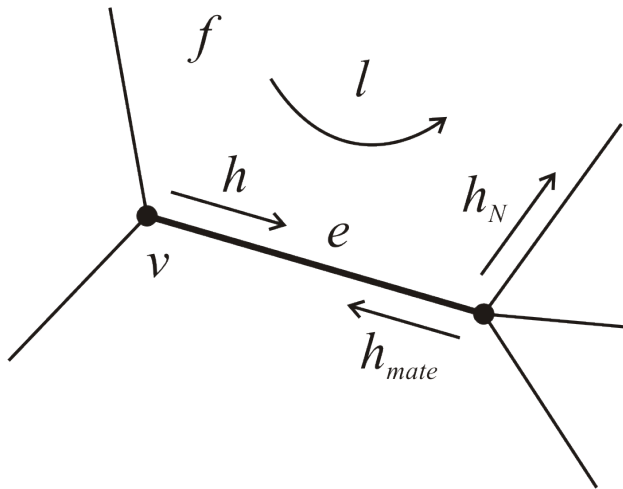


Table of vertexes

v	x	y	z	h

Table of half-edges

h	e	v	l	h_N

Table of edges

e	h_1	h_2

Table of loops

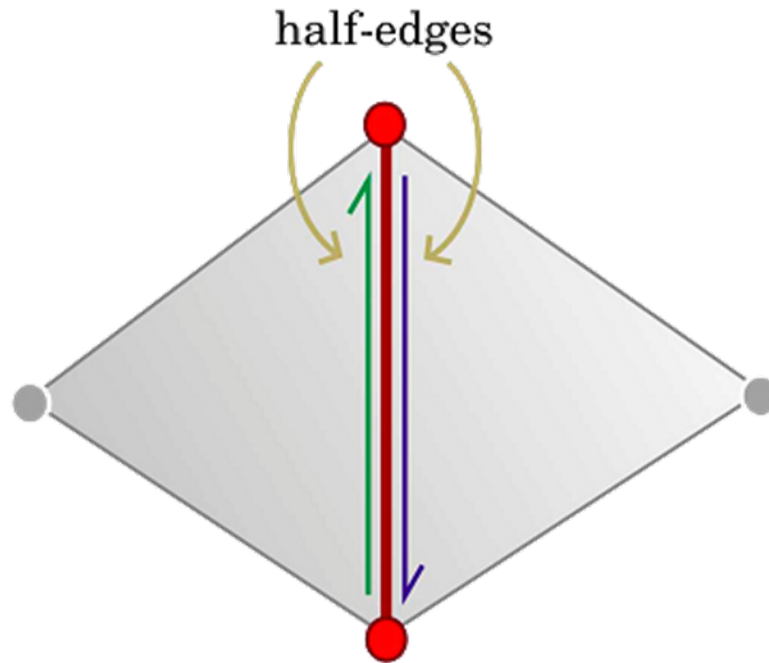
l	h	f	l_N

Table of faces

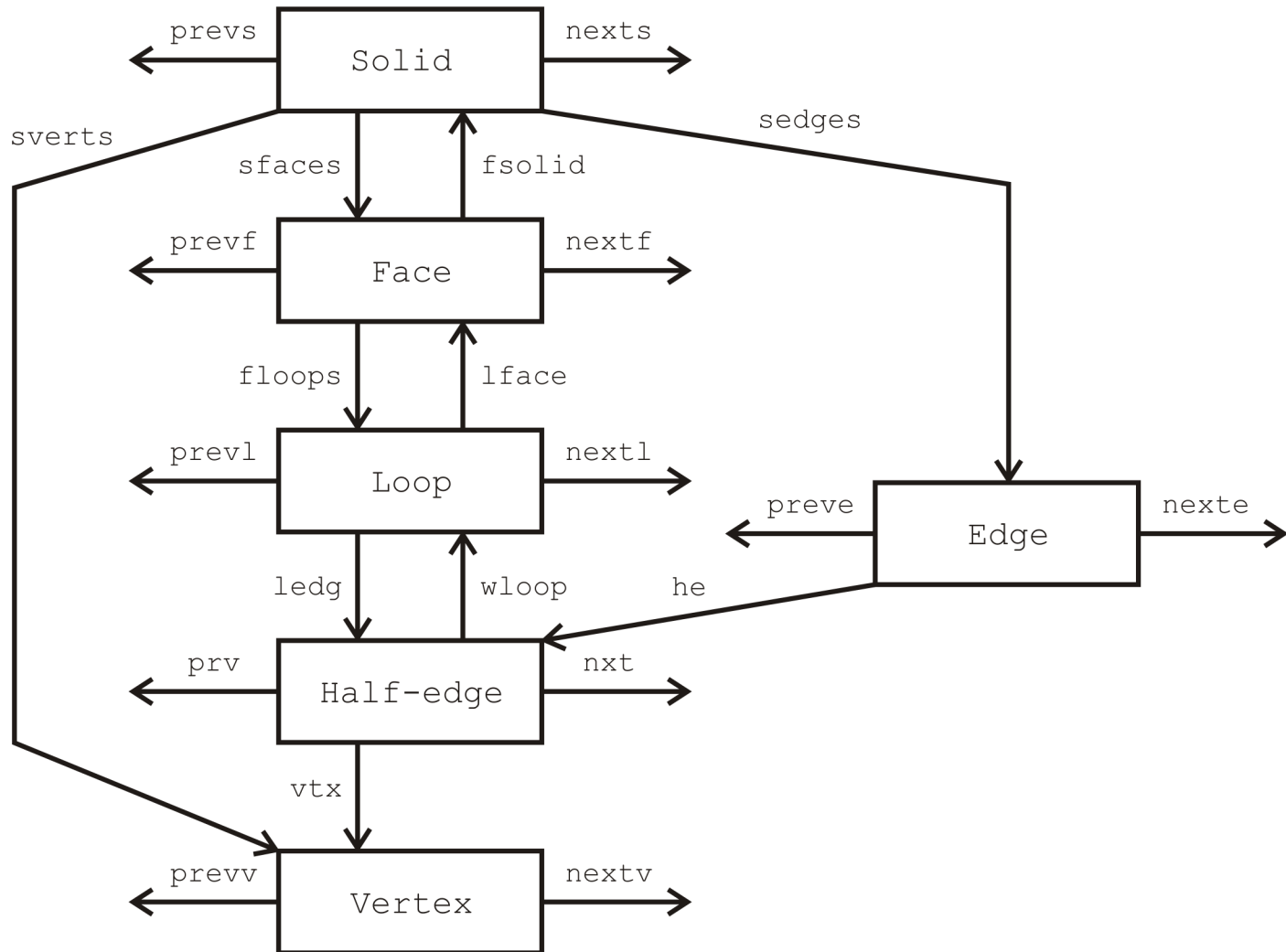
f	l_{out}	l_{in}

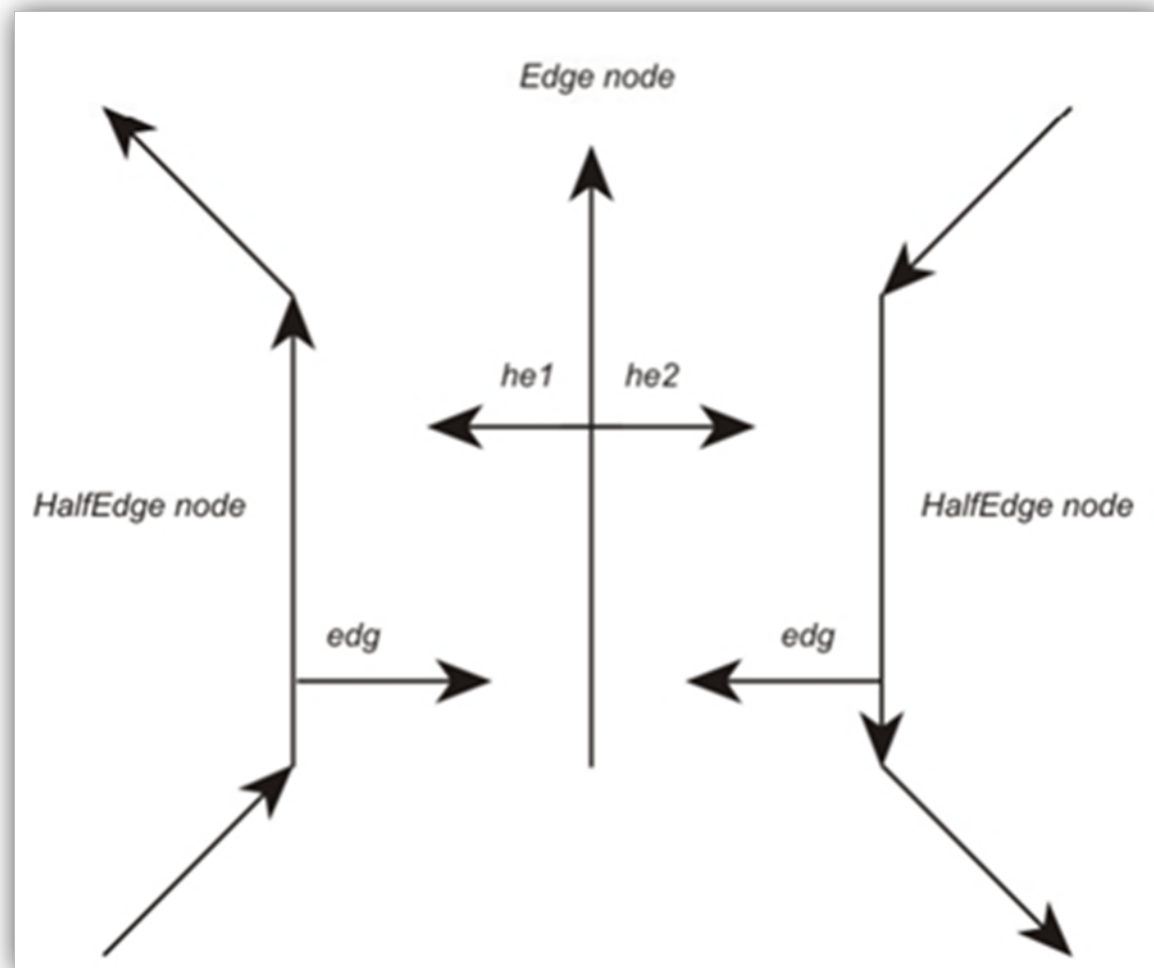
Hierarchy of Topological Levels

- Solid
- Face
- Loop
- *Half-Edge*
- Vertex
- Edge*



Half-Edge Data Structure Entities



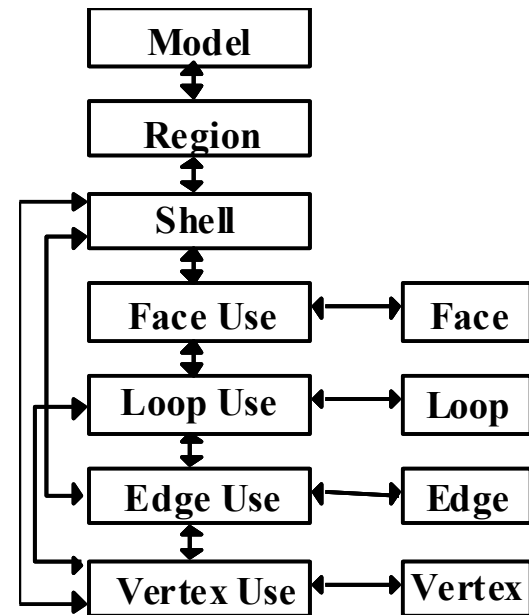
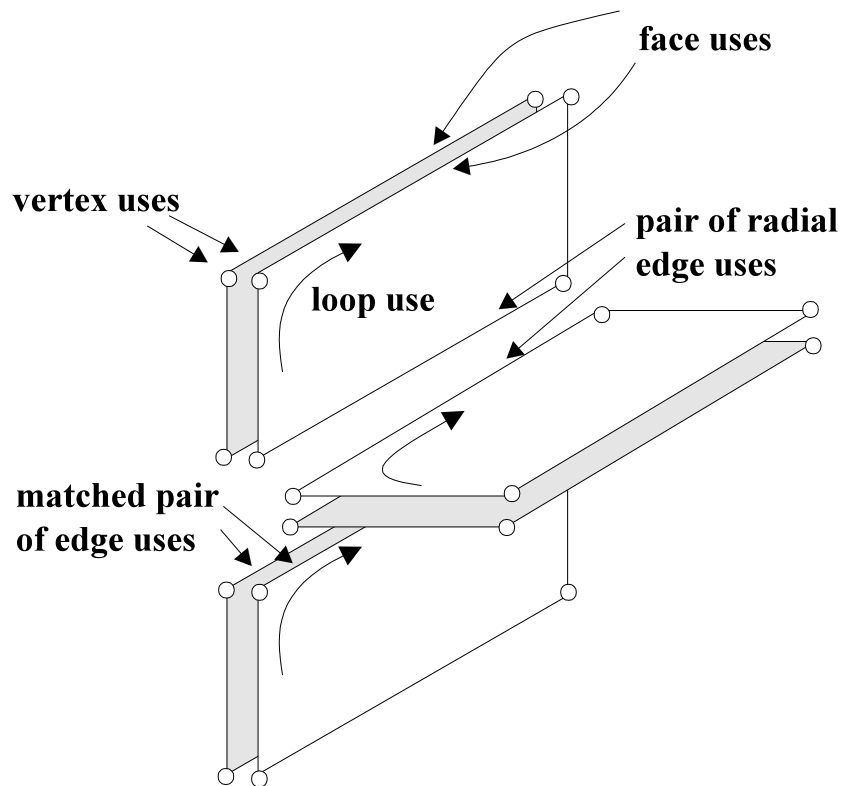
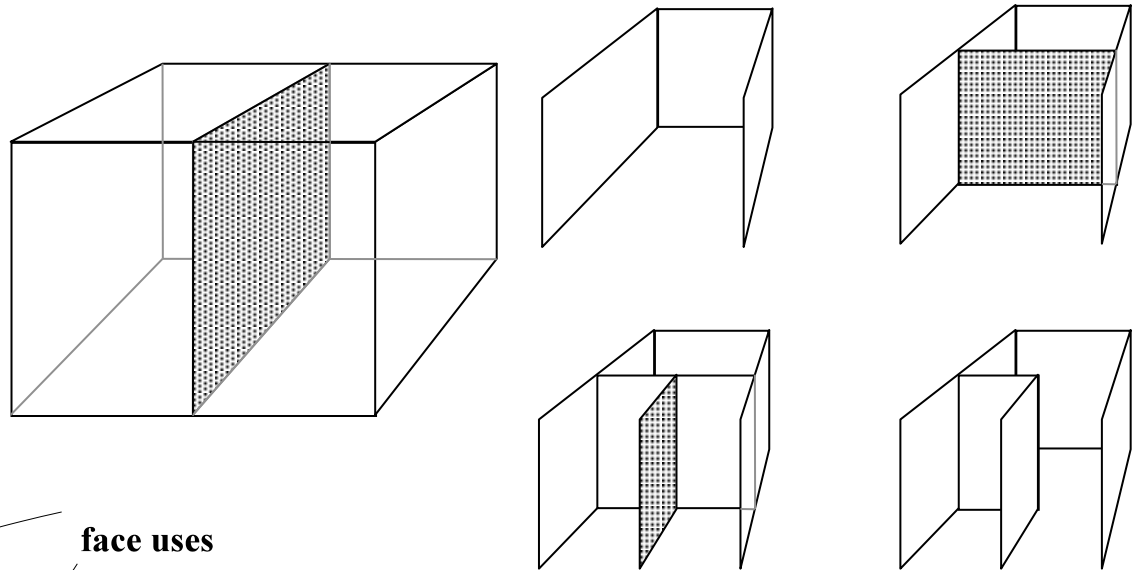


Non-manifold Geometric Modeling

Geometric Modeling

- **Topology in *non-manifold* representations**
 - Application areas of geometric modeling that take advantage of the additional features of non-manifold representation
 - **Modeling** – transition between models, regions detections, storing arbitrary geometric information
 - **Analysis** – implementation of building tools and simultaneous analysis of the model
 - **Representation of heterogeneous objects** – regions with common volumes, coincident faces, internal structures, solids consisting of different materials

Radial-Edge (Weiler 1986)

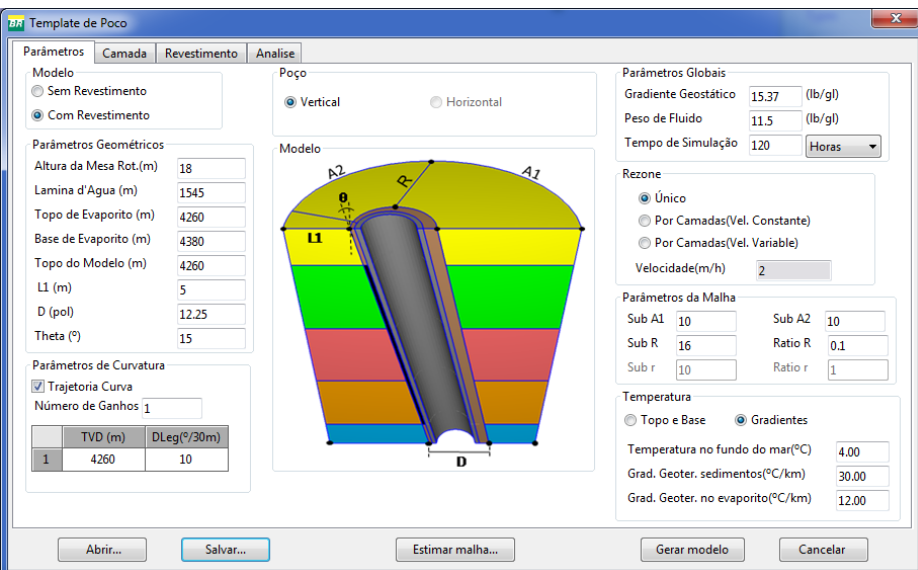
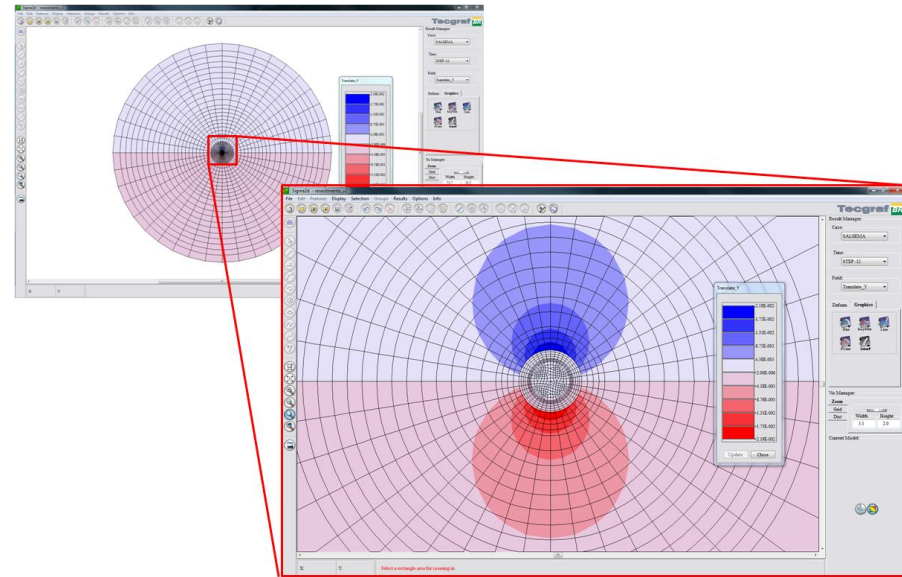
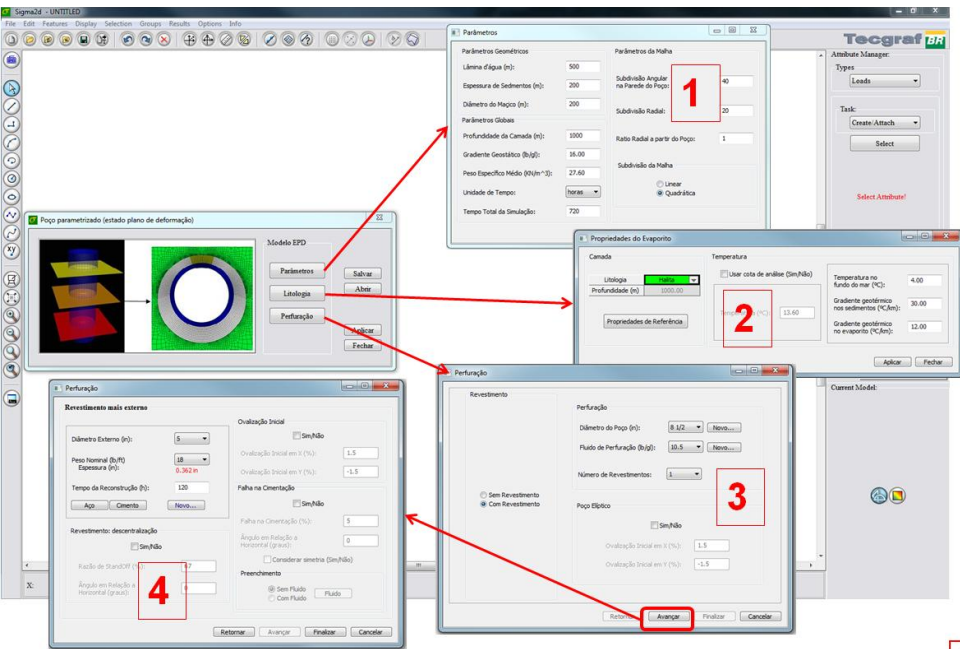


Applications

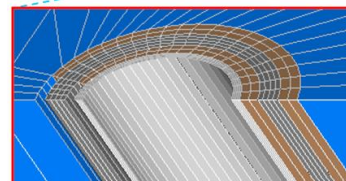
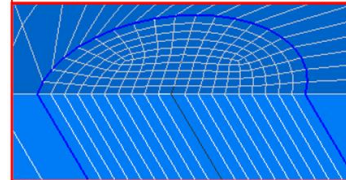
Applications

- Simulation of well bore stability during perforation
- Analysis of well bore integrity (rock, casing, and cementation)
- Simulation of stress field perturbation due to salt rock intrusion
- Simulation of reactivation of geological faults
- Storage of CO₂ and gas in salt cavities
- Design of “torpedo” piles

Simulation of well bore stability and integrity



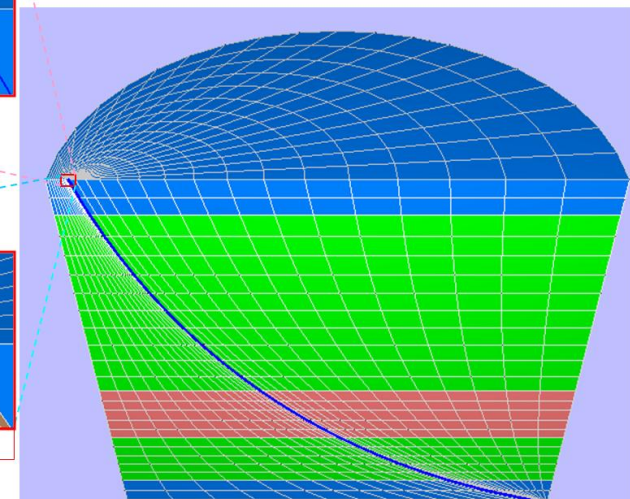
Modelo para análise de **estabilidade** de poço



Modelo para análise de **integridade** de poço

Modelo gerado com template

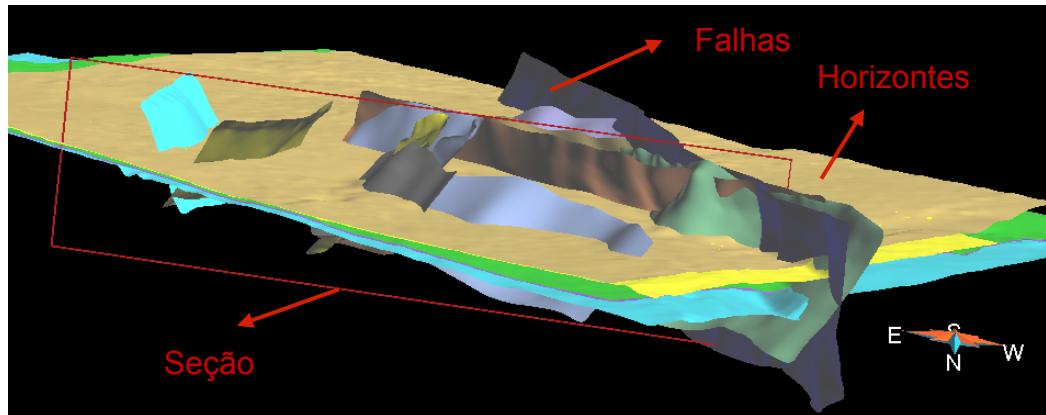
Tempo para preencher os dados = 5 a 20 min (depende do usuário)
Tempo para gerar o modelo = 30 seg



Simulation of reactivation of geological faults

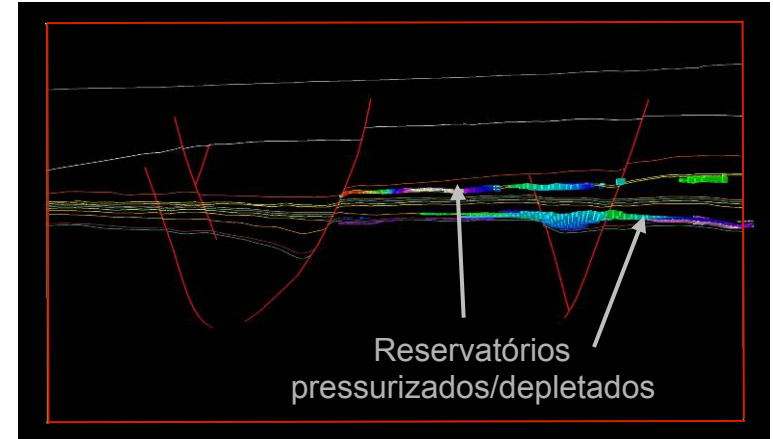
3D geological surface patches

(GoCAD)



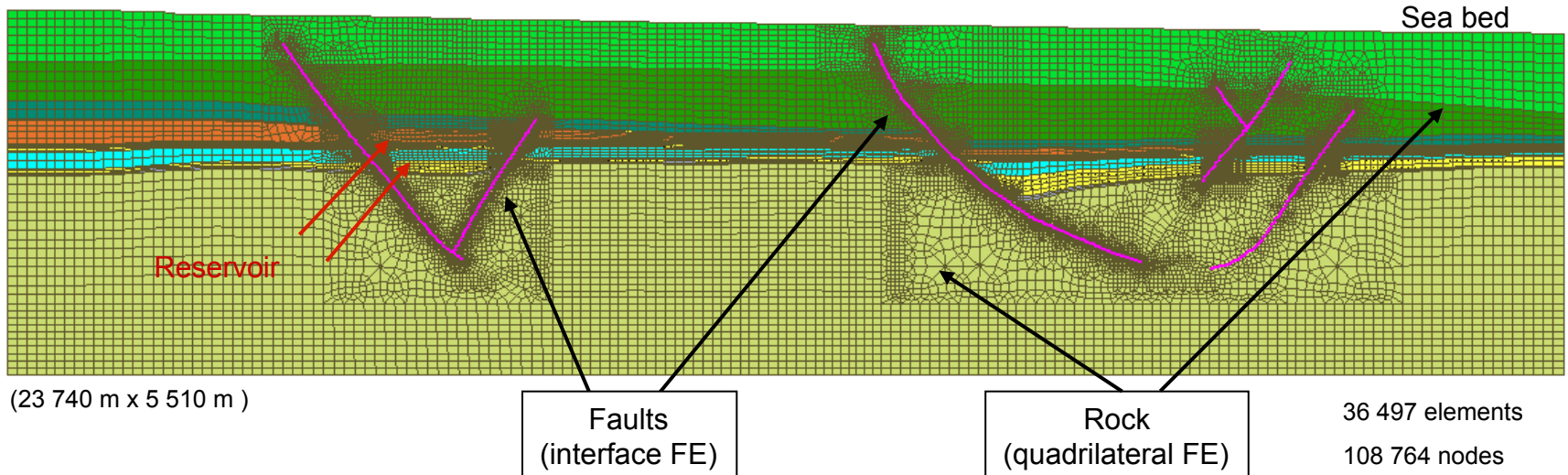
Cross section

(GoCAD)



Effectic stress FE elasto-plastic analysis

(Sigma2D)



Simulation of reactivation of geological faults

Effective stress FE elasto-plastic analysis

(Aeepecd2D e Aeepec3D)

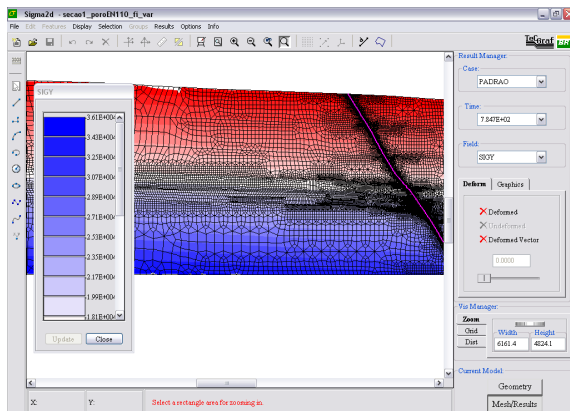
```
#
%HEADER
Sigma2d (5.13) - AEEPEC2D (2.3): Mon Jun 23 19:01:04 2008
#
```

```
%PLATFORM, WINDOWS
#
%SOLVER, DIRECT, NAME=SNLL
#
```

```
%NODE
102068
1 11867.9 -1795.62
2 11828.4 -1744.31
3 11867.9 -1749.44
4 11786.2 -1780.61
5 11788.8 -1739.19
6 11749.6 -1734.10
7 11744.0 -1815.40
8 11783.6 -1822.03
9 11825.8 -1831.91
10 11776.8 -1858.17
11 11867.9 -1841.80
12 11867.9 -1887.98
13 11707.3 -1768.89
14 11710.3 -1729.02
15 11671.4 -1723.97
16 11754.2 -1888.01
17 11704.4 -1808.77
18 11665.5 -1804.82
19 11701.4 -1845.23
20 11698.4 -1881.70
21 11697.6 -1912.16
```

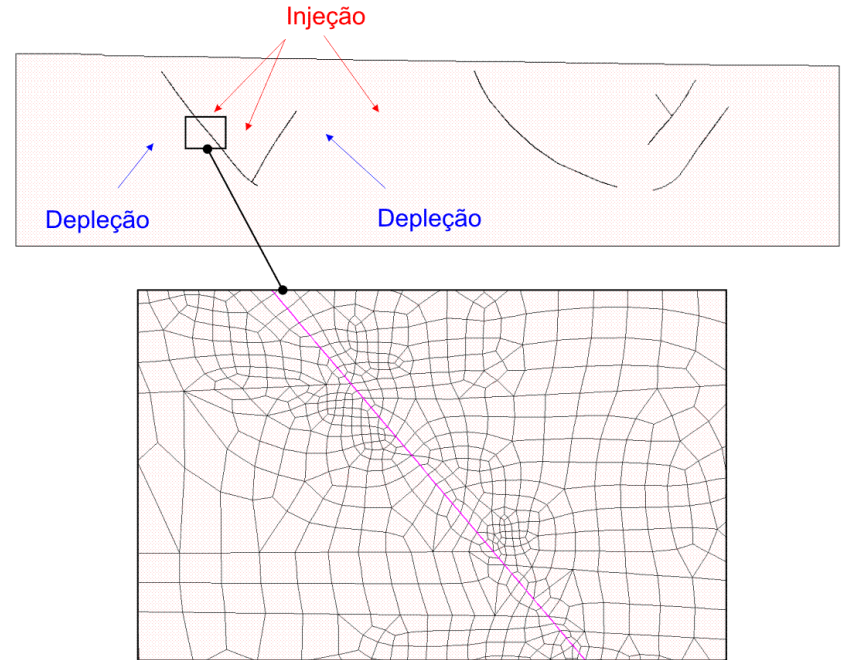
```
C:\Documents and Settings\admin\Desktop\teste\AEEPEC2D3...
FORNEÇA O NOME DO ARQUIVO DE ENTRADA DE DADOS
falha45.dat
NUMERO DE ELEMENTOS DA MATRIZ CCS= 1297655
INCREMENTO = 1 TEMPO = 1.000E-04
INCREMENTO = 2 TEMPO = 5.000E+02
INCREMENTO = 3 TEMPO = 1.000E+03
INCREMENTO = 4 TEMPO = 1.500E+03
INCREMENTO = 5 TEMPO = 2.000E+03
INCREMENTO = 6 TEMPO = 2.500E+03
```

(Sigma2D e Sigma3D)

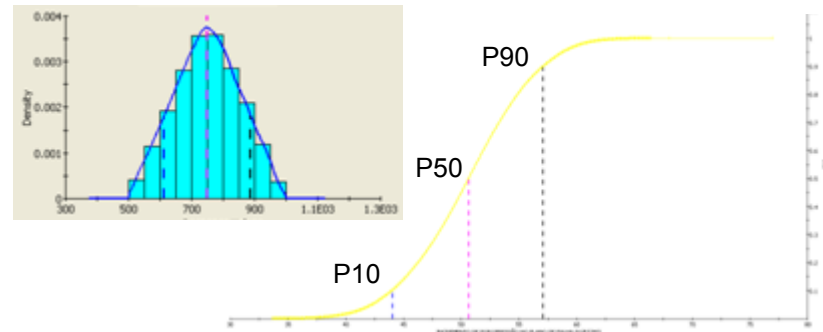


Determination of highest injection pressure

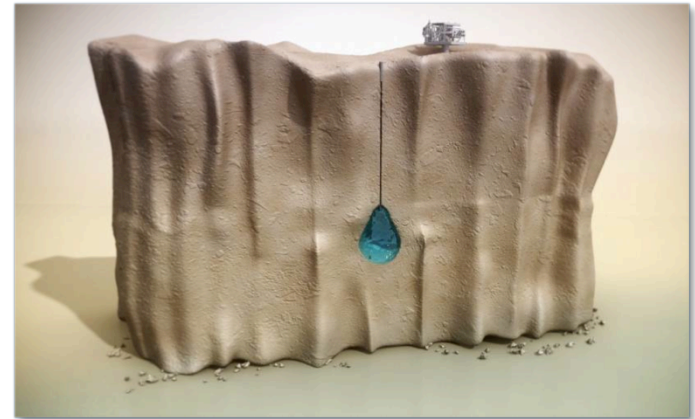
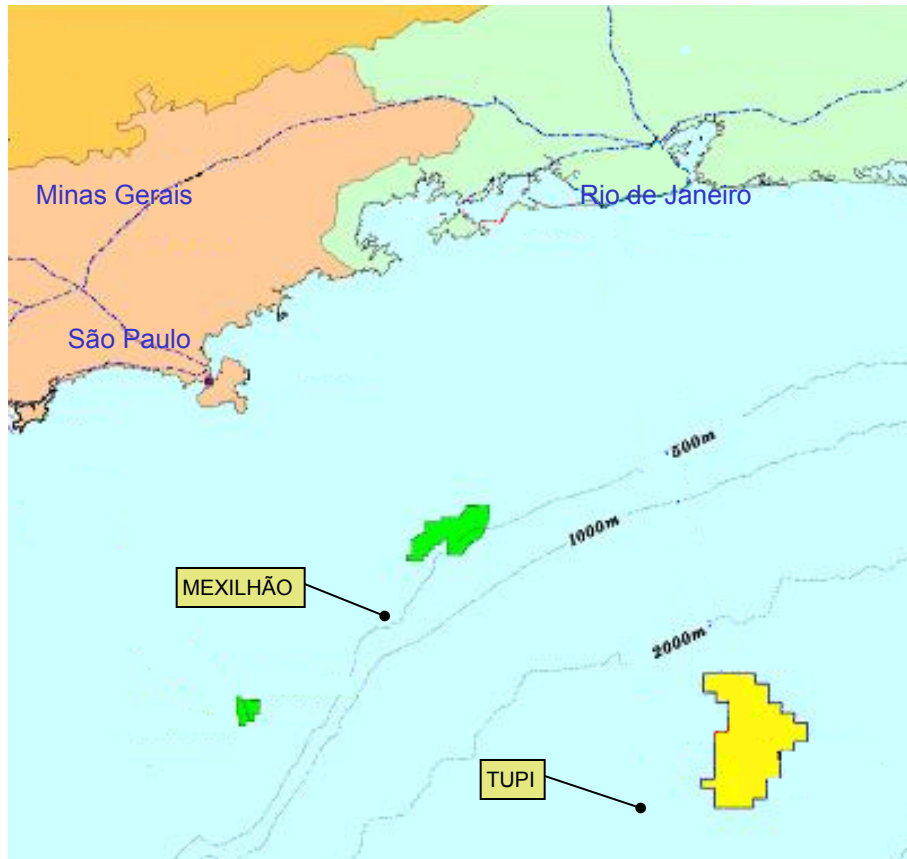
Deterministic analysis



Stochastic analysis



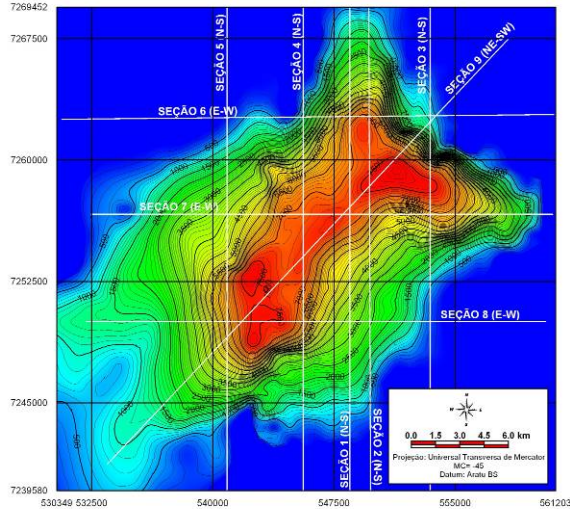
Storage of CO₂ and gas in salt cavities



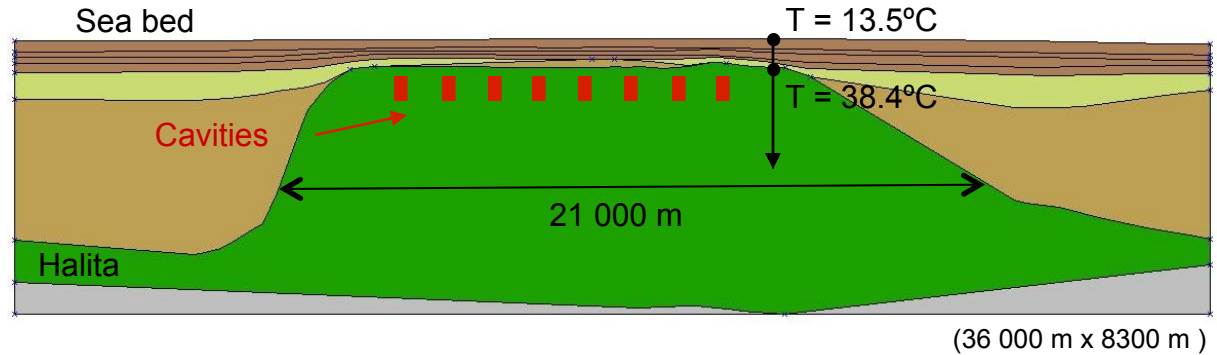
- Mexilhão
- Tupi

Storage of CO₂ and gas in salt cavities

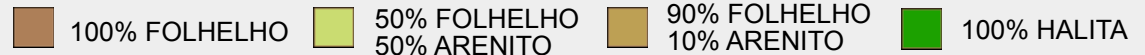
Halita surface contour



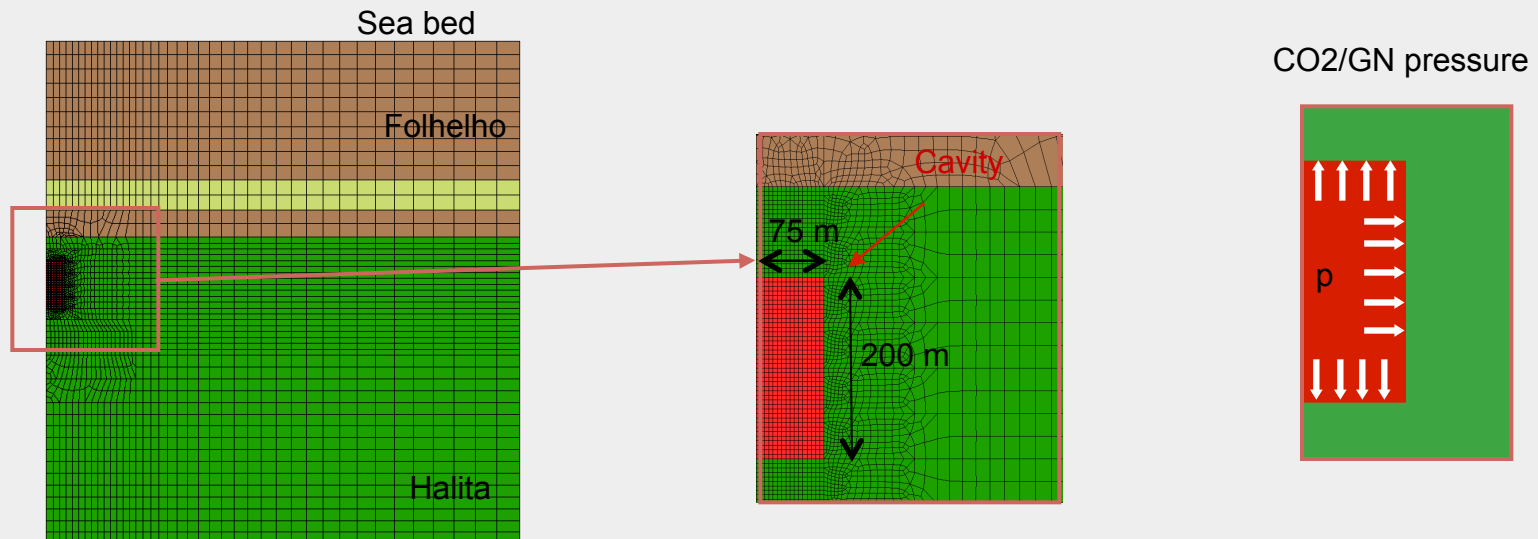
Geolocial section



Litology



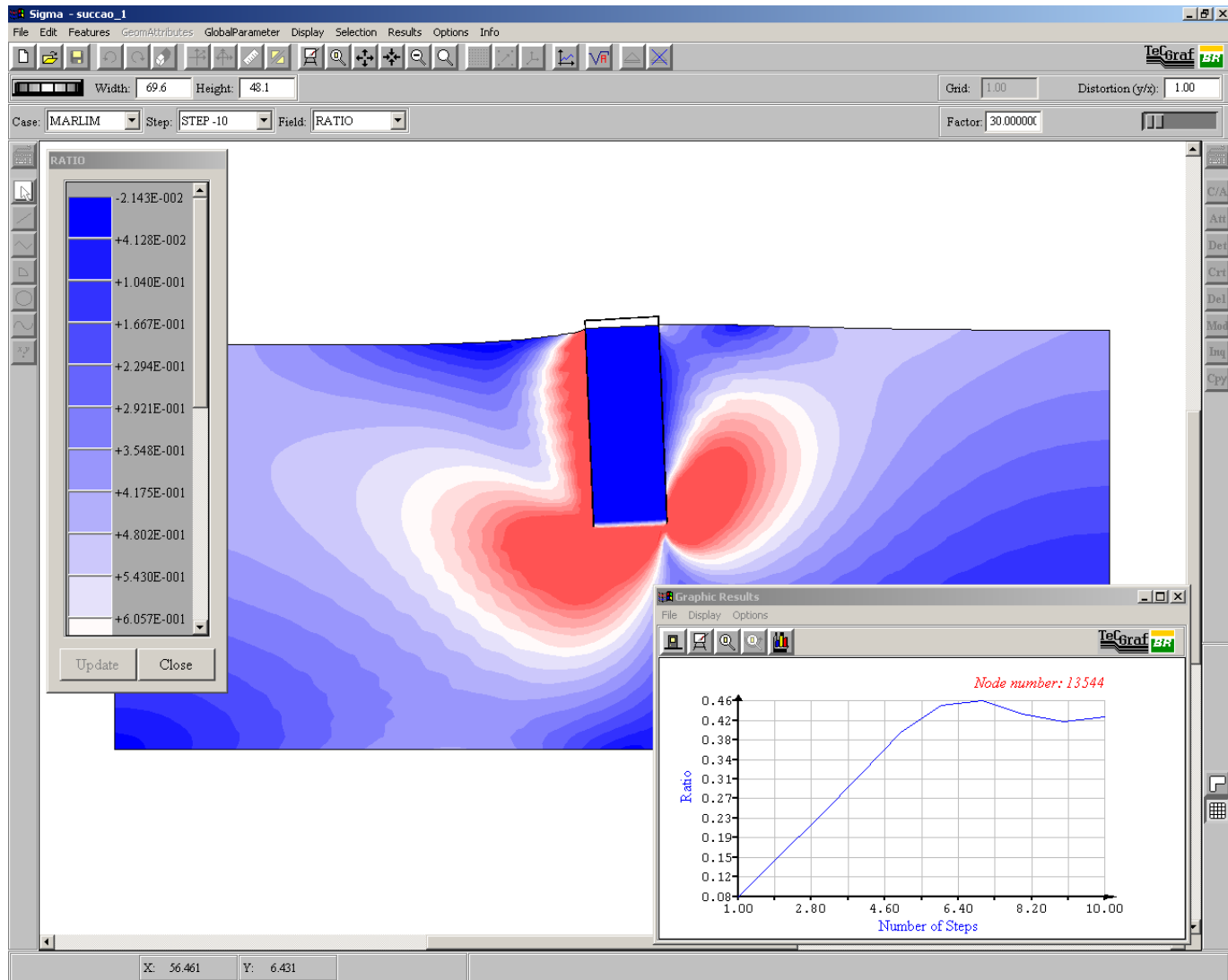
Axysimetric elastic-plastic FE stress analysis



Design of “torpedo” piles

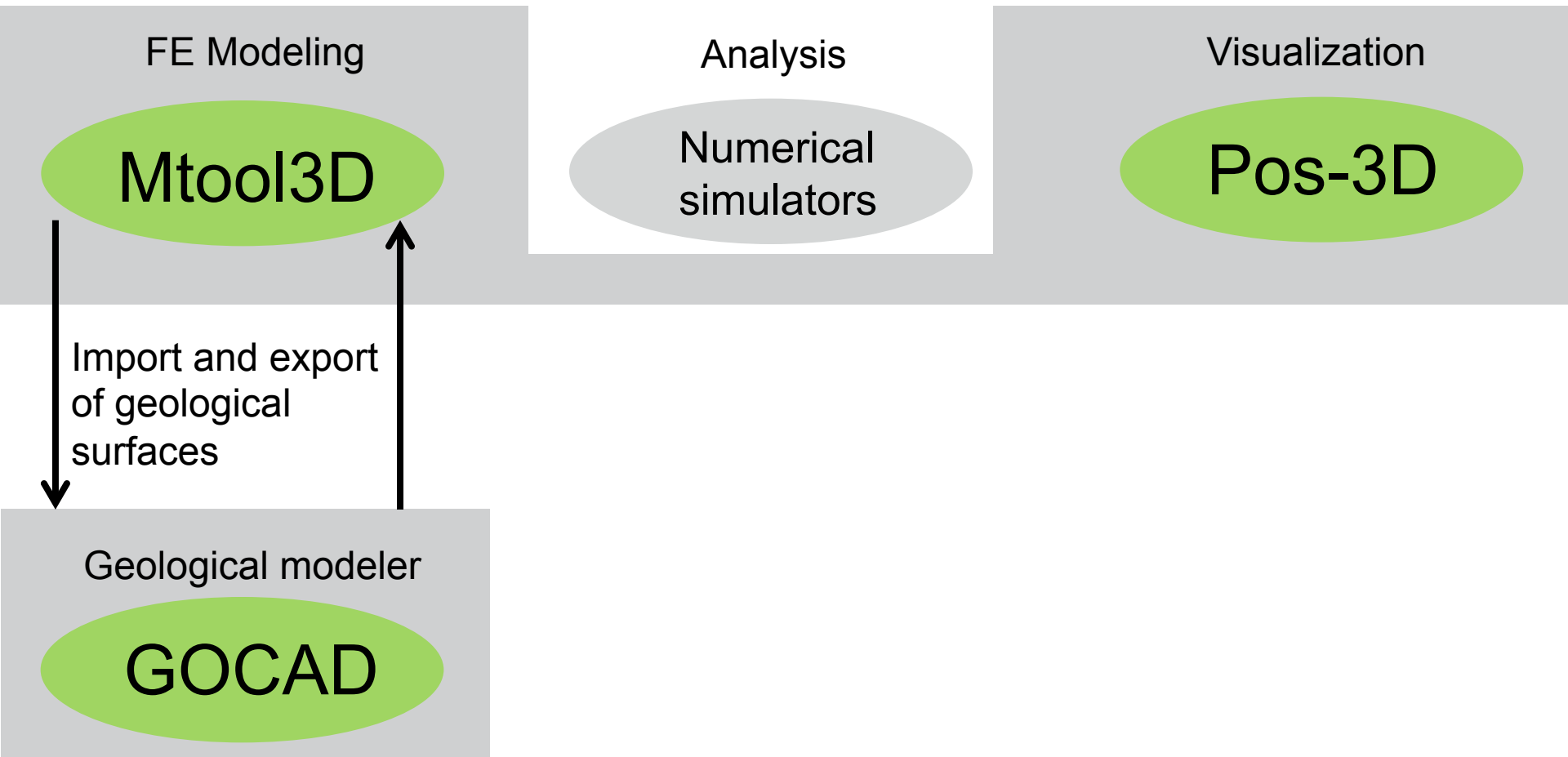


Design of "torpedo" piles



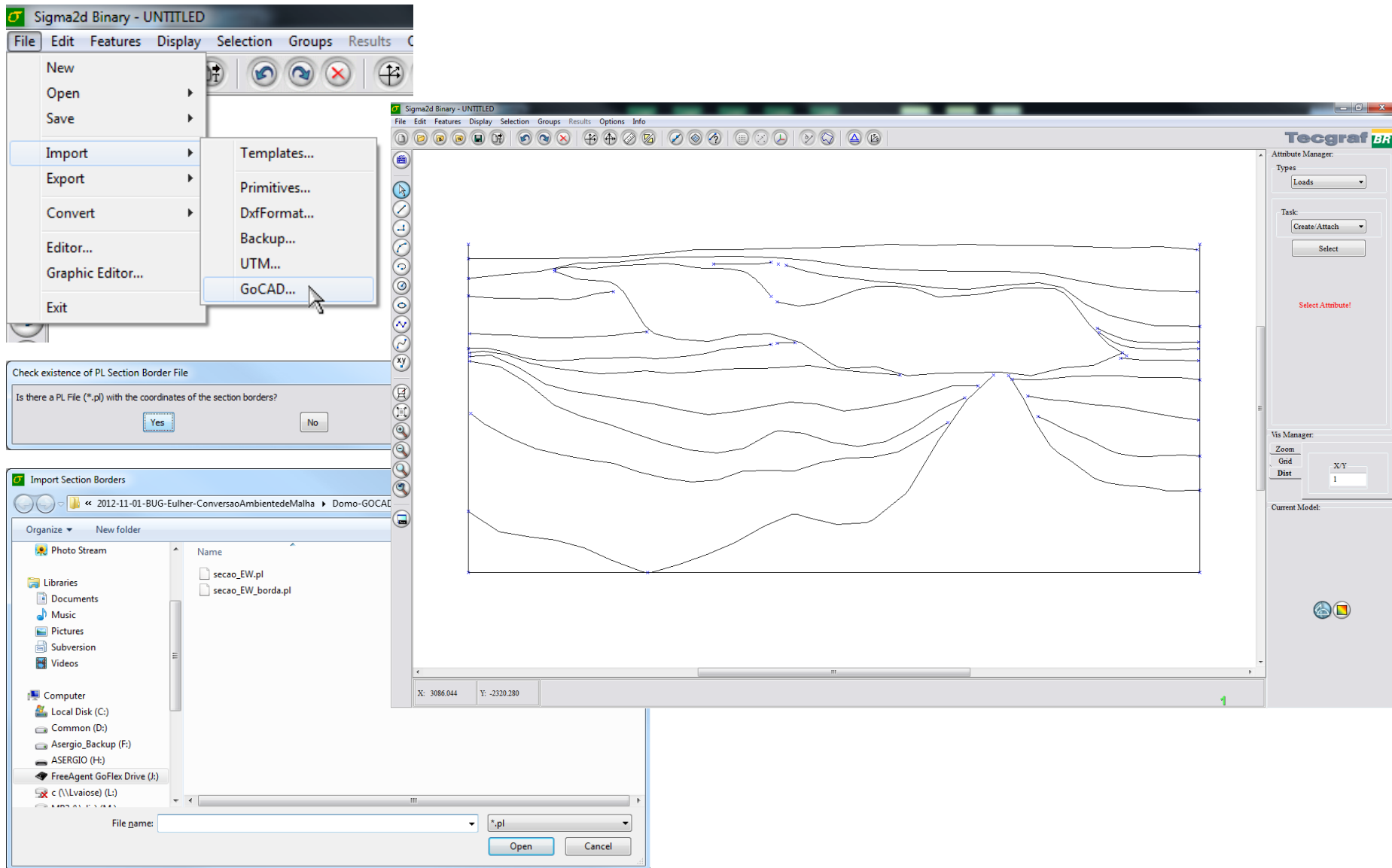
Workflow of 3D modeling and visualization

Sigma3D

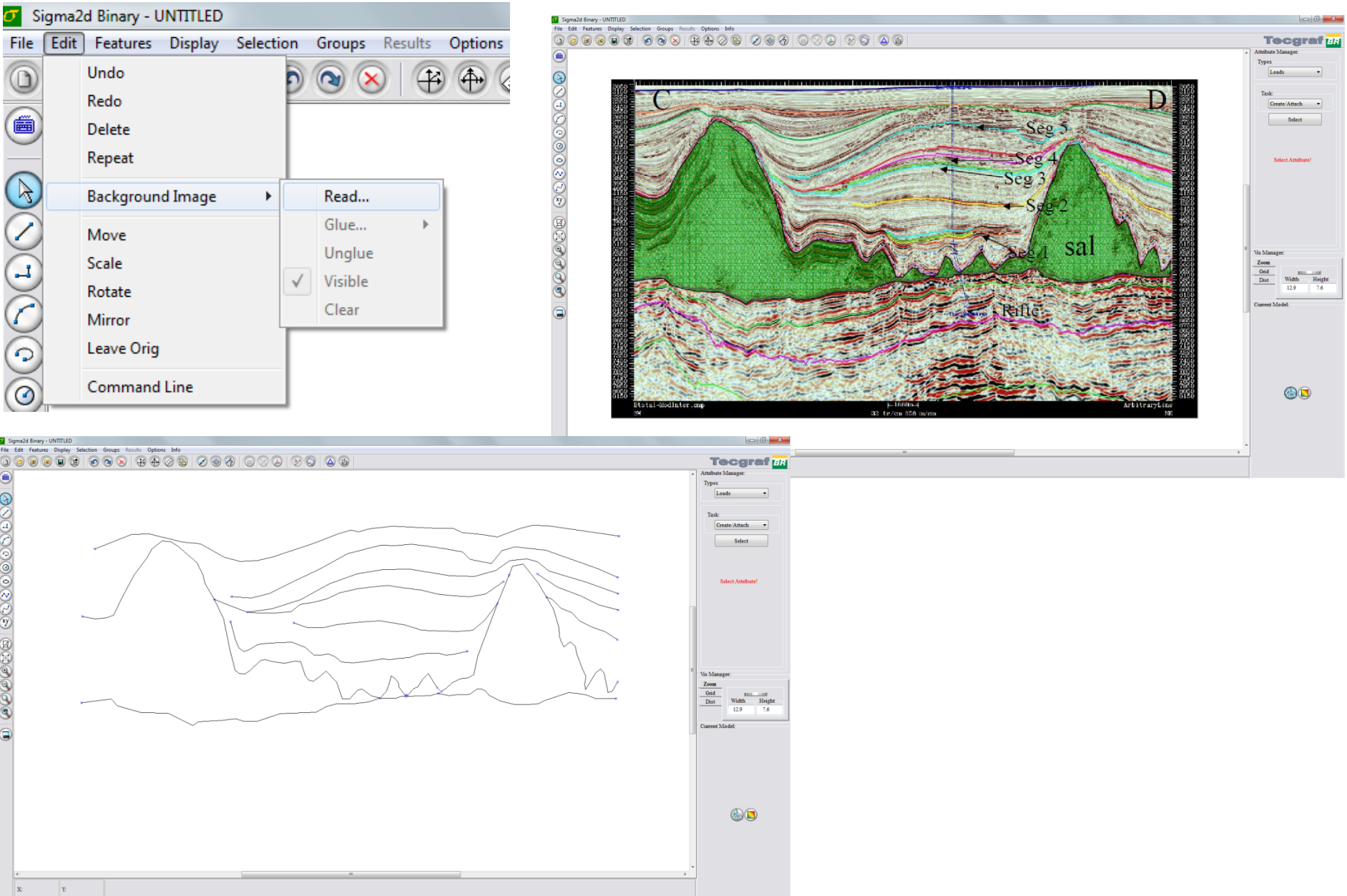


- Sigma2D
 - Mtool – Mesh generation tool 2D
 - Mview – Mesh visualization tool 2D

Mtool – Several input formats

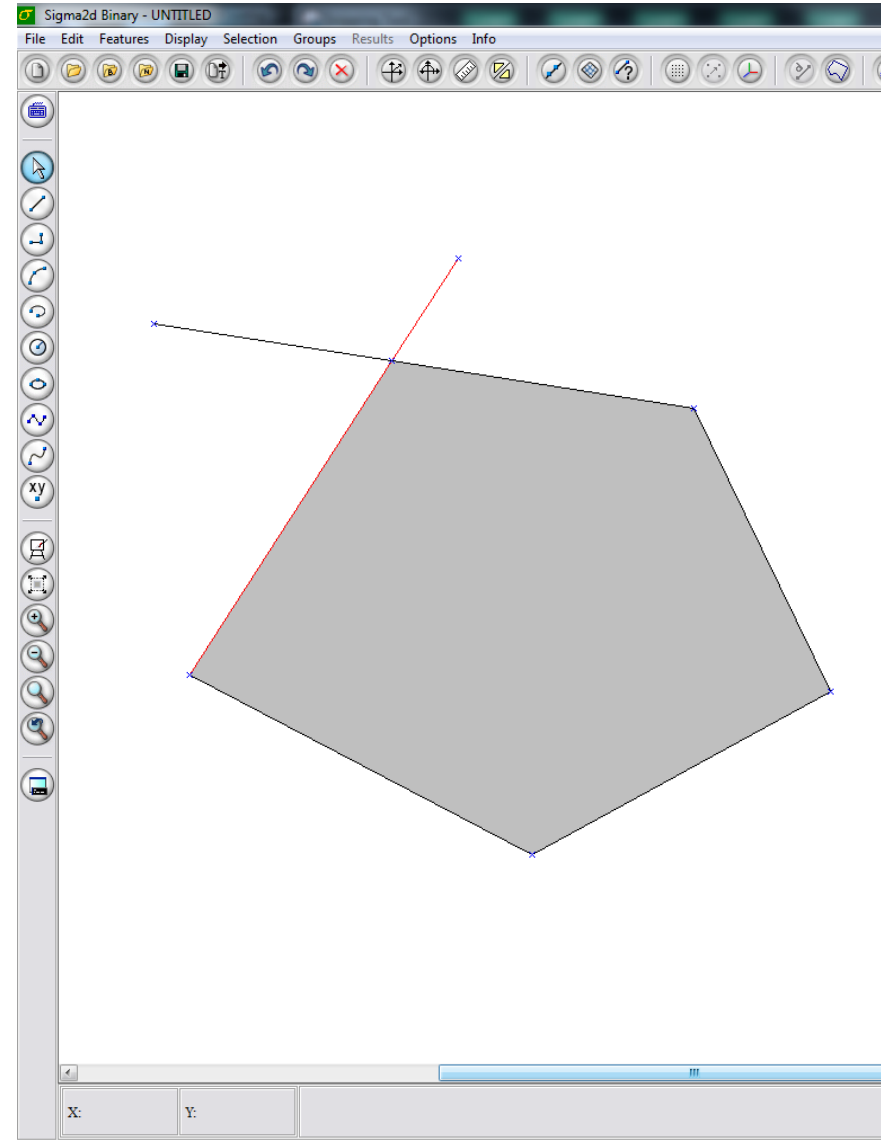
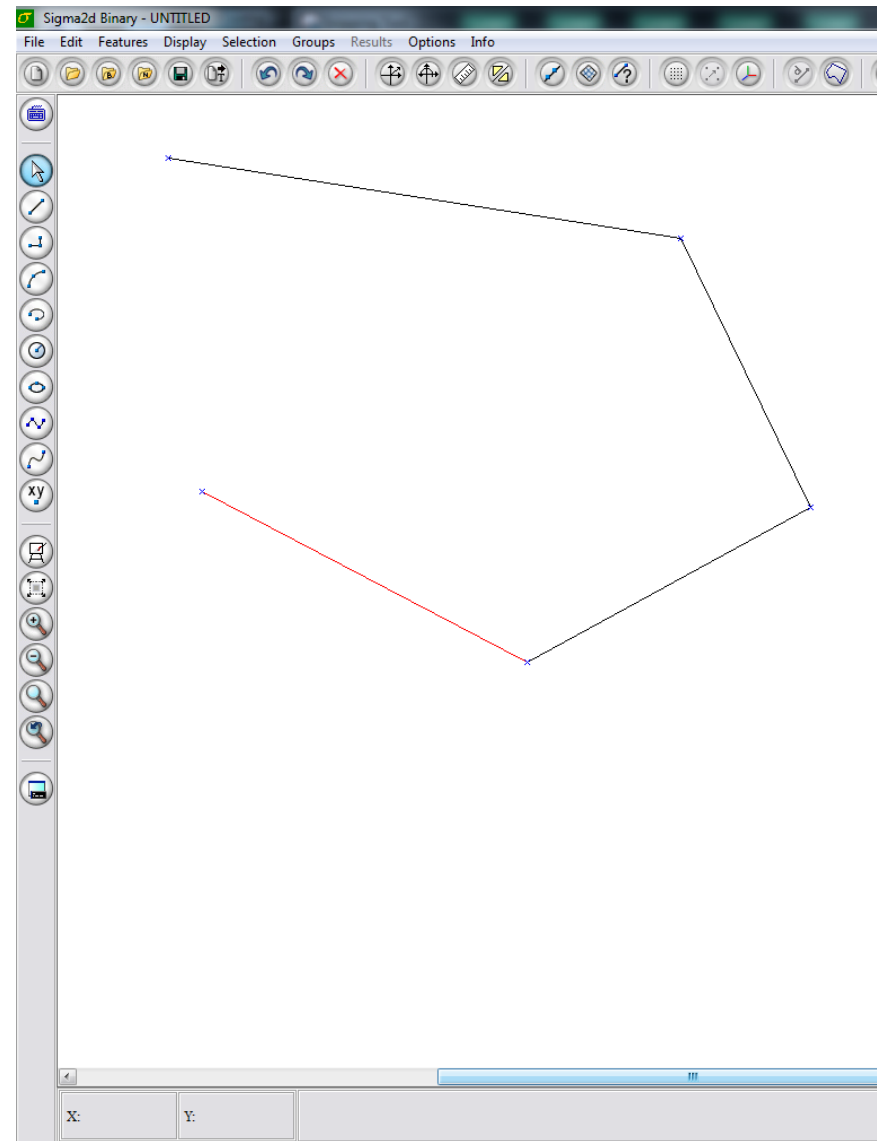


Mtool – Digitizing on top of background image

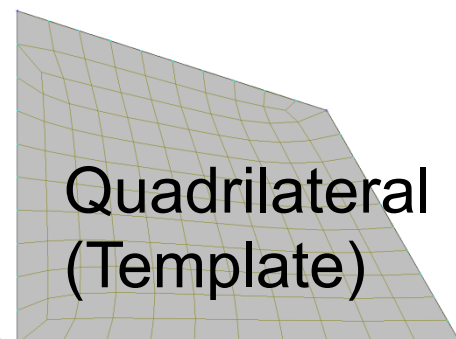
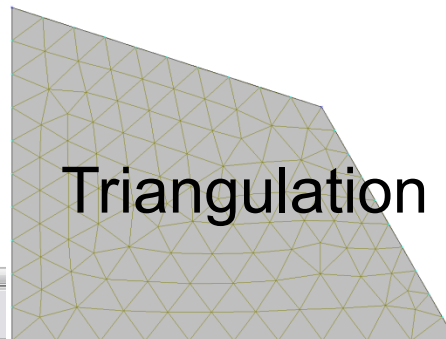
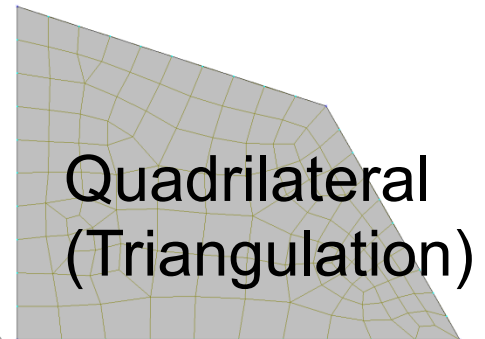
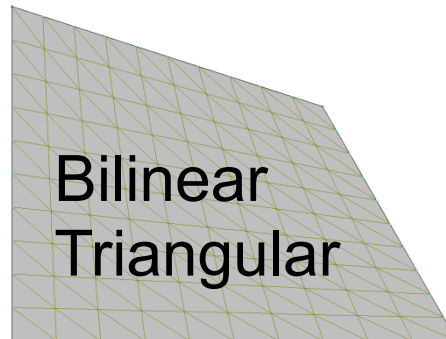
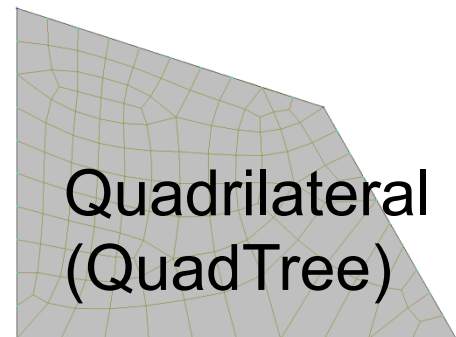
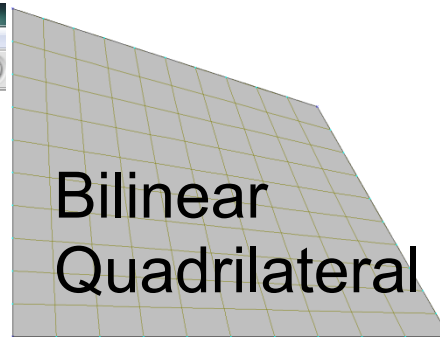
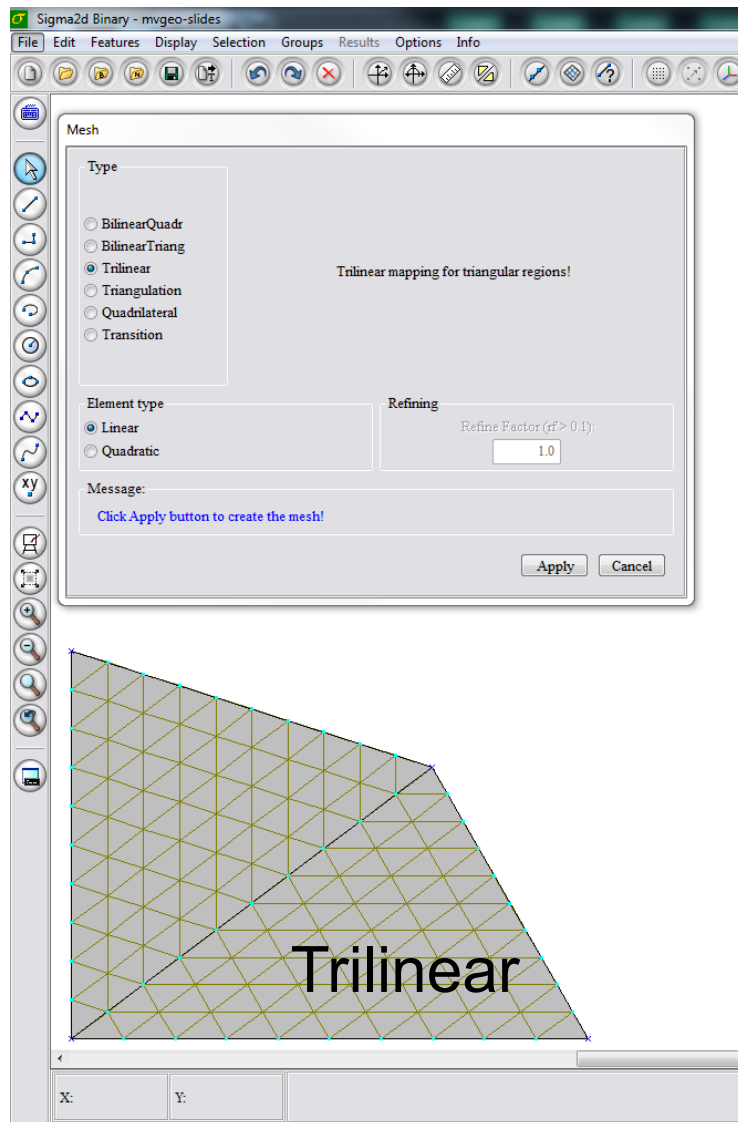


Mtool – Several modeling tools

Curve insertion; automatic region recognition; etc.

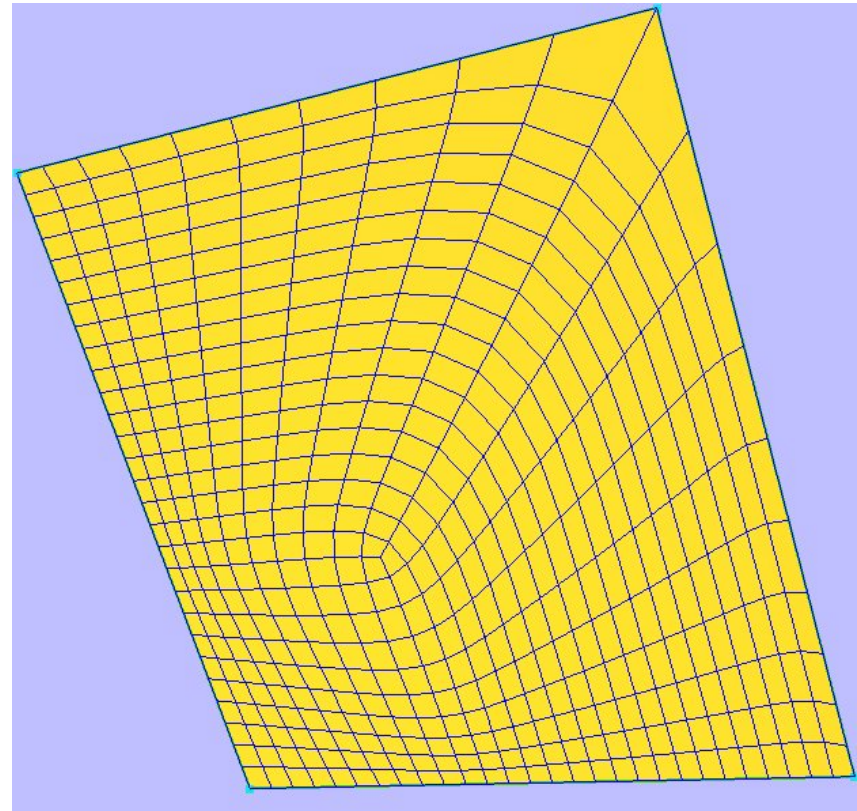
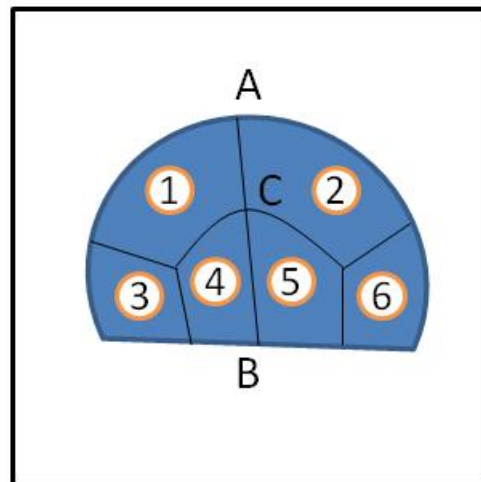
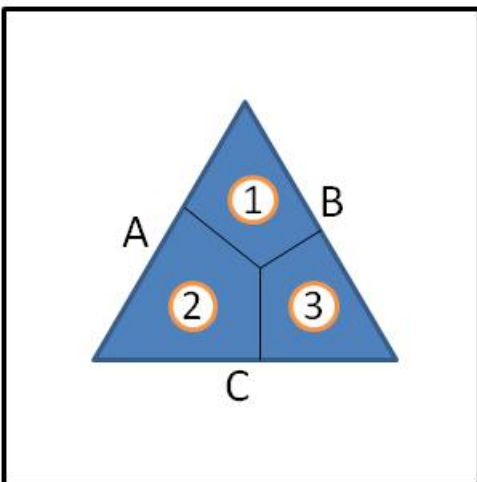
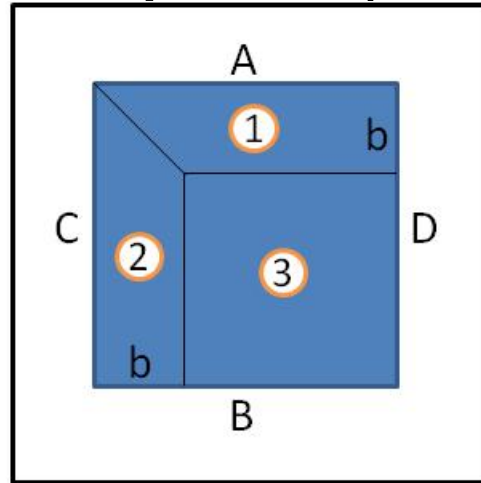
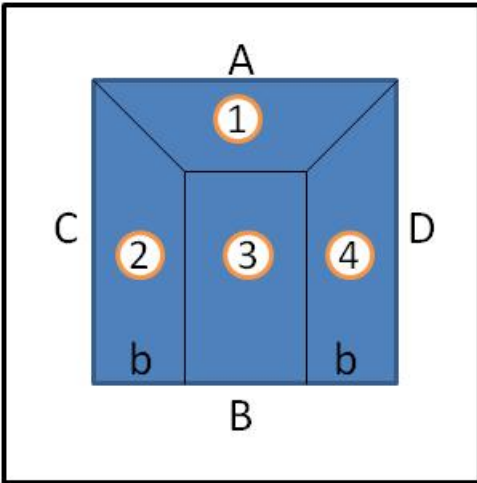


Mtool – Mesh generation algorithms

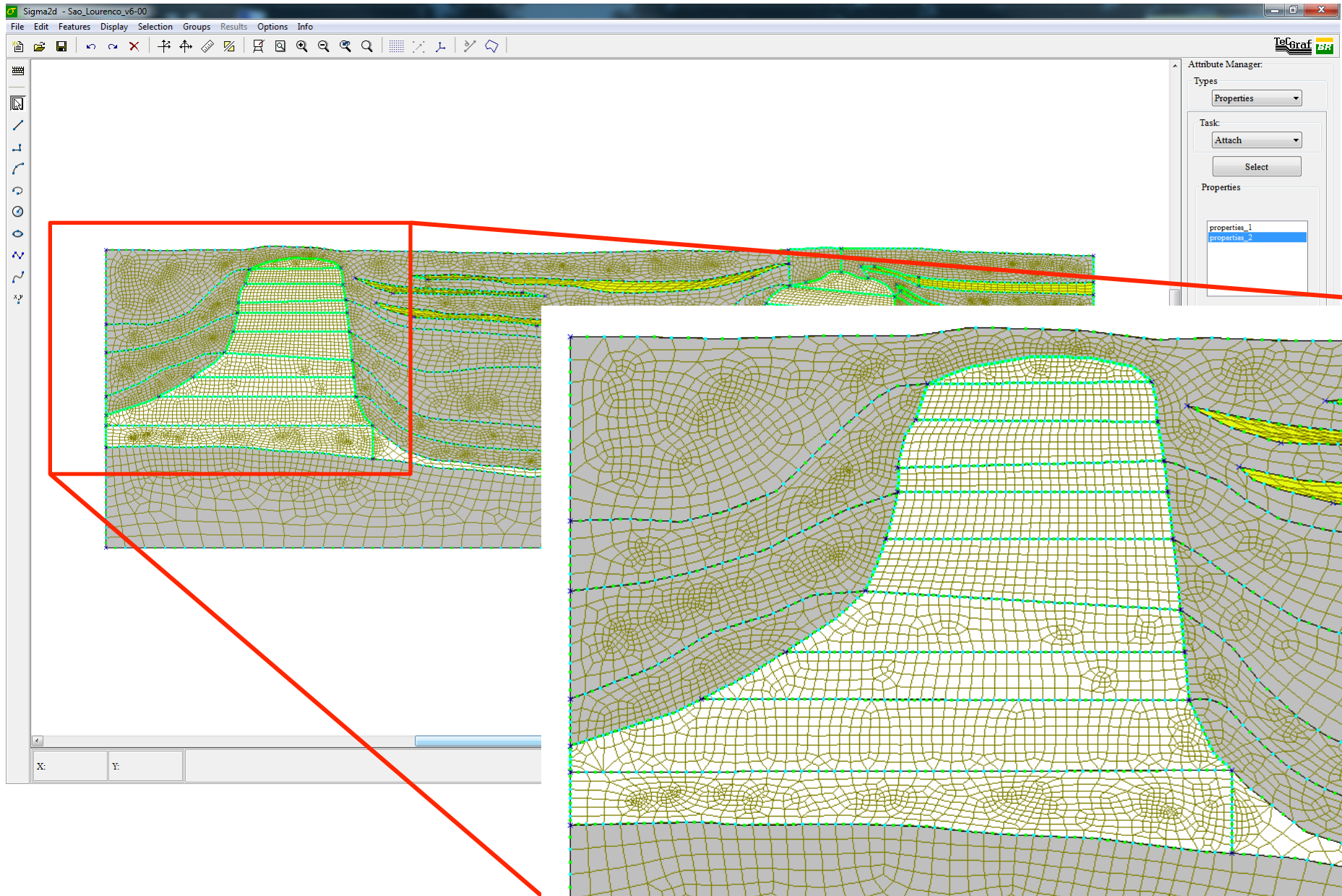


Mtool – Mesh generation algorithms

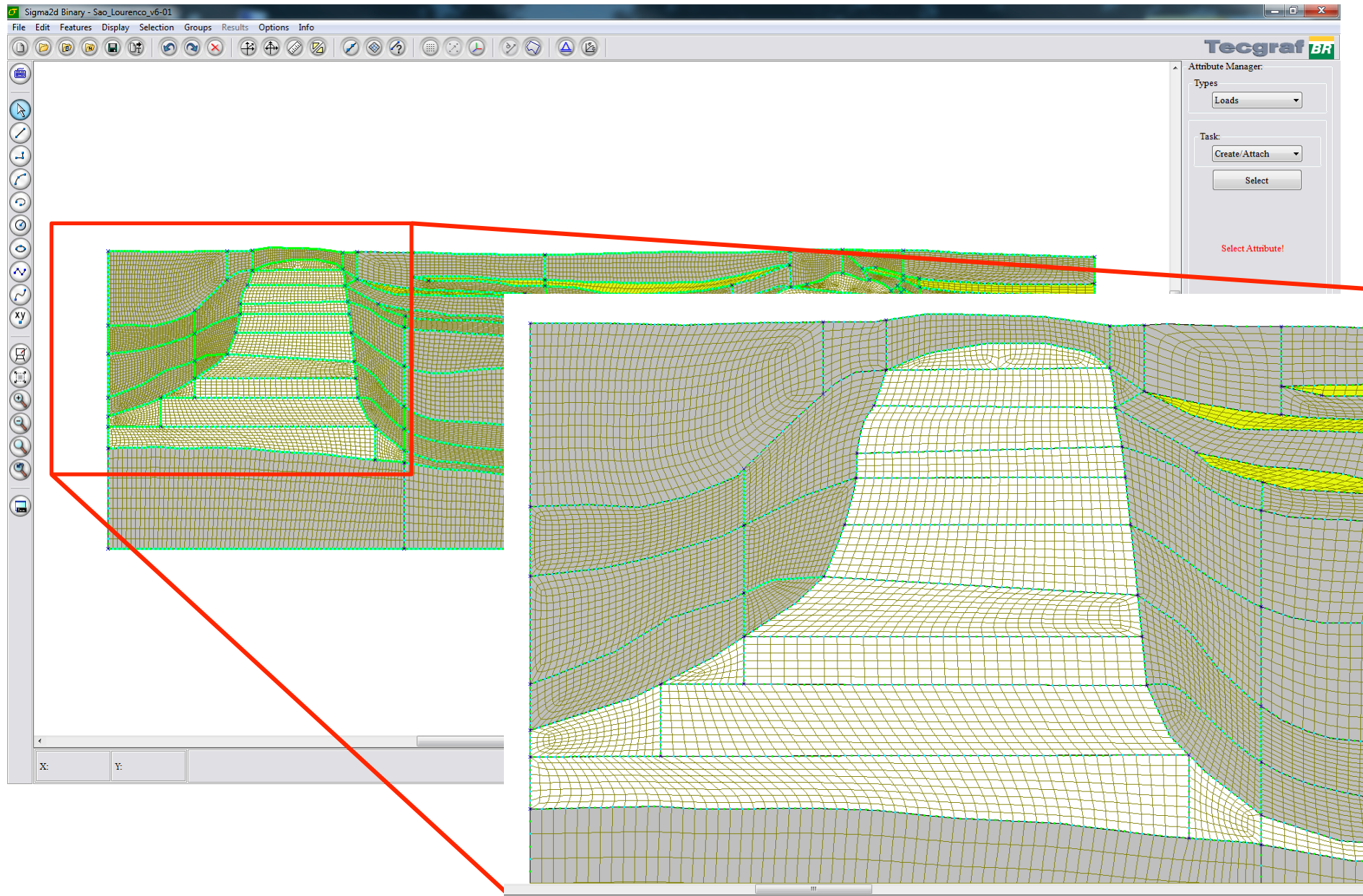
Quadrilateral template (Antonio Miranda)



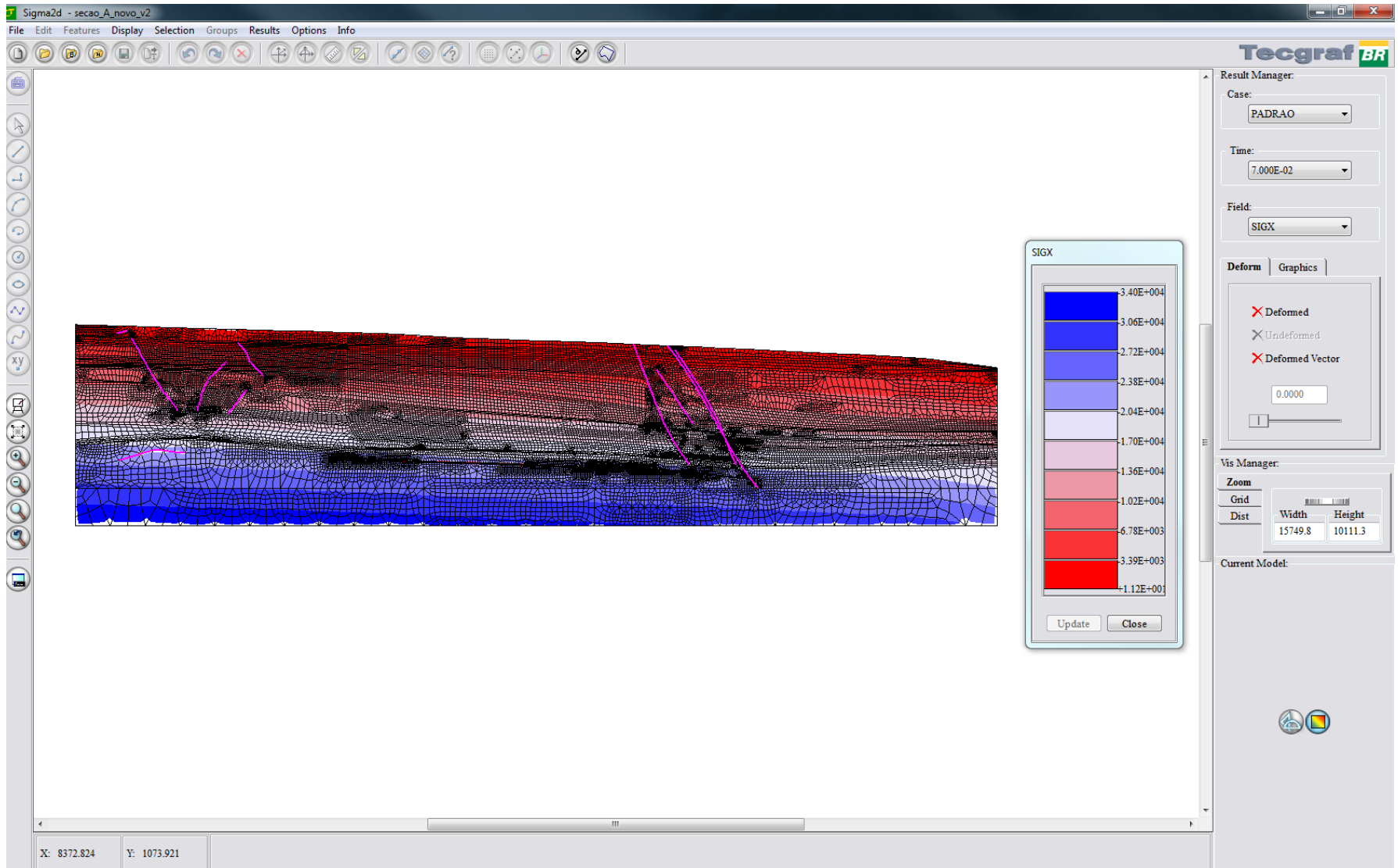
2D subsurface model – Mesh generated using Qmorph



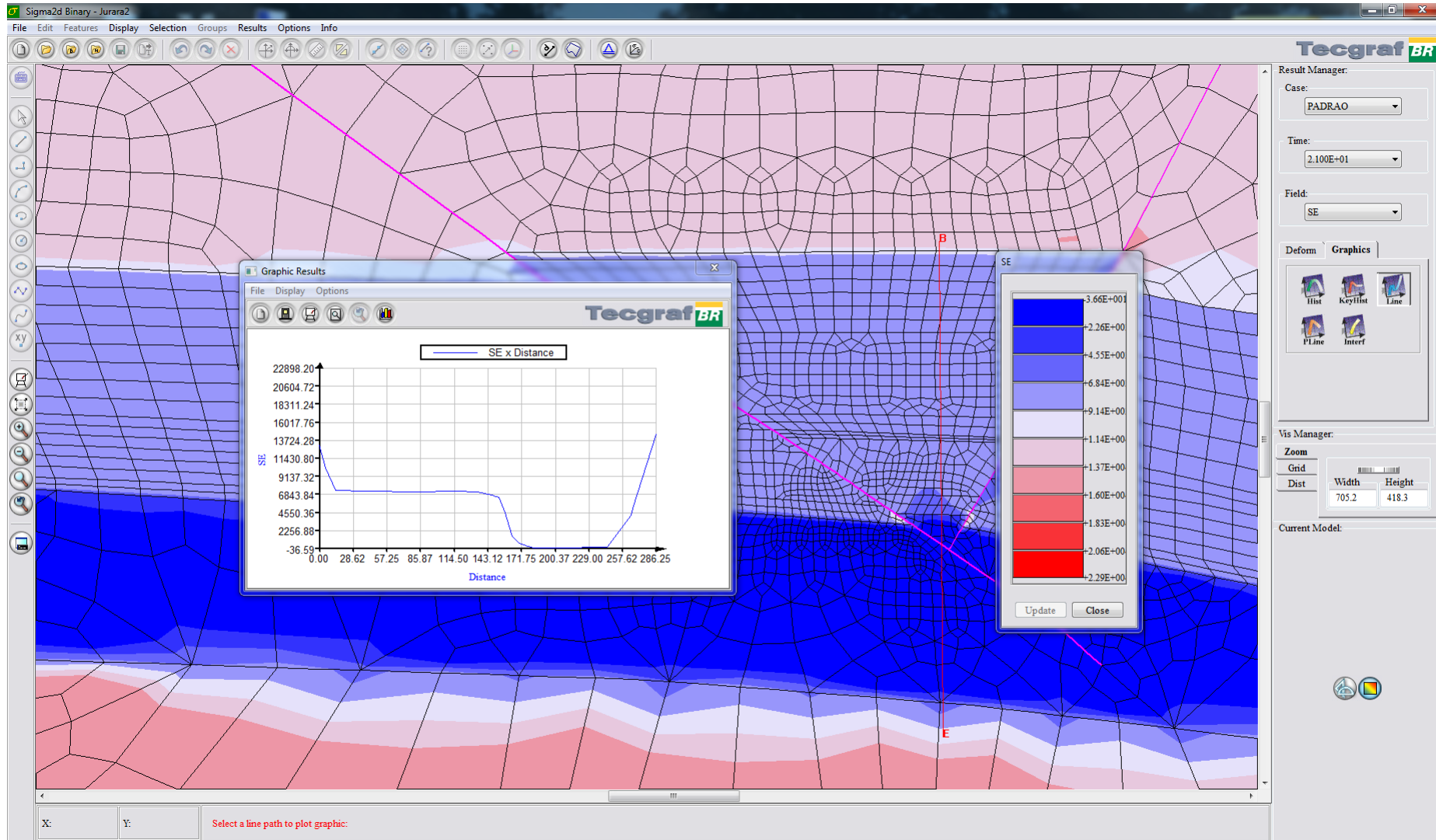
2D subsurface model – Mesh generated using quad-template



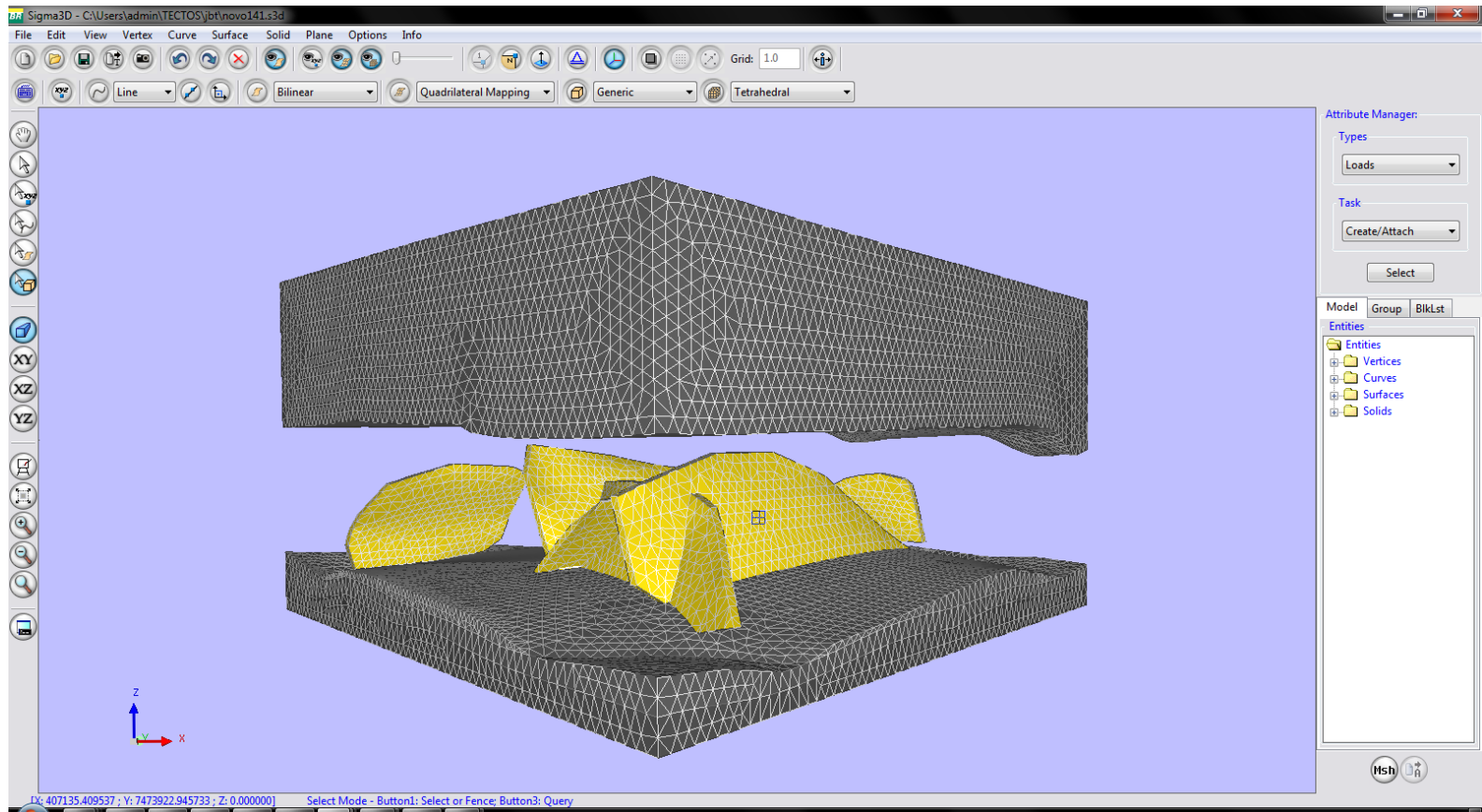
Mview – Result analysis



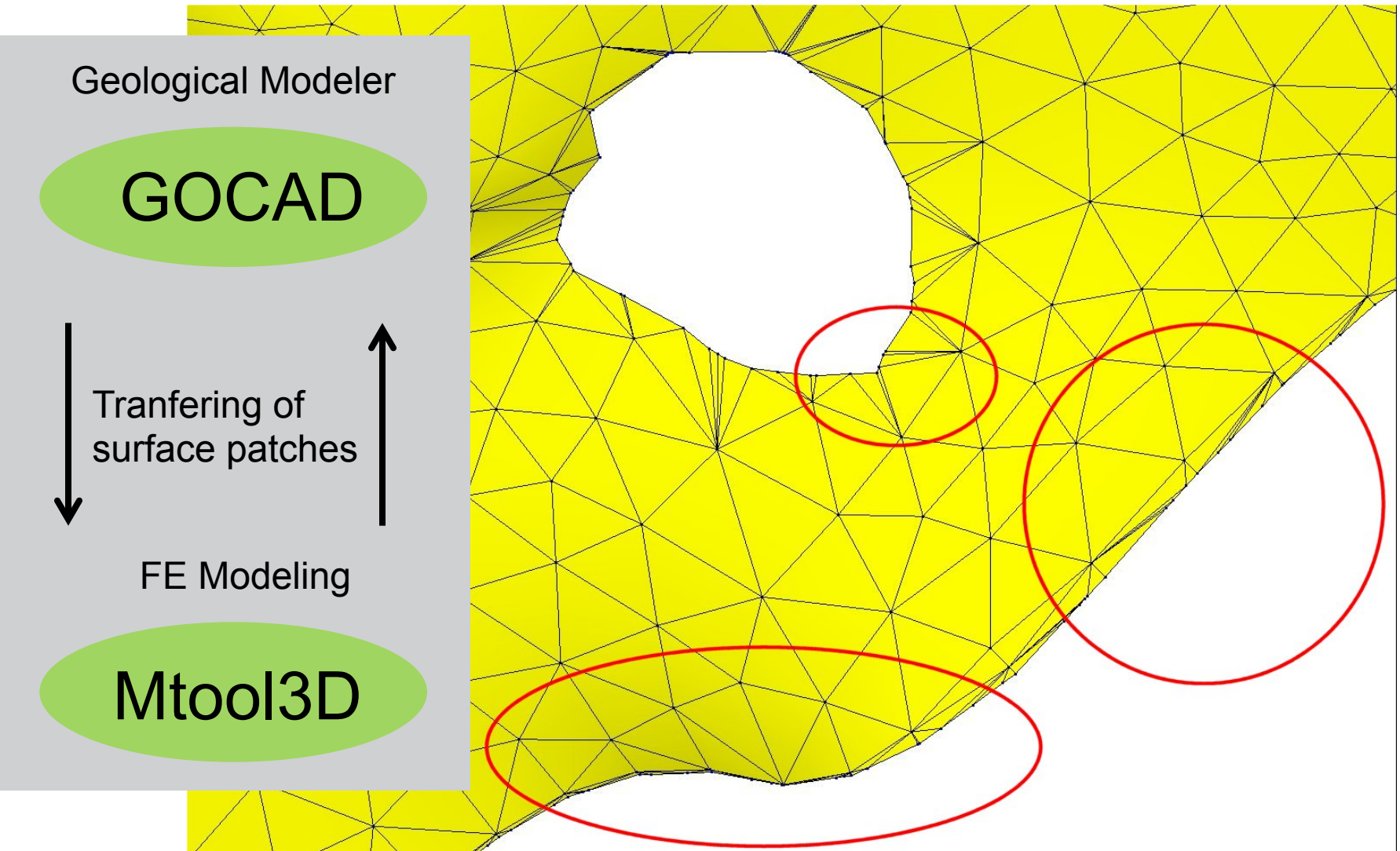
Mview – Result analysis



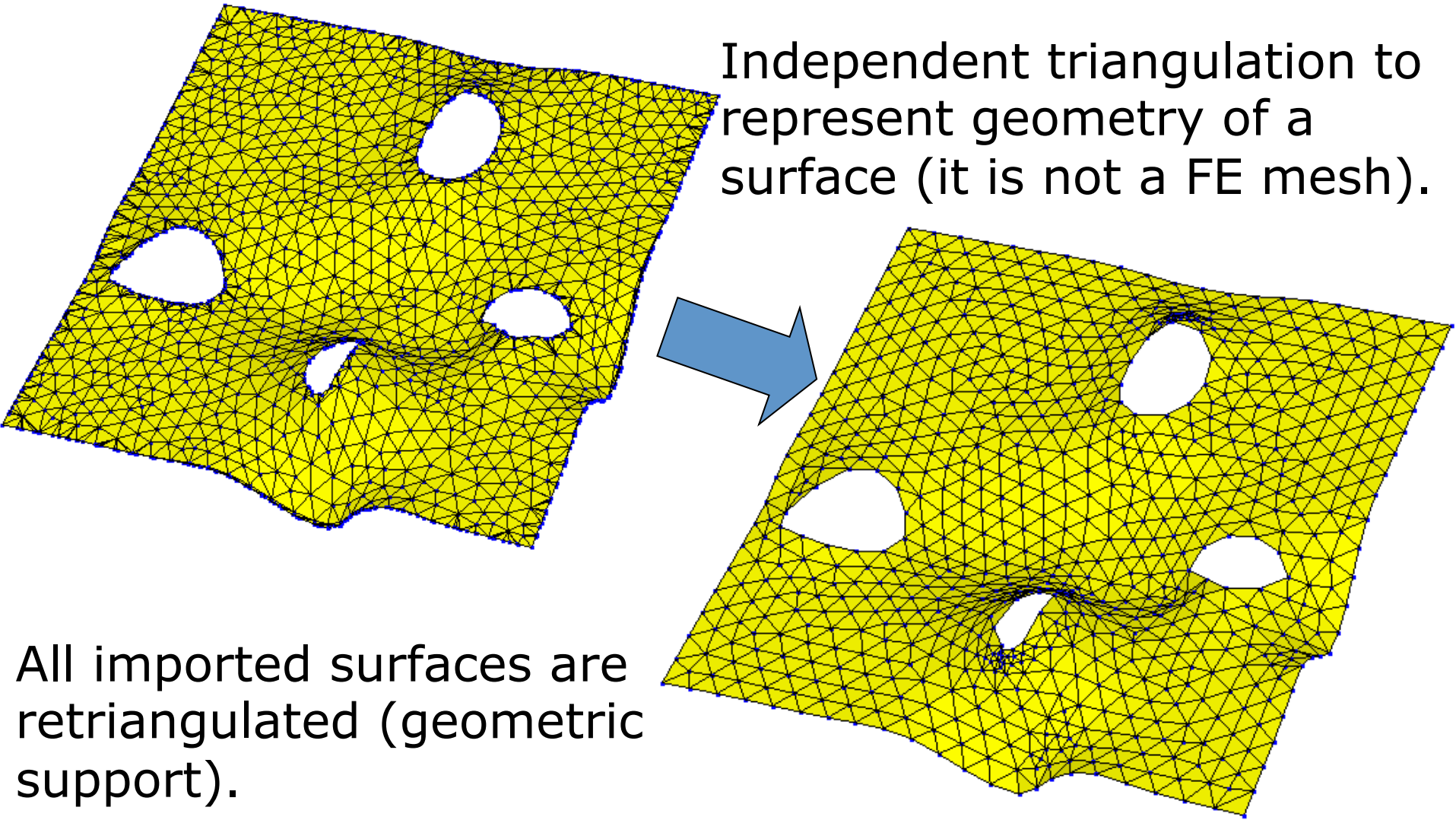
- Mtool3D – Mesh generation tool 3D



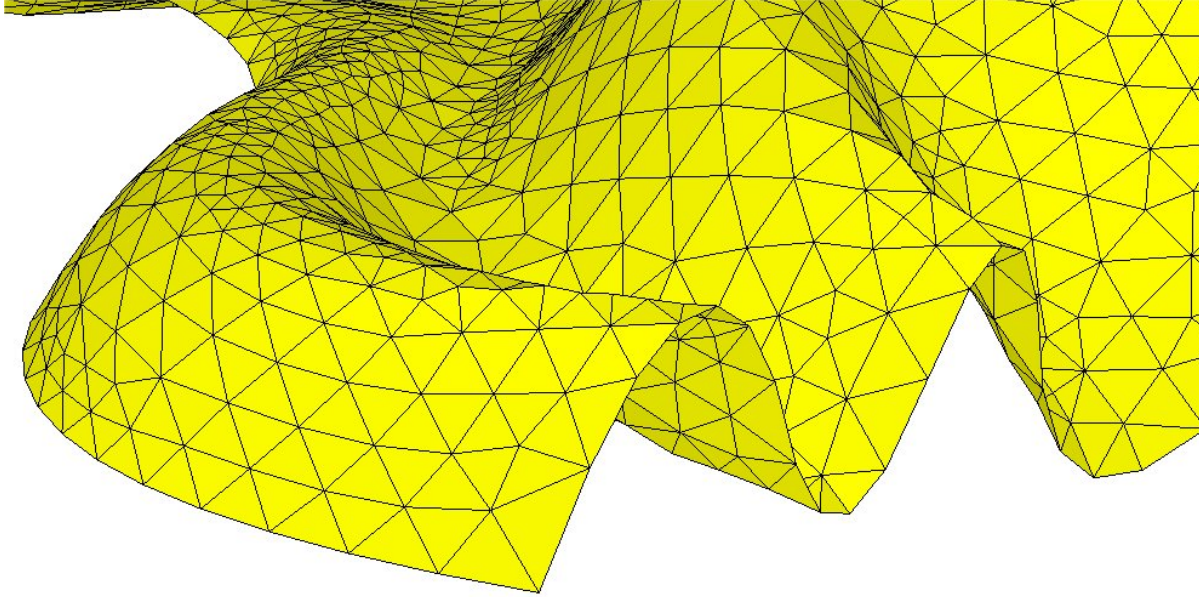
Imported surfaces: defects and imprecision



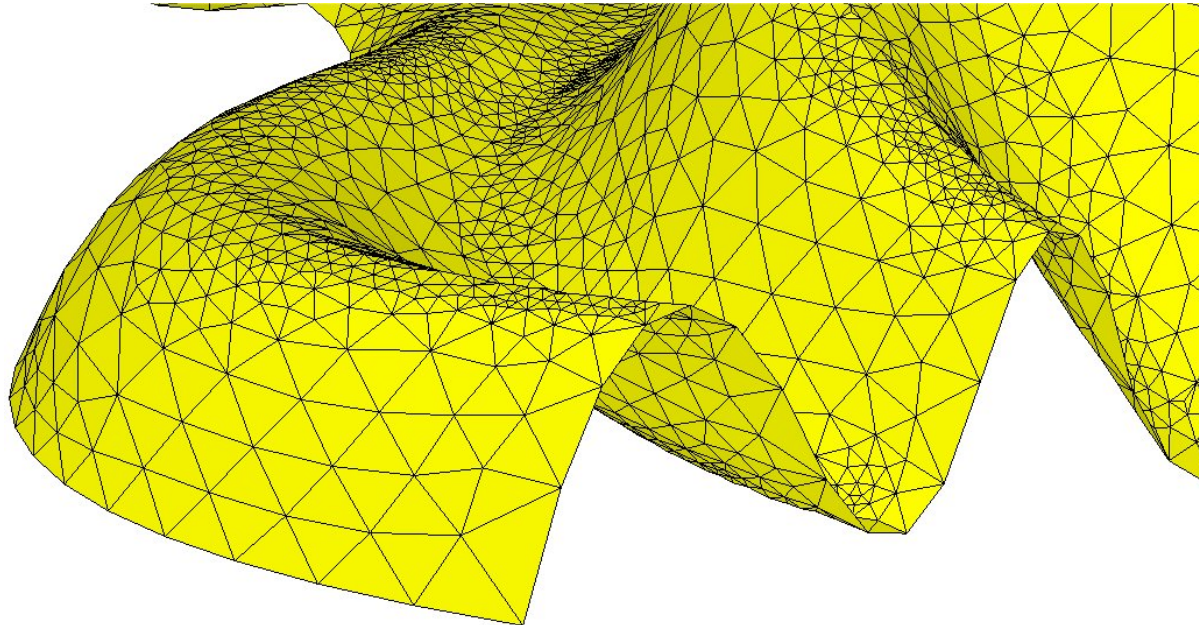
Mtool3D – Geometric support of surfaces



Mtool3D – Geometric support takes into account surface curvatures

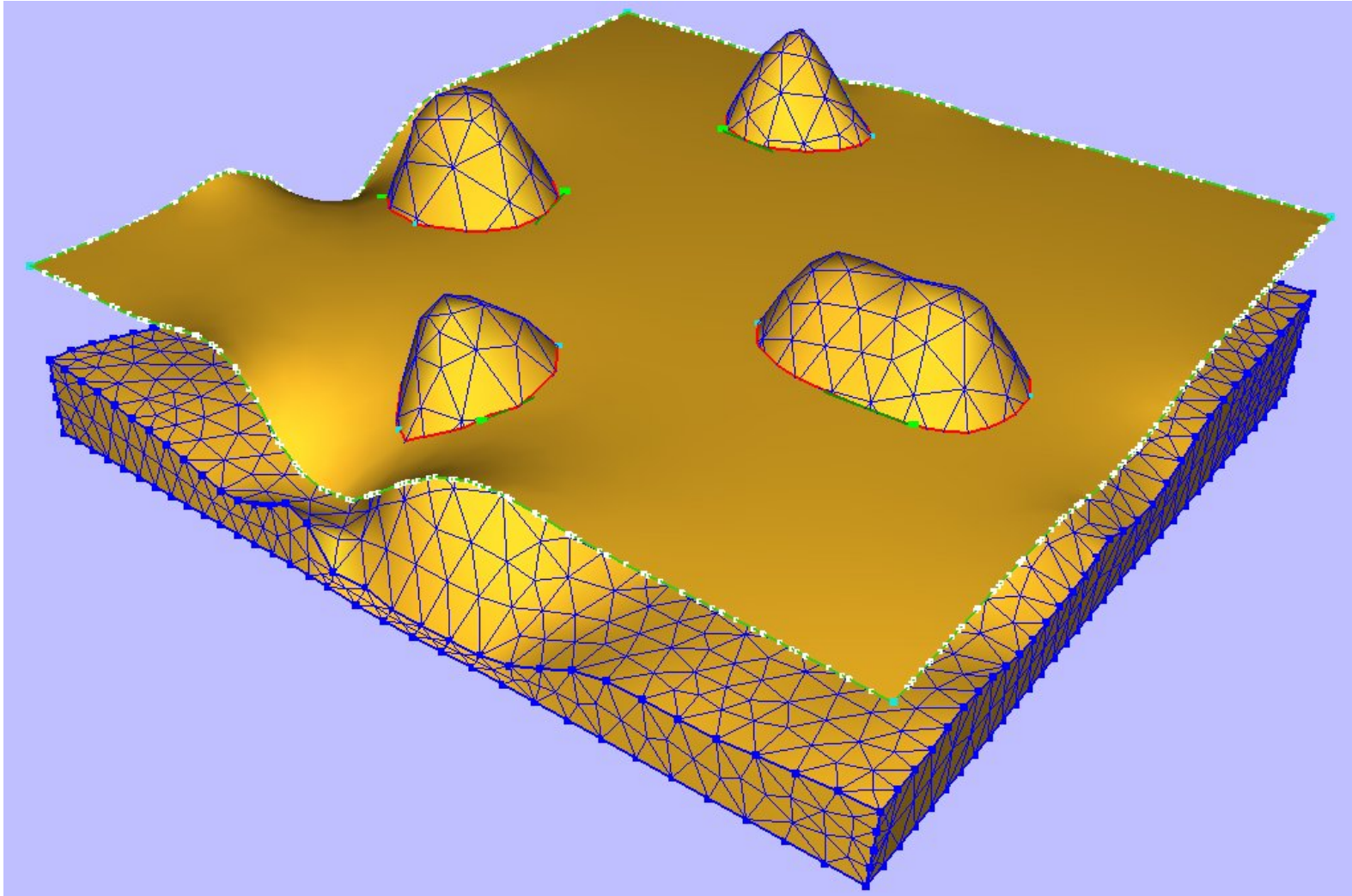


Without
considering
curvature

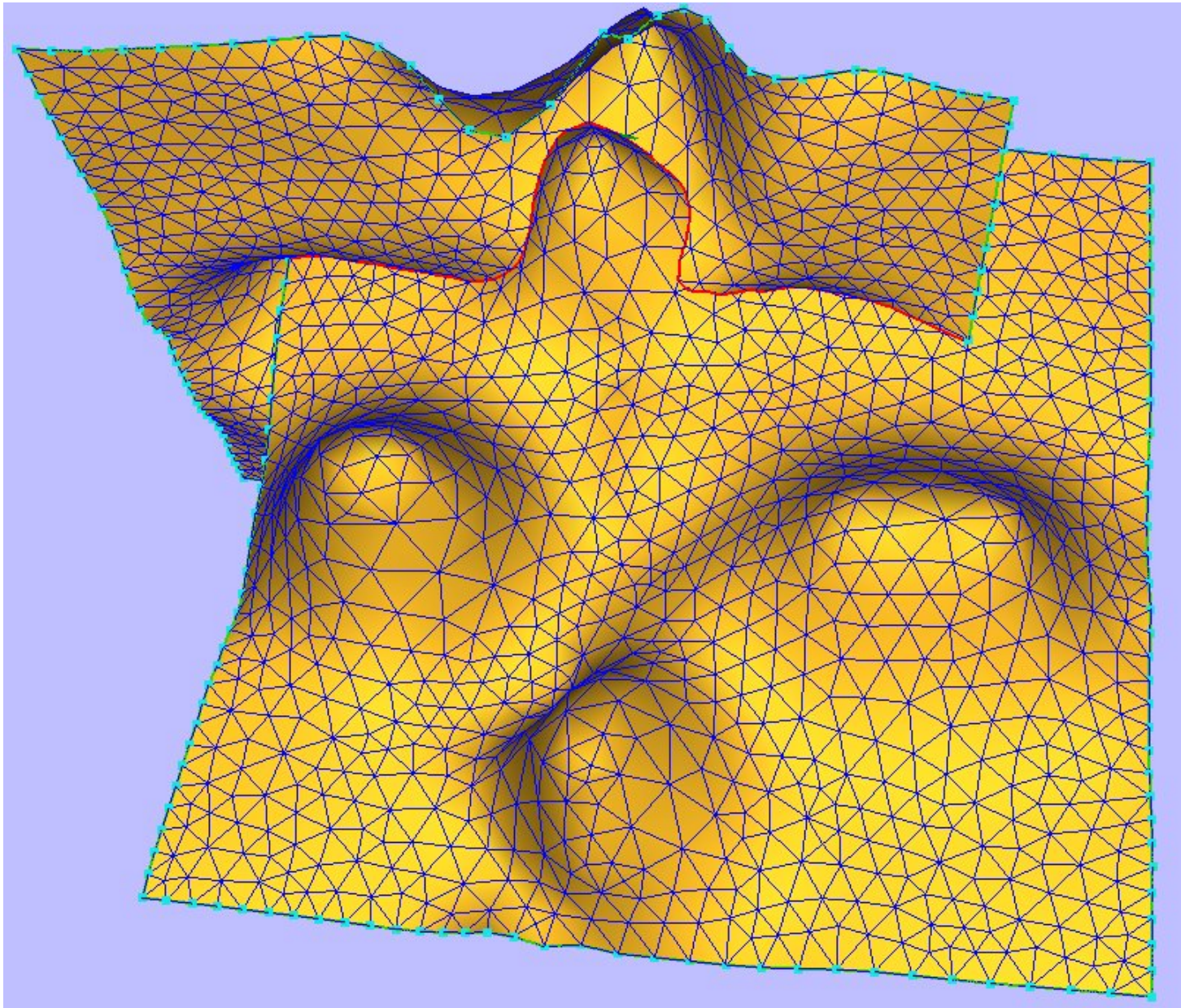


Considering
curvatures

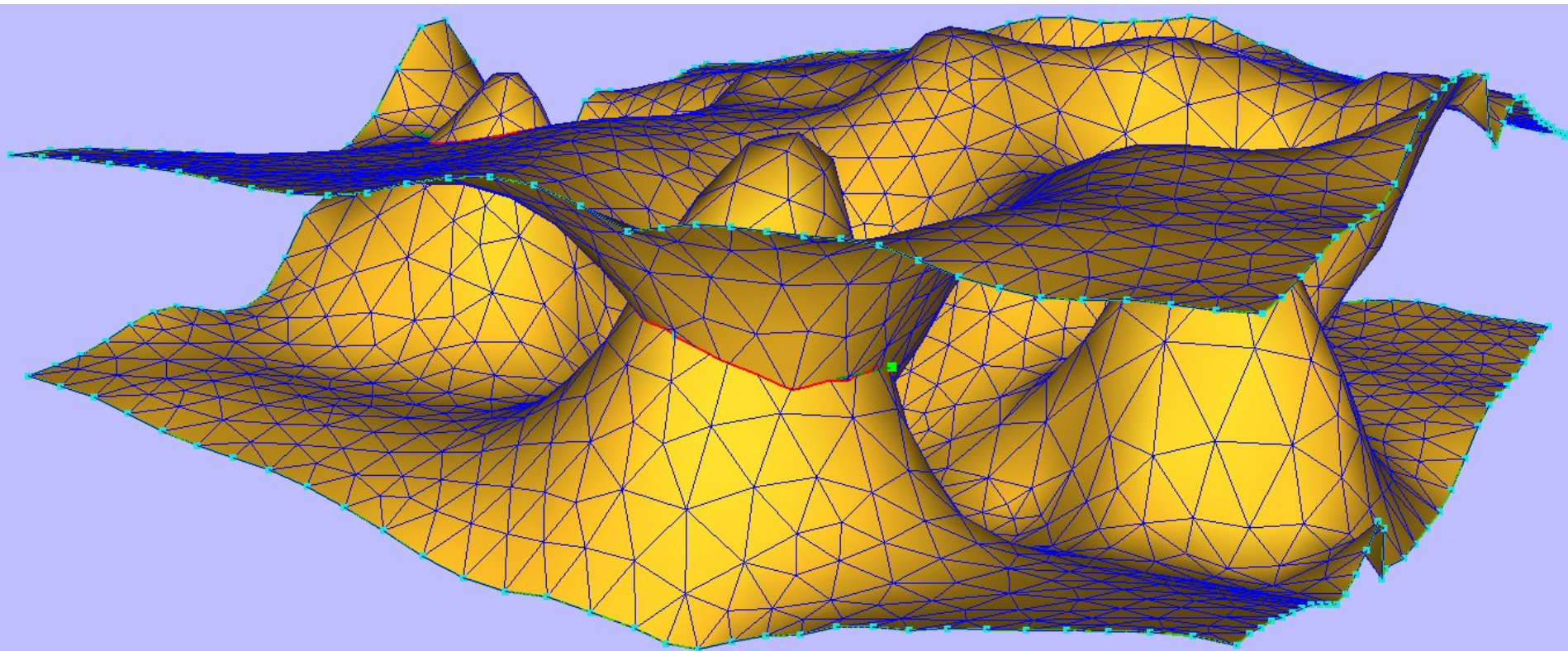
Mtool3D – Surface intersection



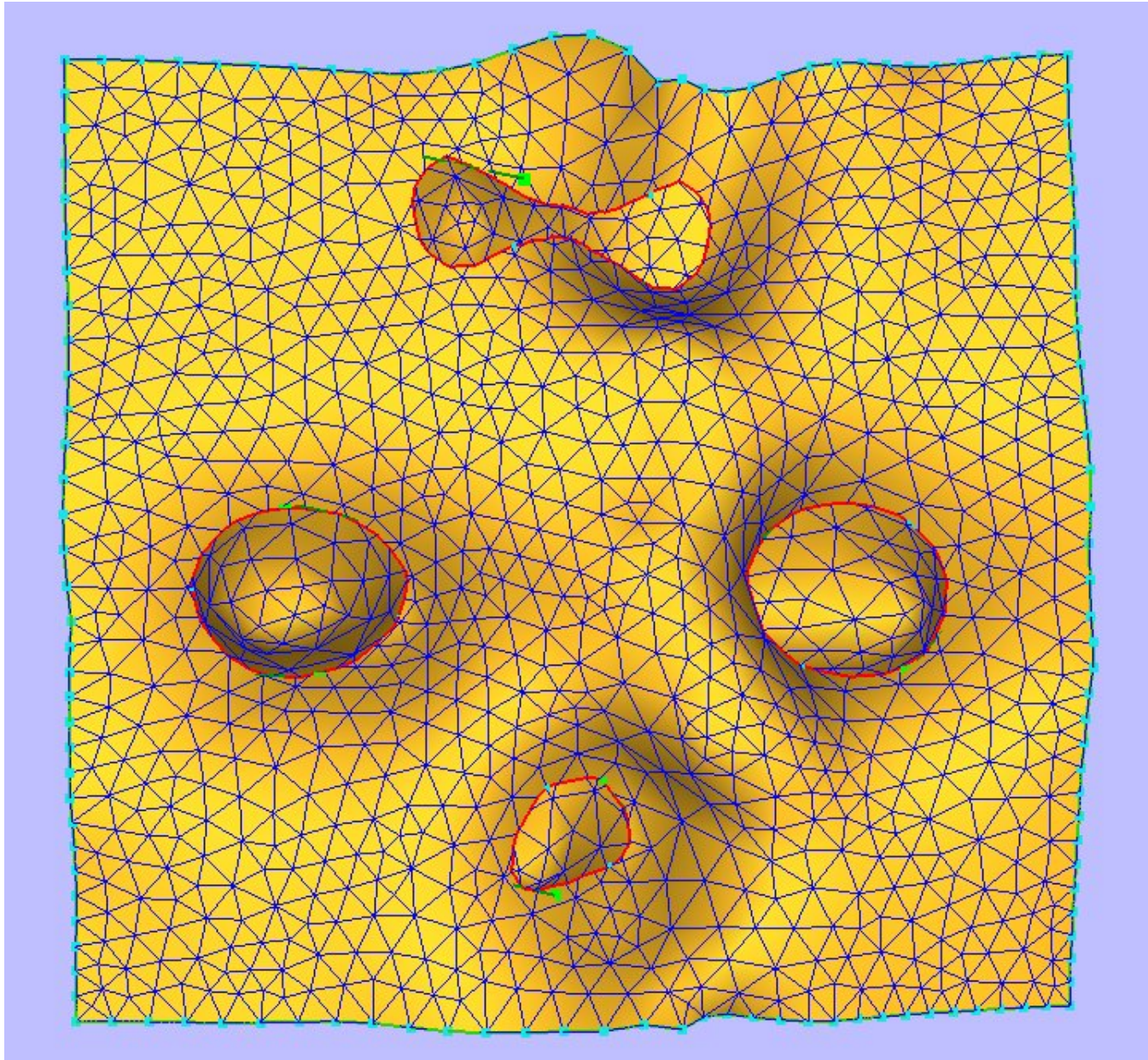
Mtool3D – Surface intersection



Mtool3D – Surface intersection

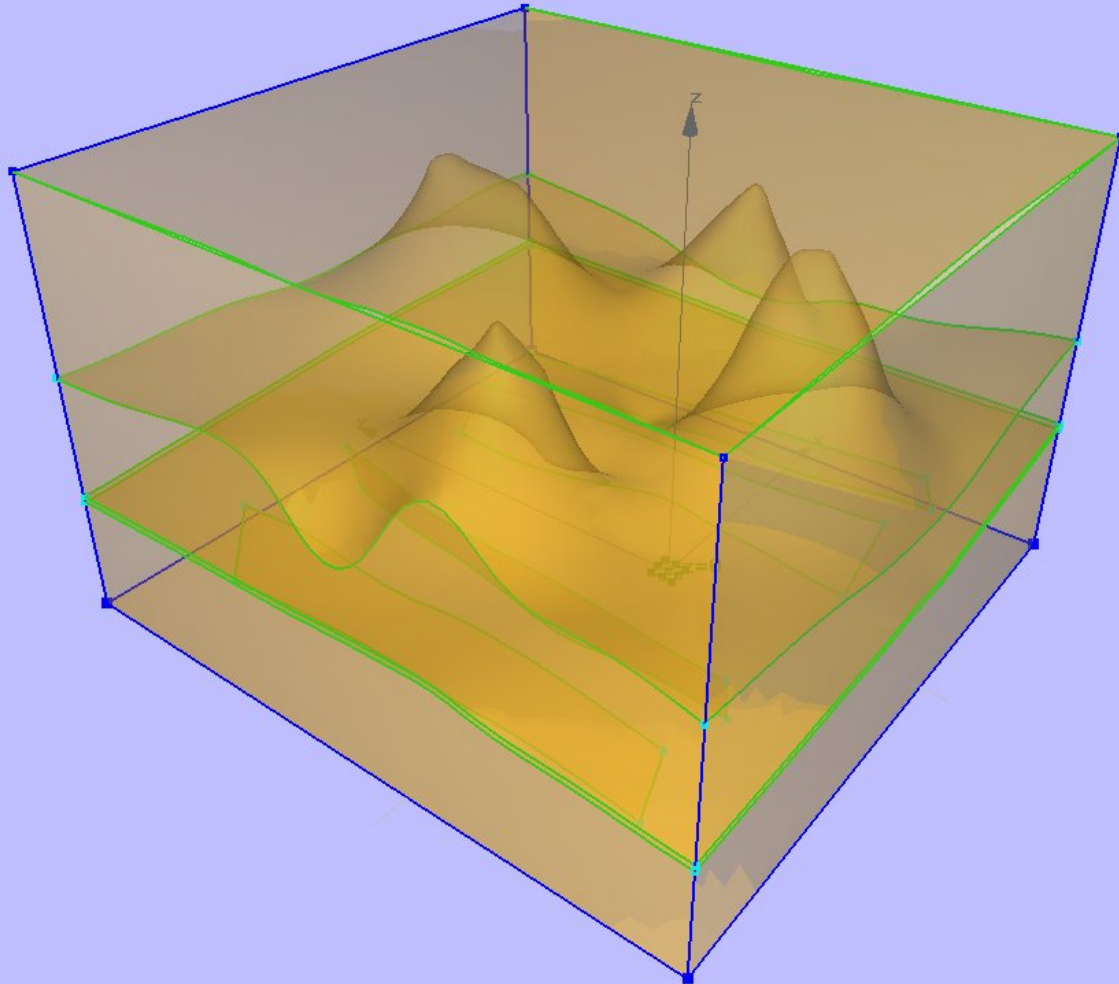


Mtool3D – Surface intersection



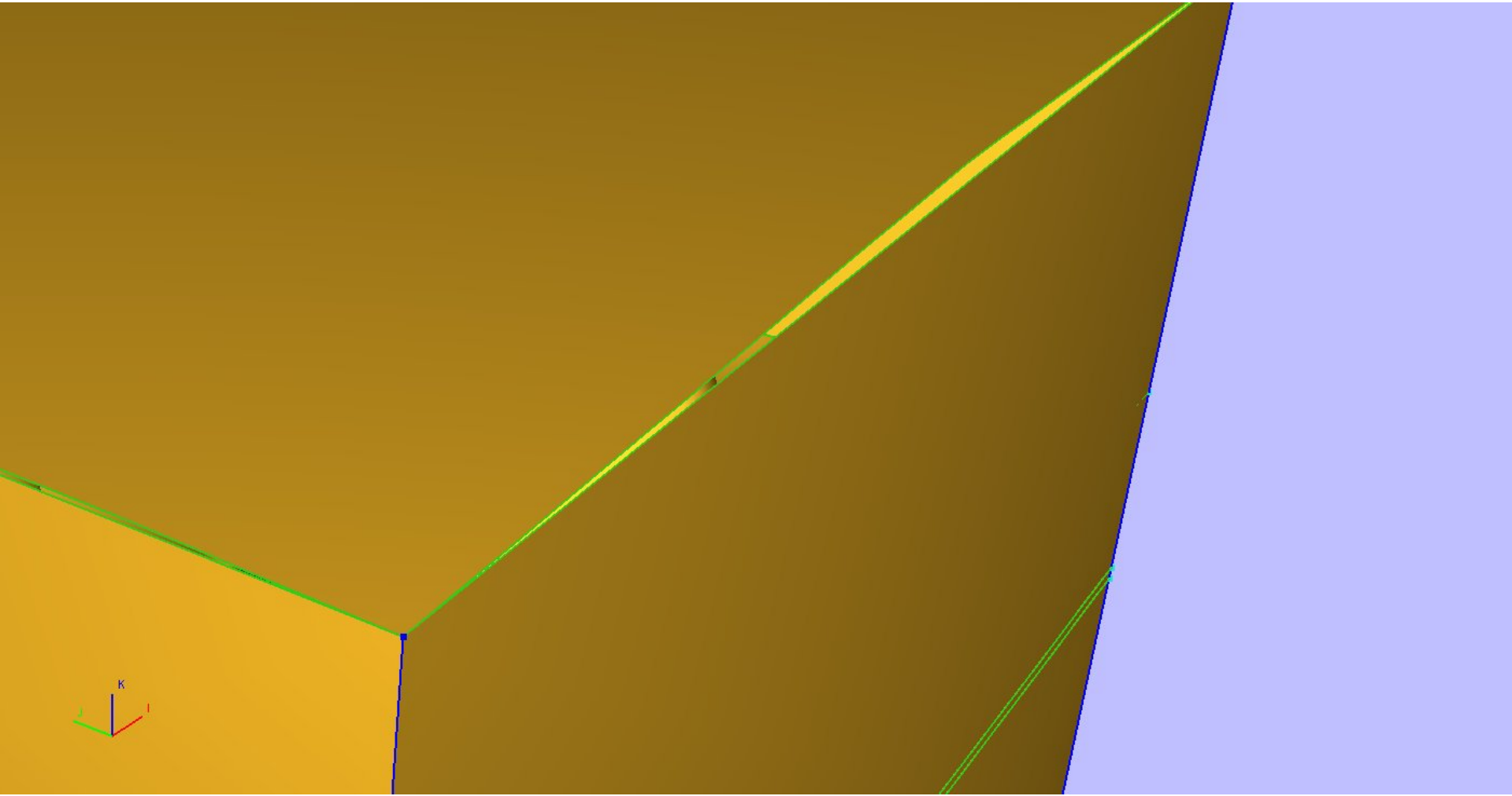
Mtool3D – Subsurface modeling

Imported surfaces from GOCAD



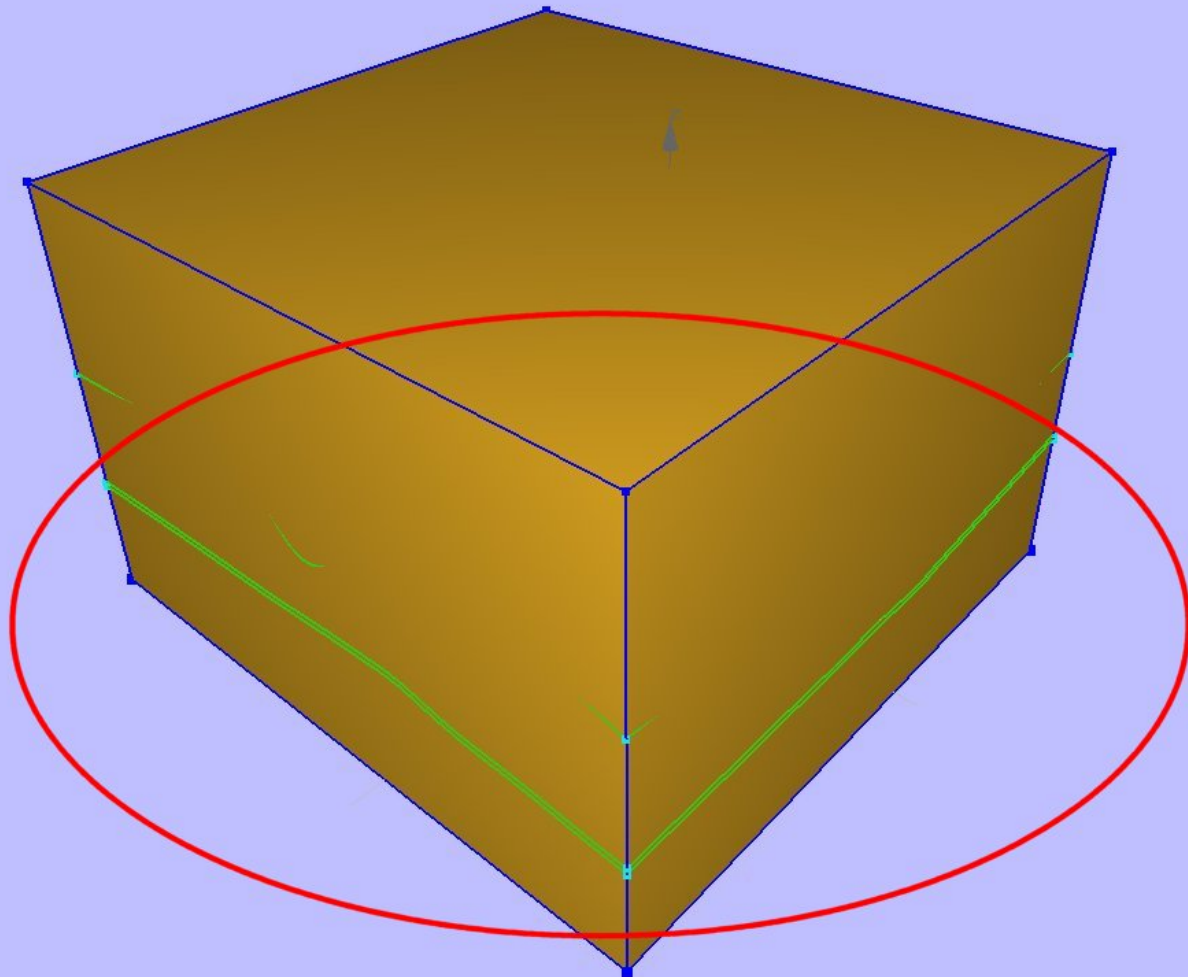
Mtool3D – Subsurface modeling

Geometric inconsistencies



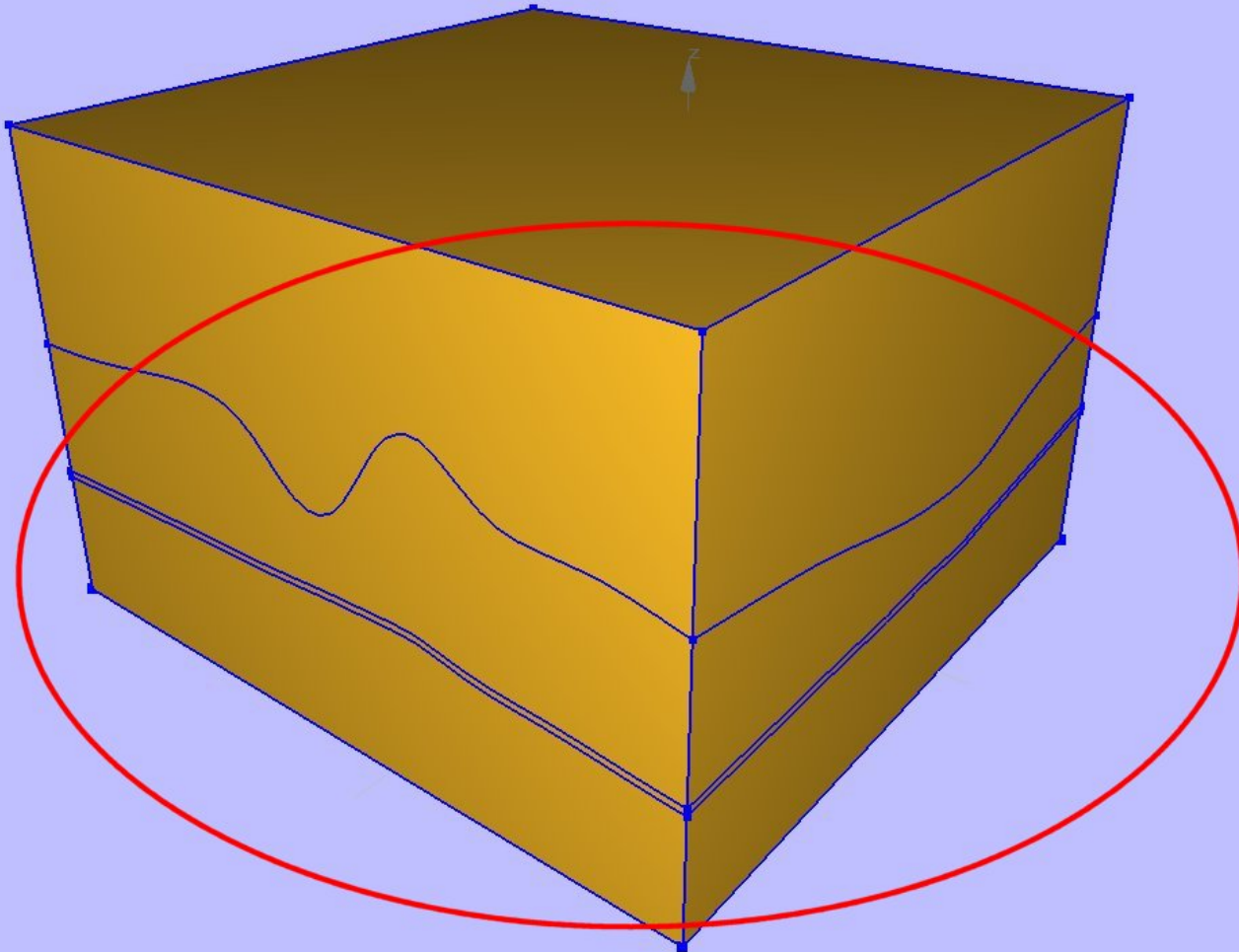
Mtool3D – Subsurface modeling

Geometric adjustment operations



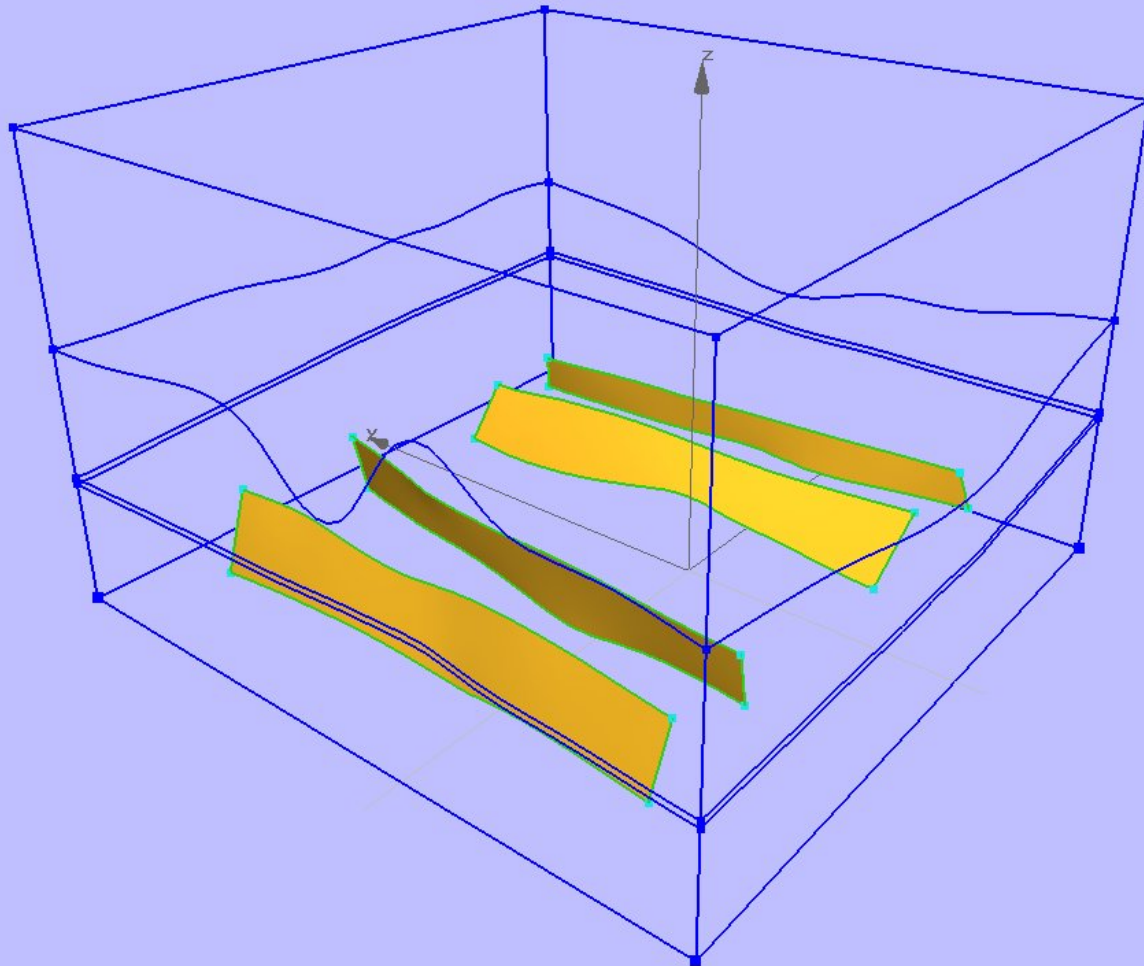
Mtool3D – Subsurface modeling

Geometric adjustment operations



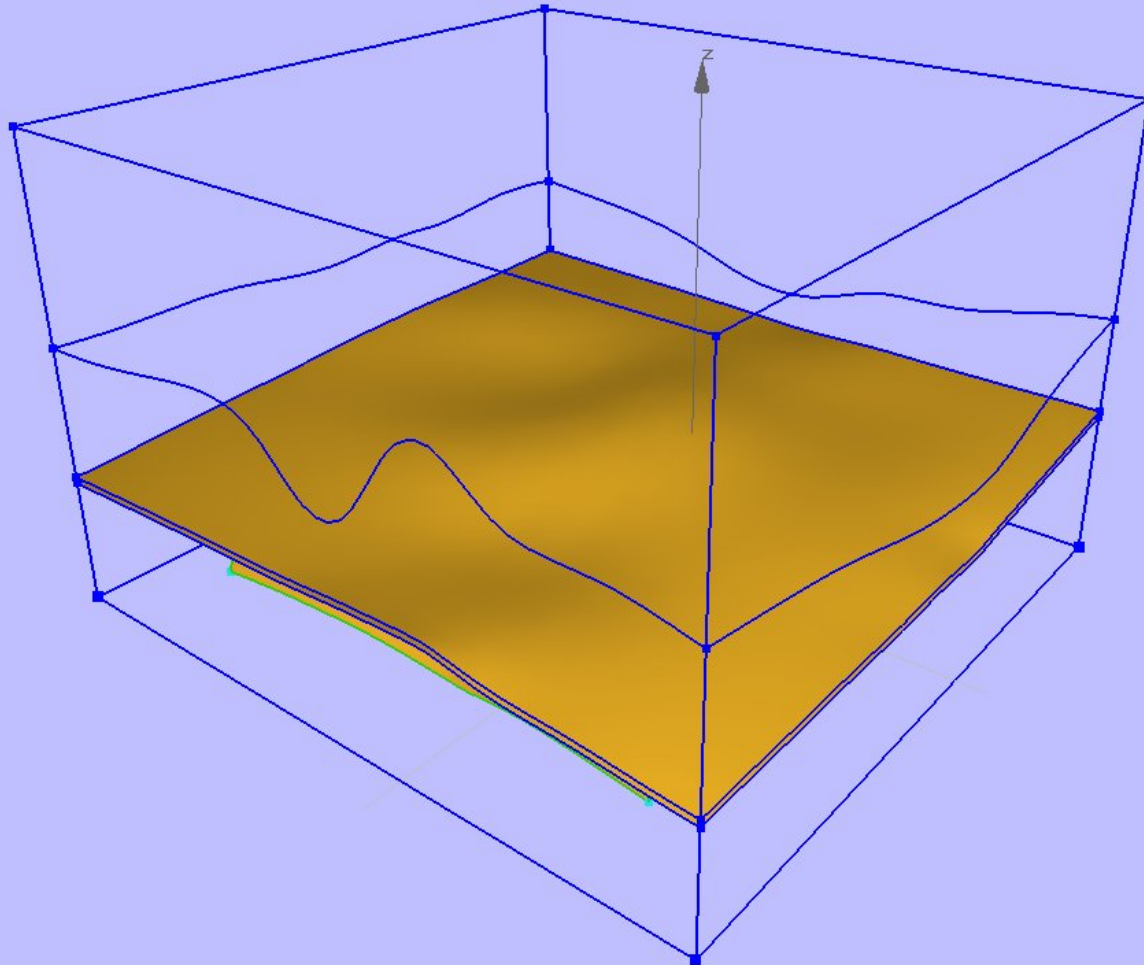
Mtool3D – Subsurface modeling

Disconnected geological faults



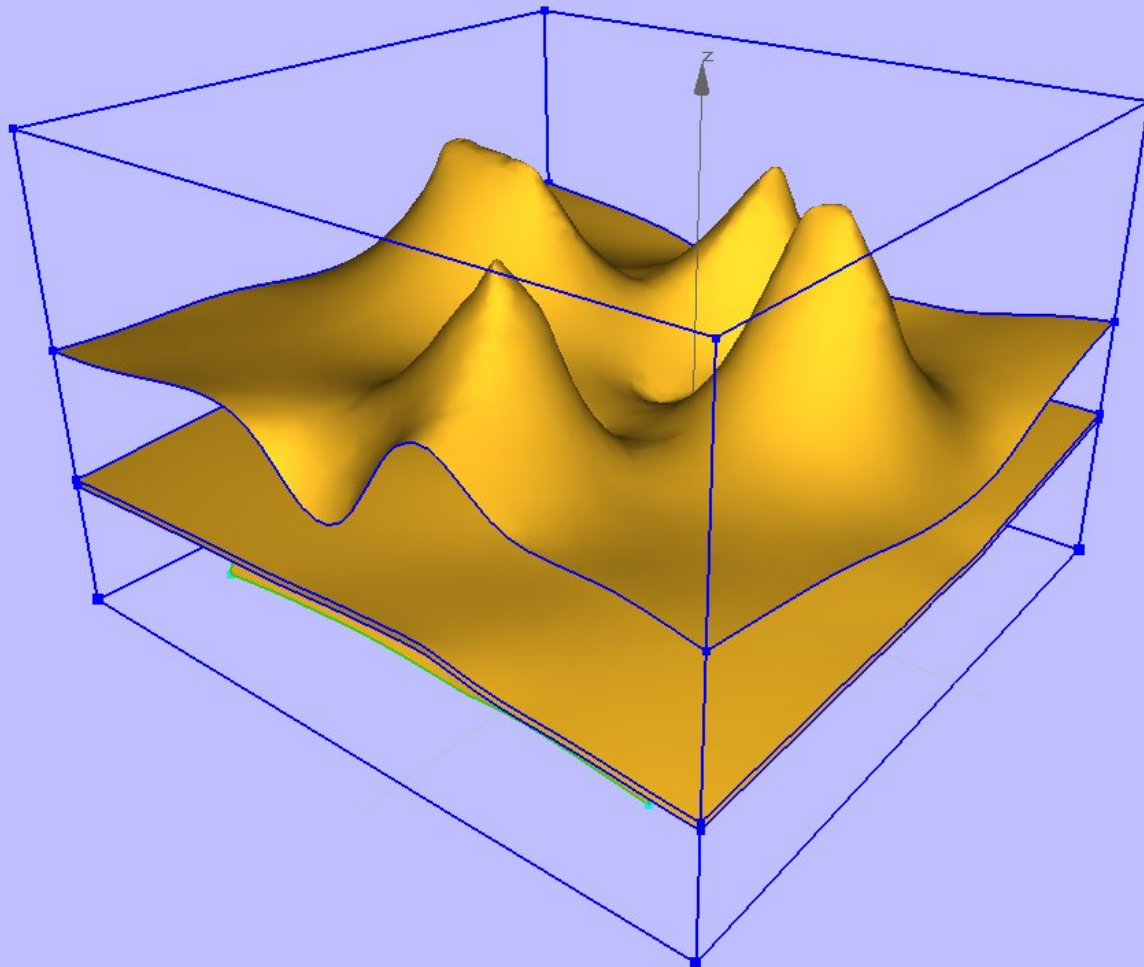
Mtool3D – Subsurface modeling

Disparity of dimensions and thicknesses



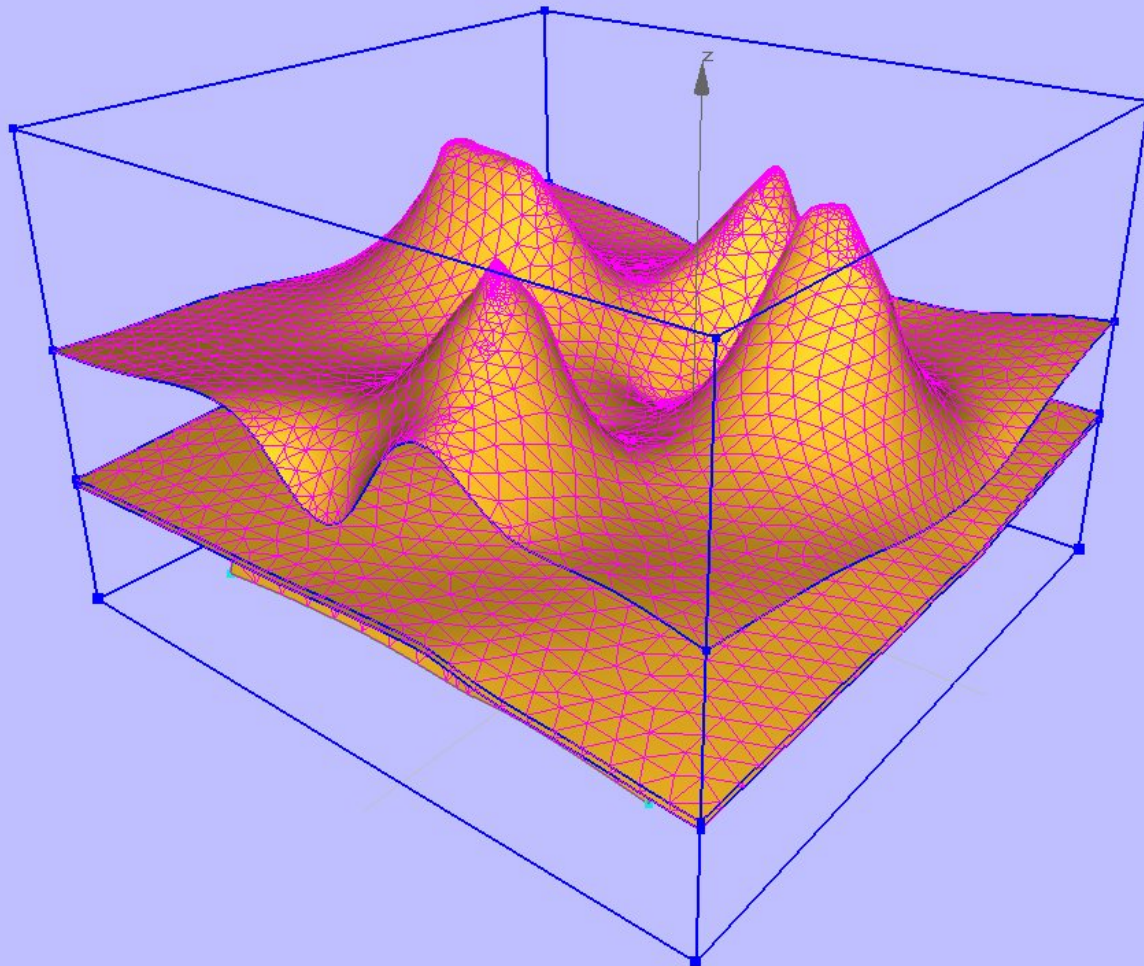
Mtool3D – Subsurface modeling

Arbitrary complex geometries



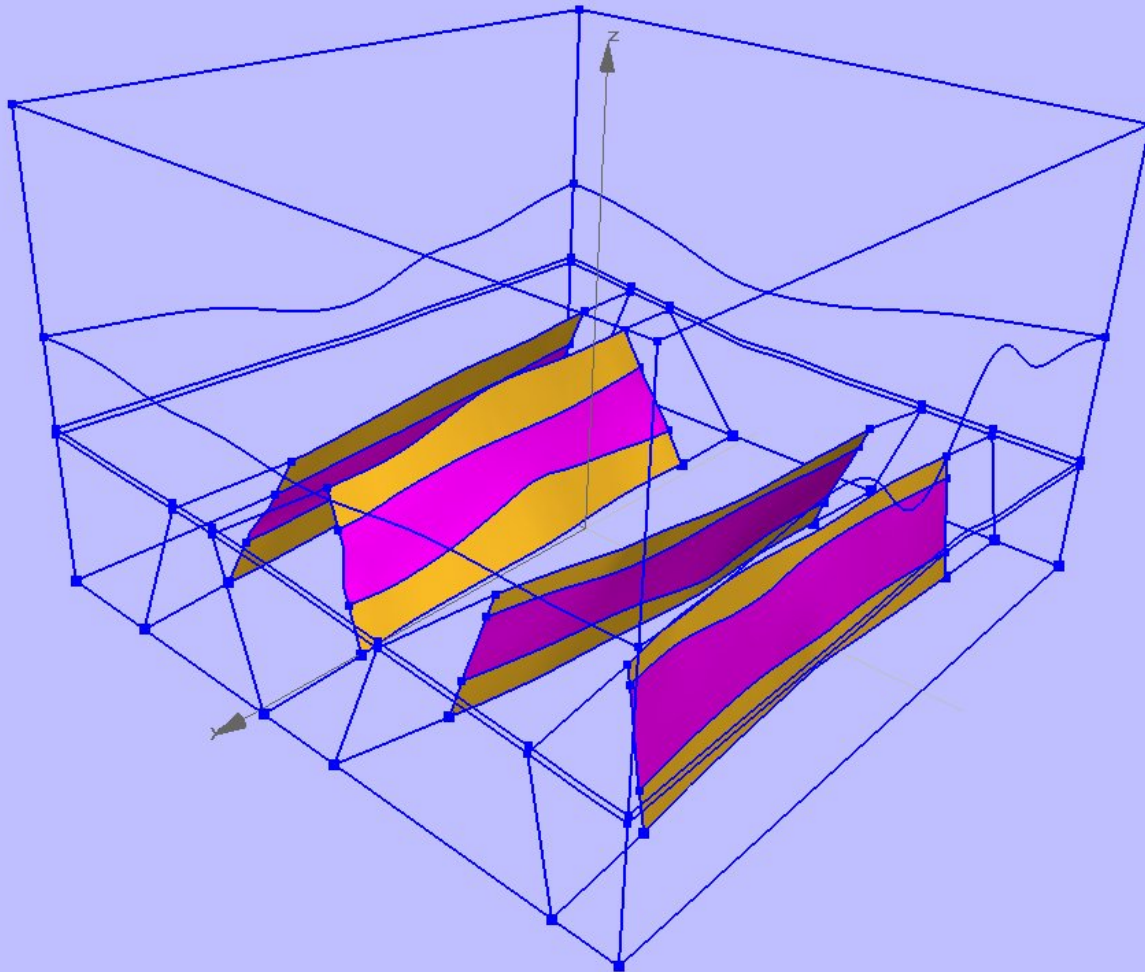
Mtool3D – Subsurface modeling

Surface discrete geometric support



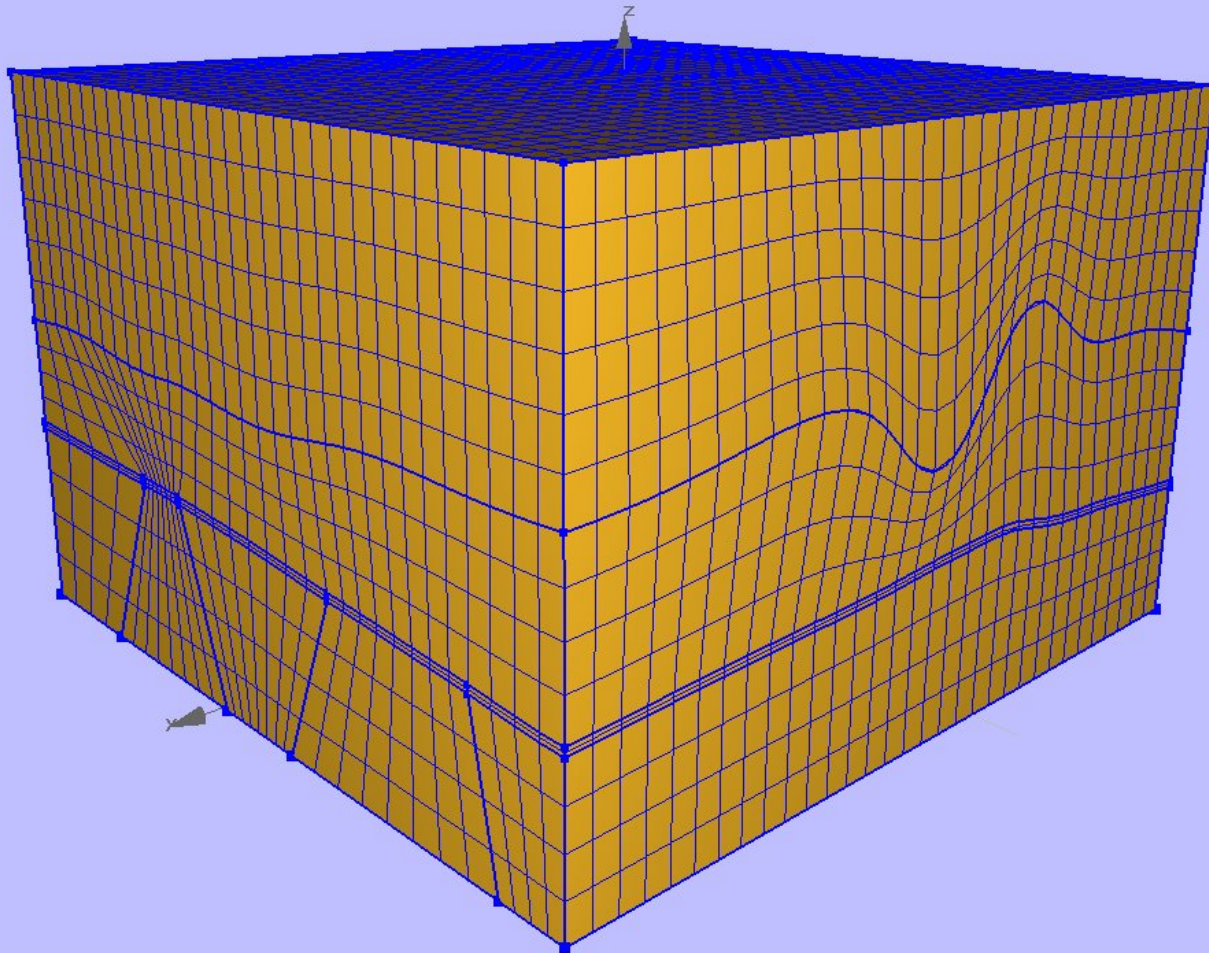
Mtool3D – Subsurface modeling

Closing off volumes for solid mesh generation



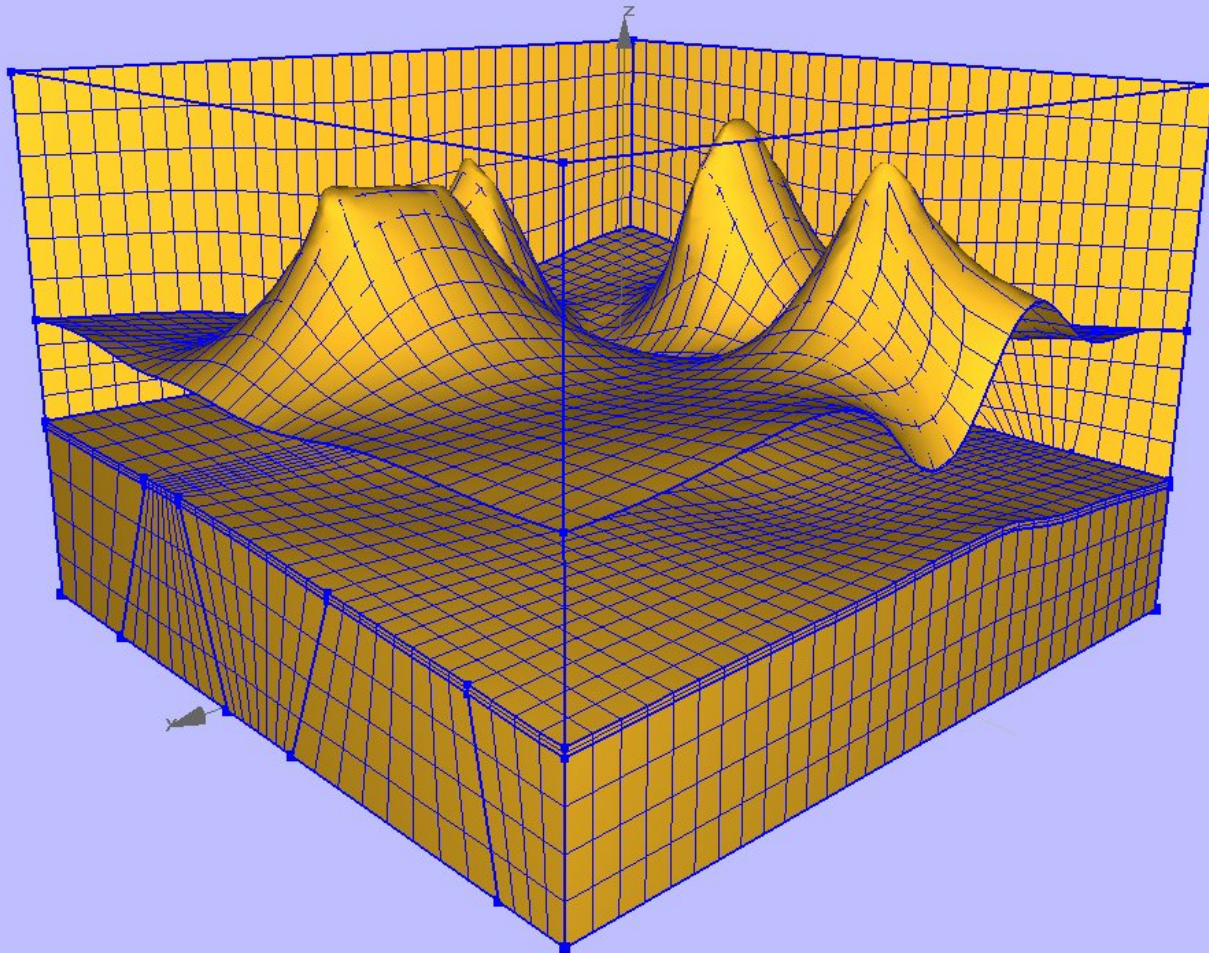
Mtool3D – Subsurface modeling

Quadrilateral FE mesh generation



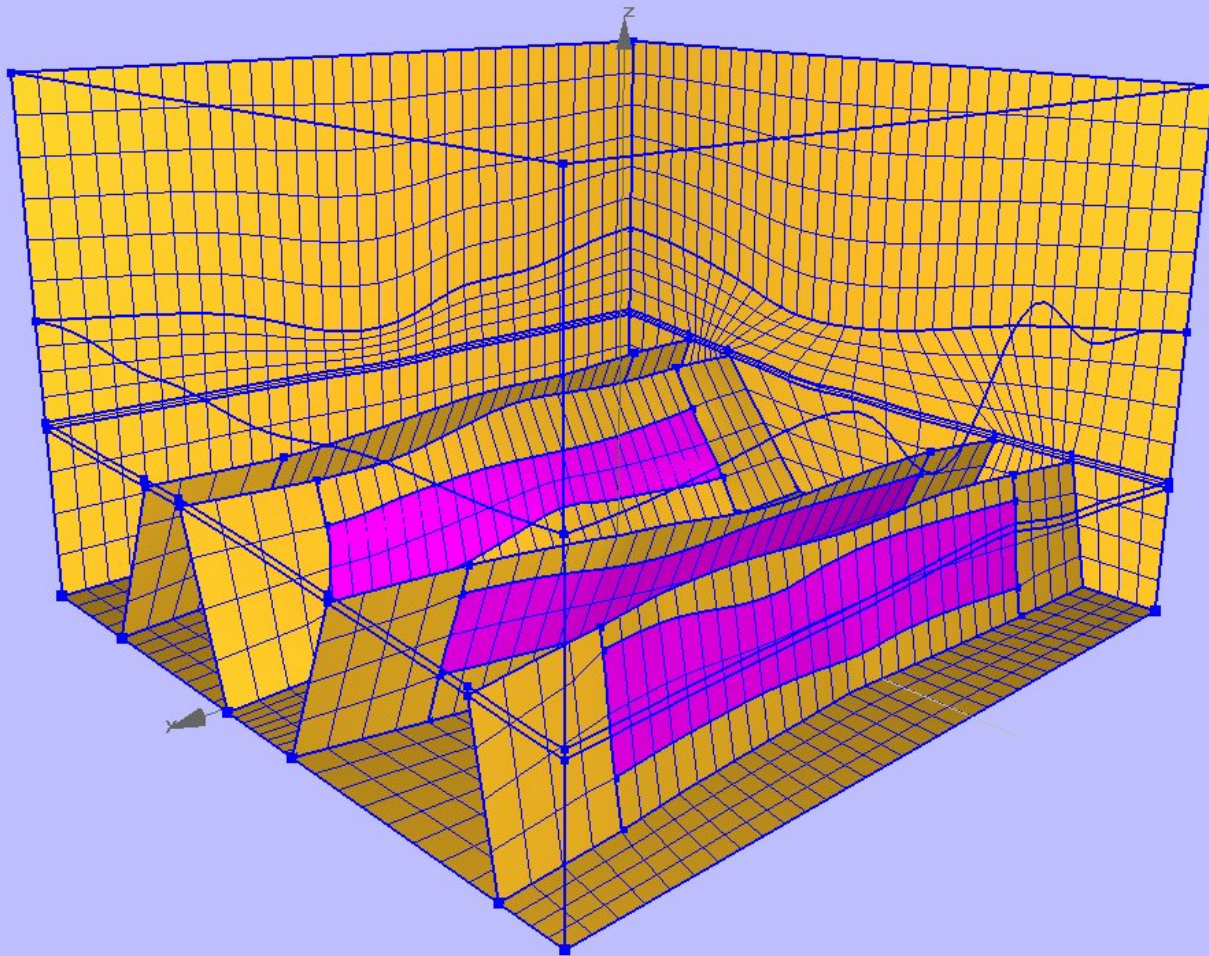
Mtool3D – Subsurface modeling

Quadrilateral FE mesh generation



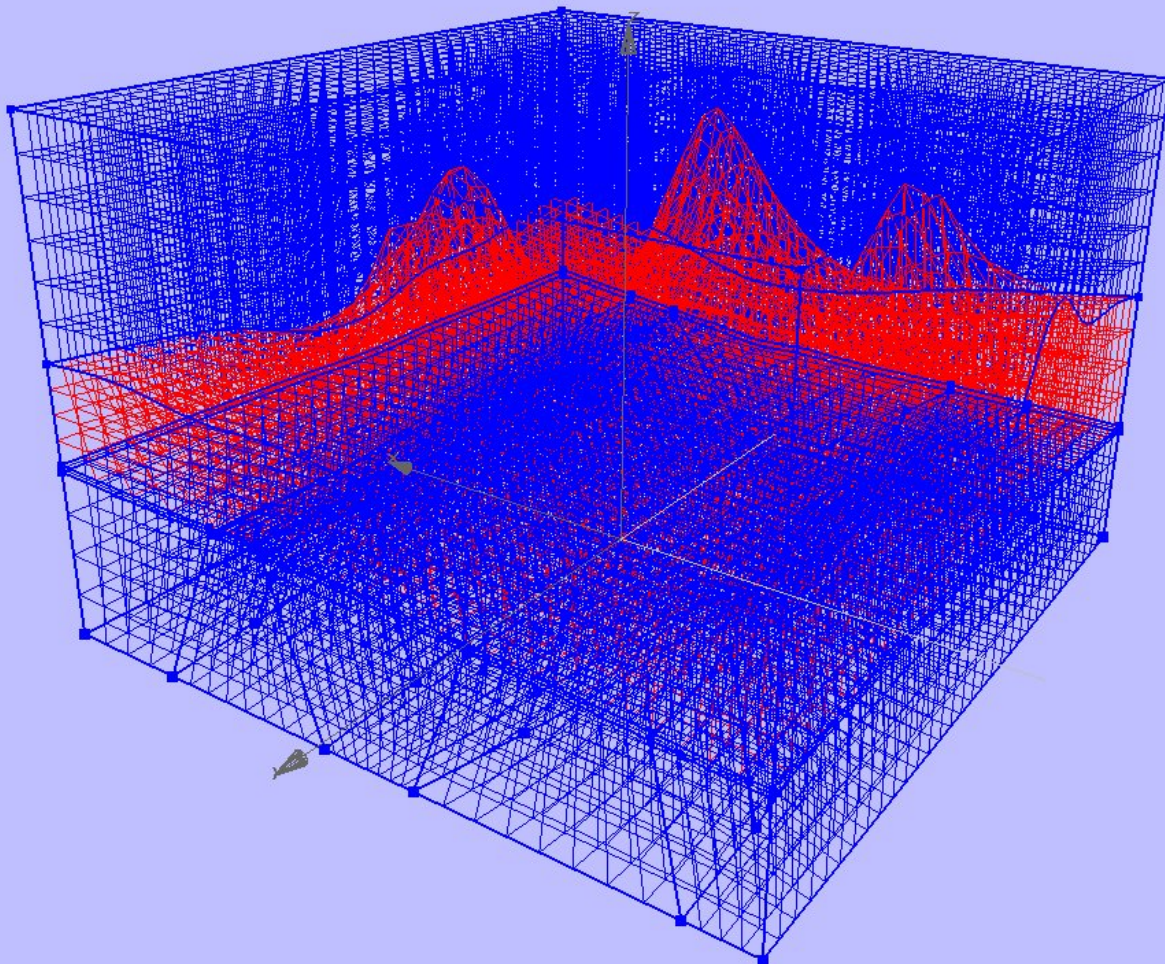
Mtool3D – Subsurface modeling

Quadrilateral FE mesh generation



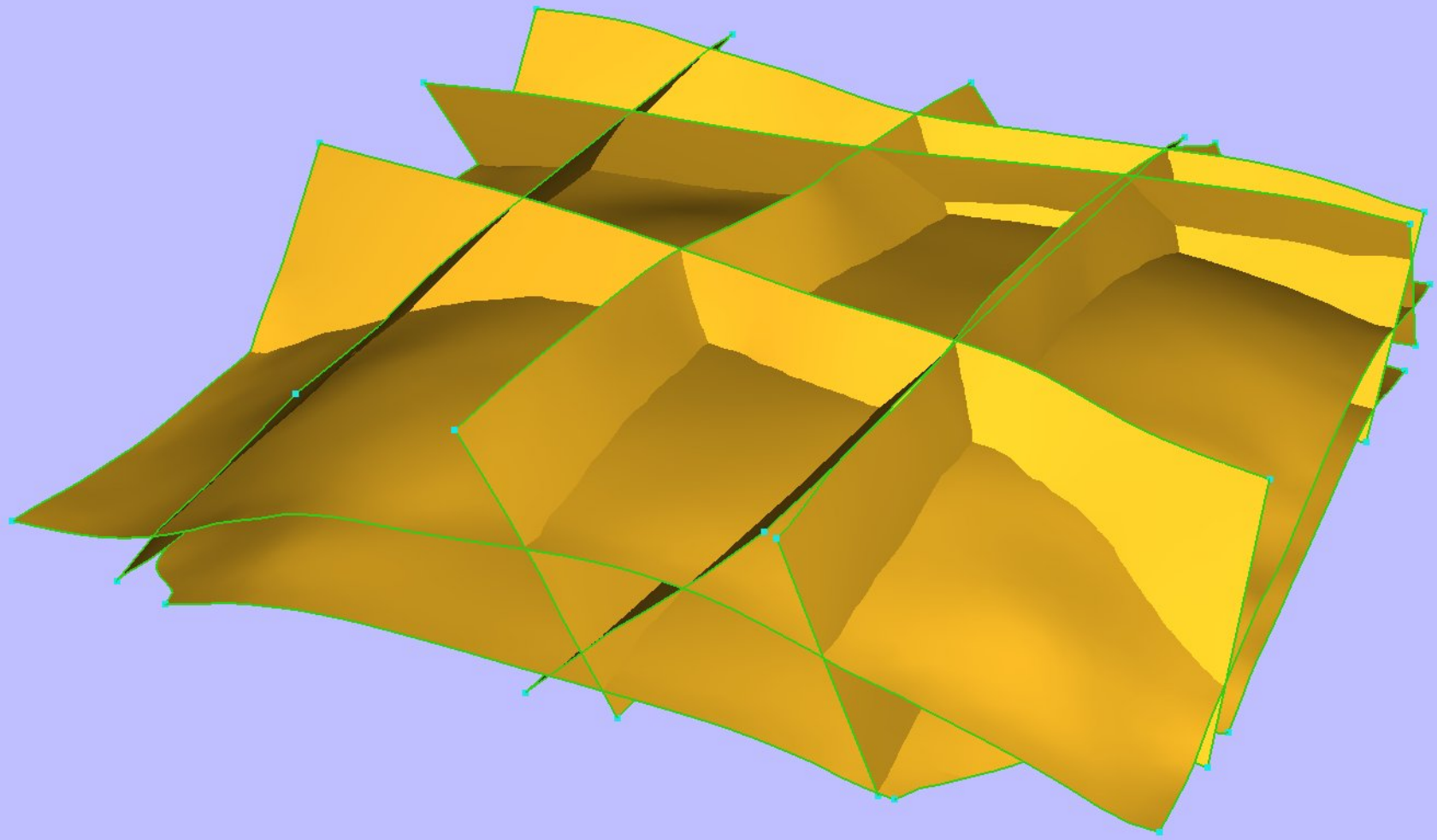
Mtool3D – Subsurface modeling

Hexahedral FE solid mesh generation



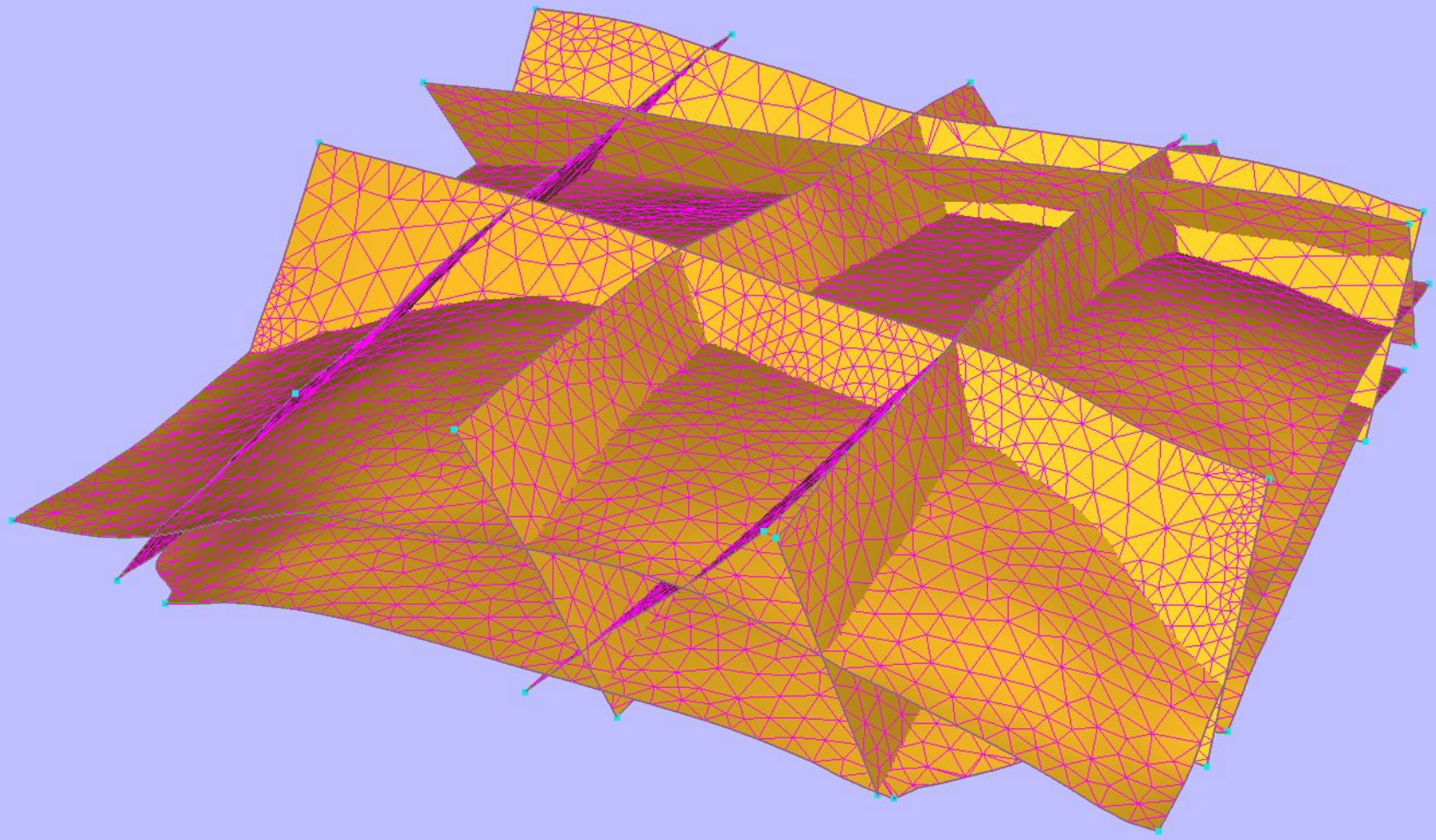
Mtool3D – Subsurface modeling

Importing horizon and fault surfaces from gOcad



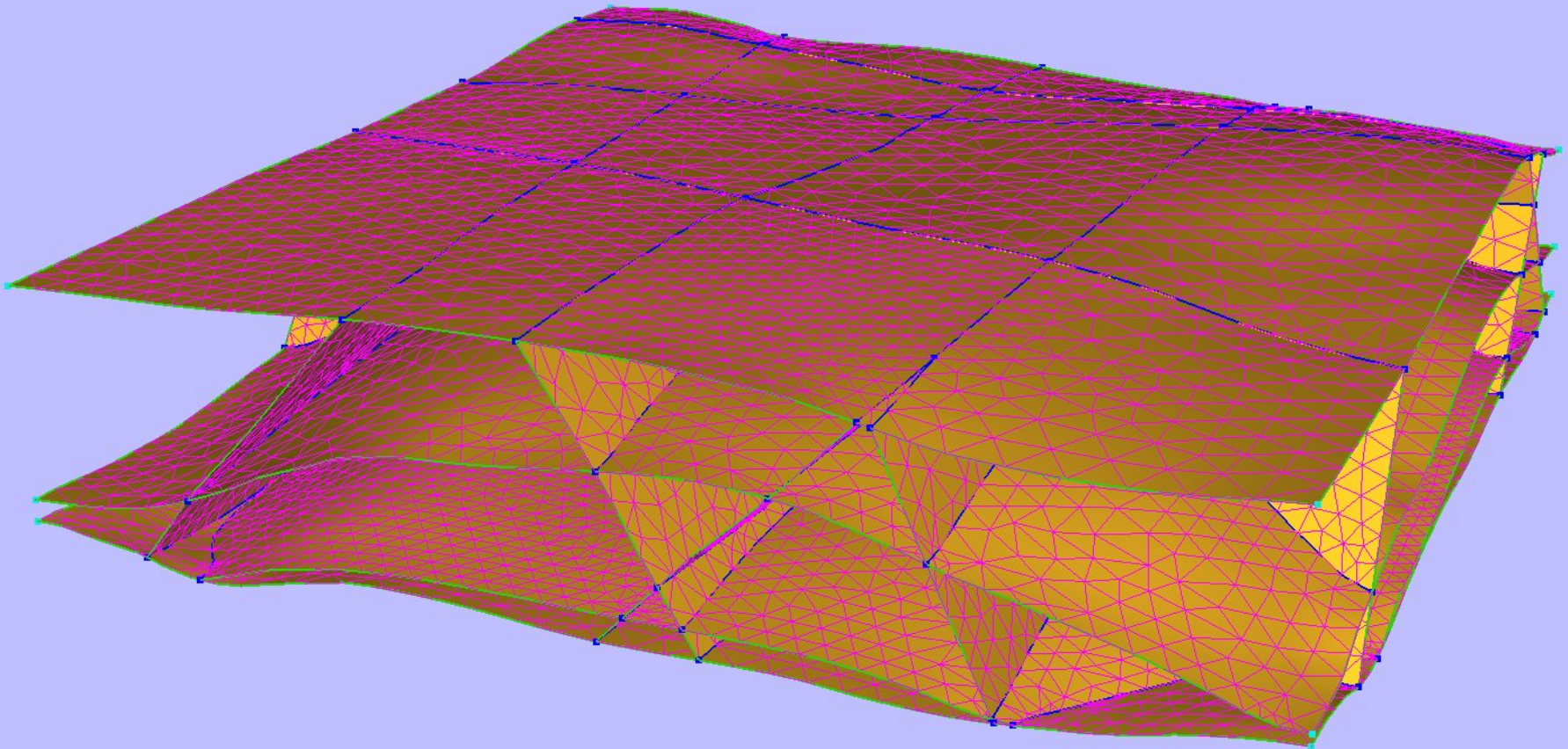
Mtool3D – Subsurface modeling

Importing horizon and fault surfaces from gOcad



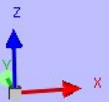
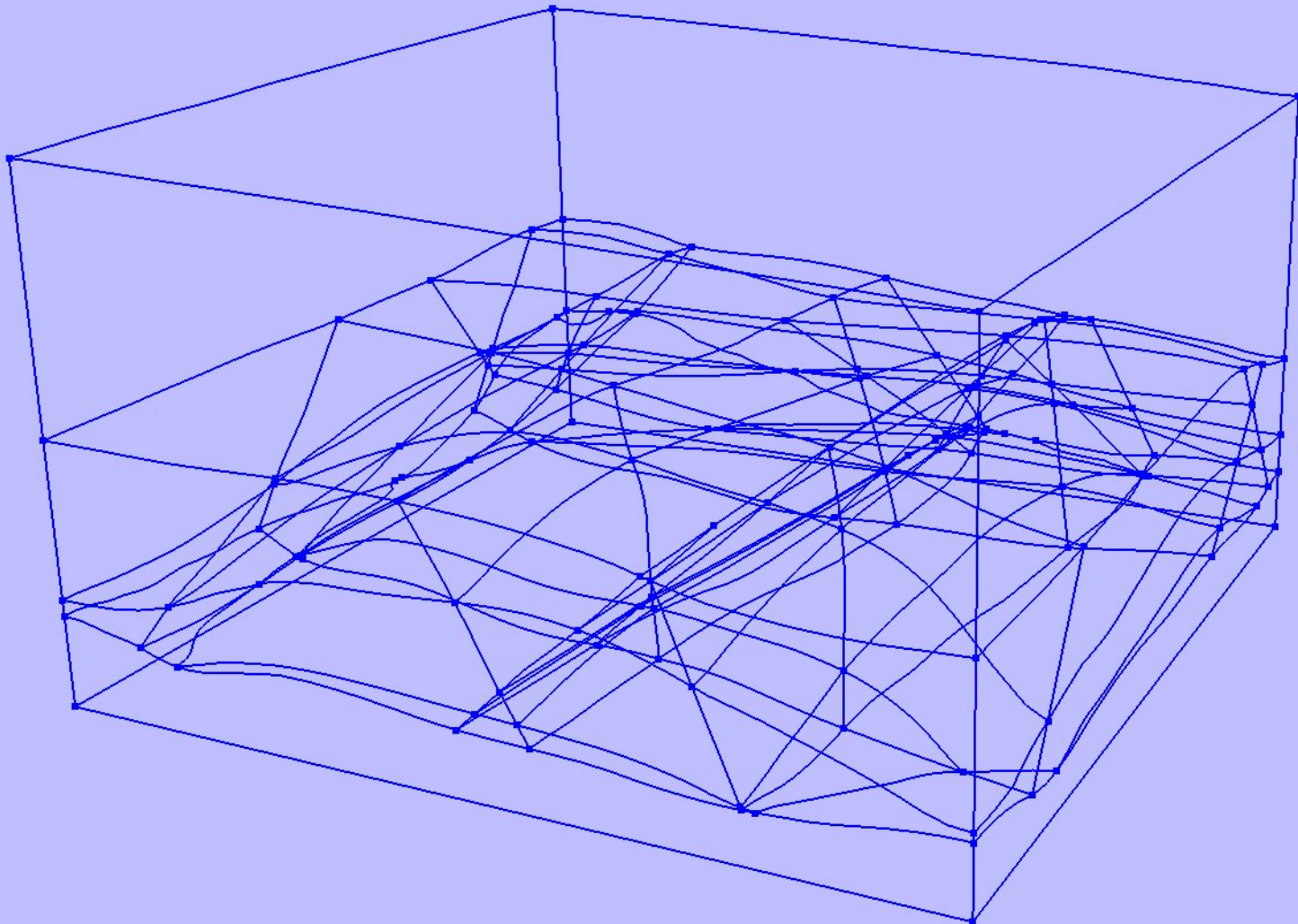
Mtool3D – Subsurface modeling

Intersection and adjustments of surfaces to generate consistent models for FE analysis



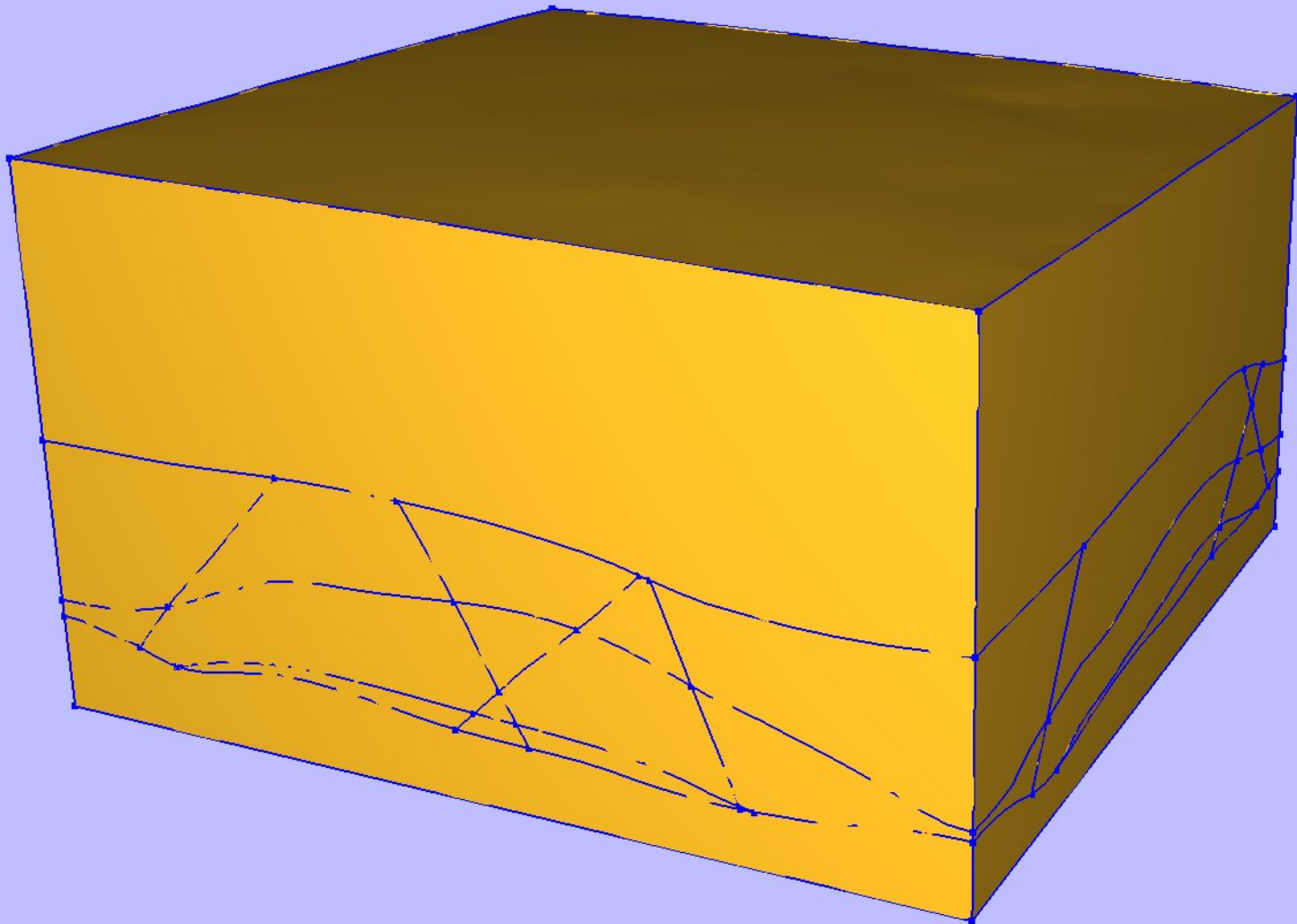
Mtool3D – Subsurface modeling

Intersection and adjustments of surfaces to generate consistent models for FE analysis

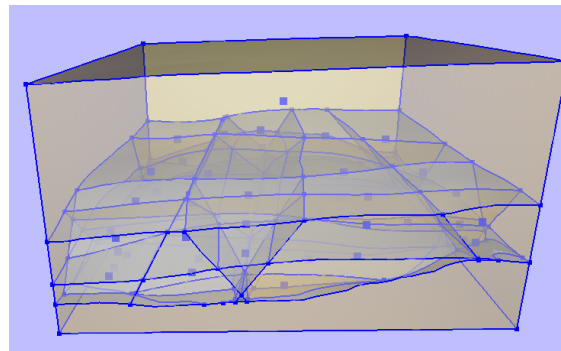
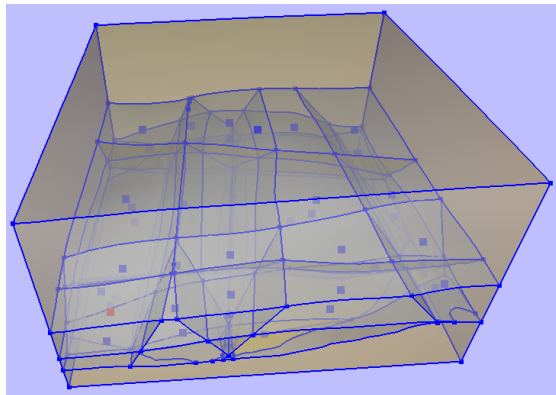
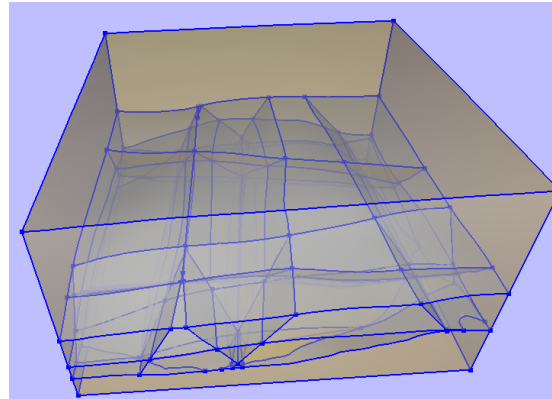
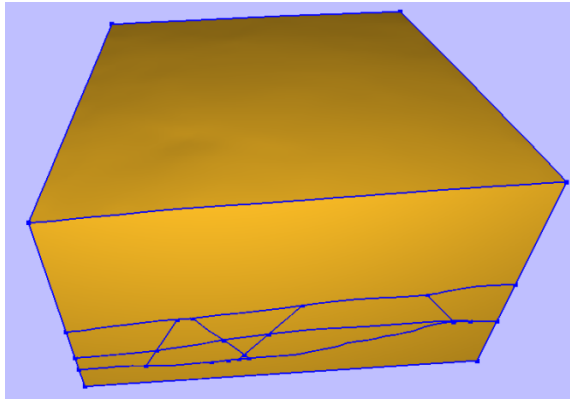
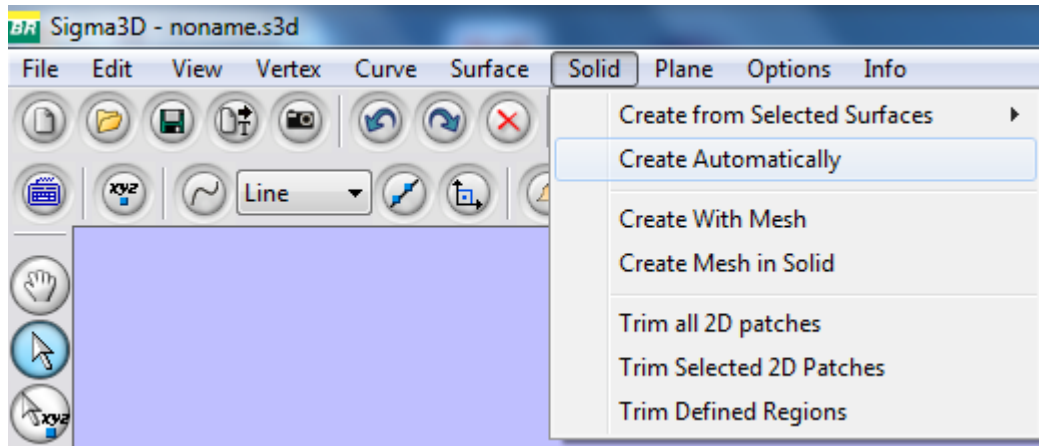


Mtool3D – Subsurface modeling

Intersection and adjustments of surfaces to generate consistent models for FE analysis

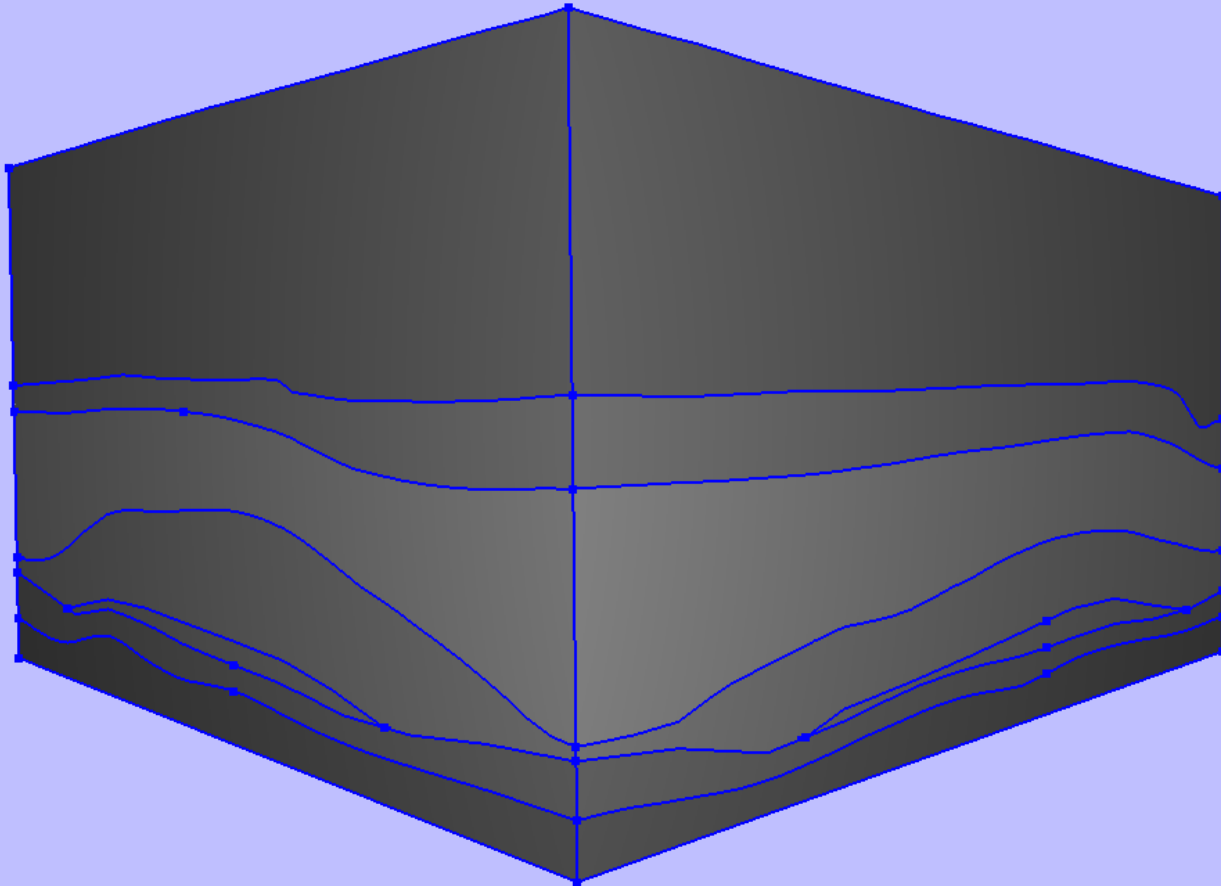


Mtool3D – Automatic volume recognition



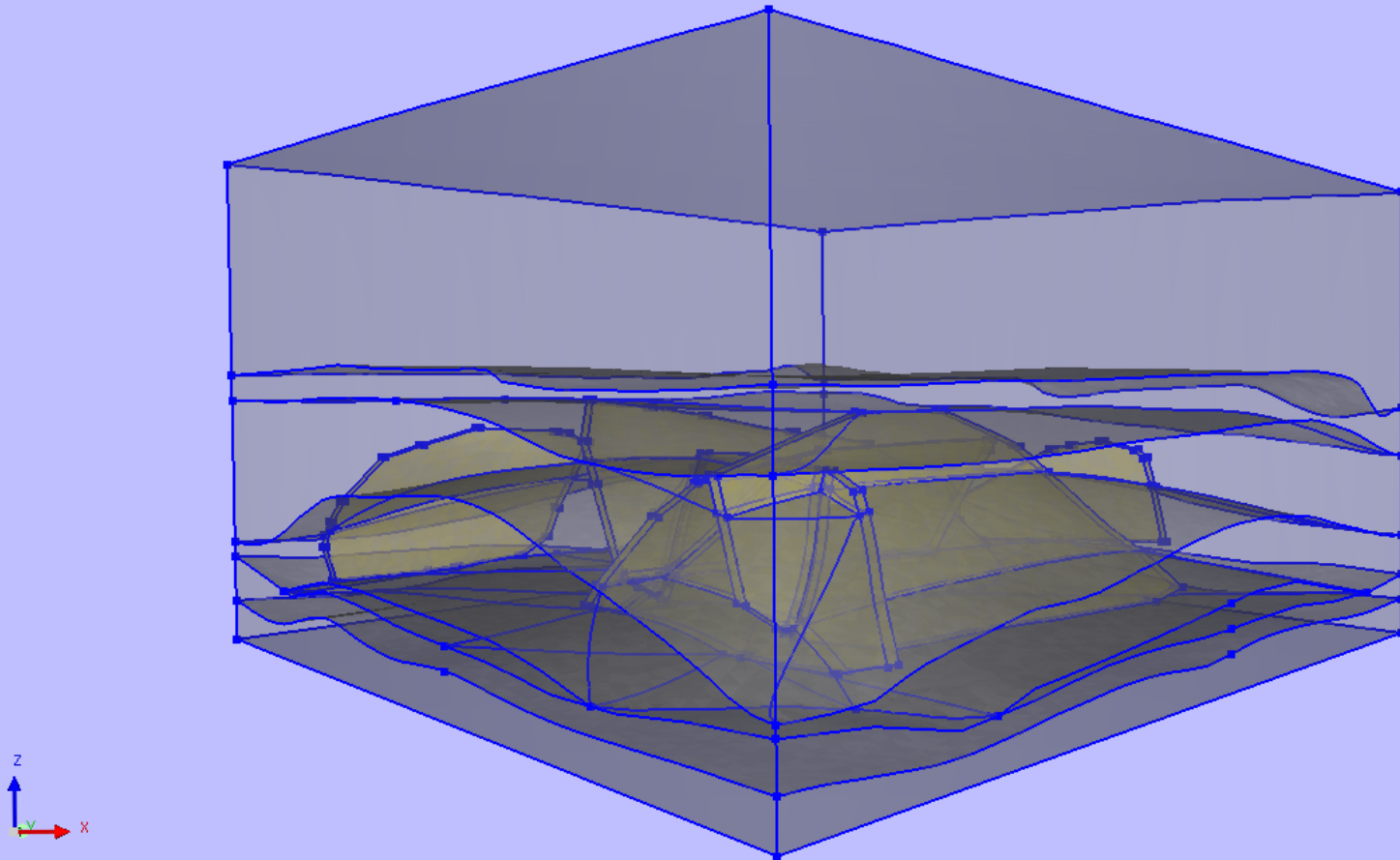
Mtool3D – Subsurface modeling

Modelo complexo sem superfícies fictícias para decomposição de domínios – malhas de tetraedros.



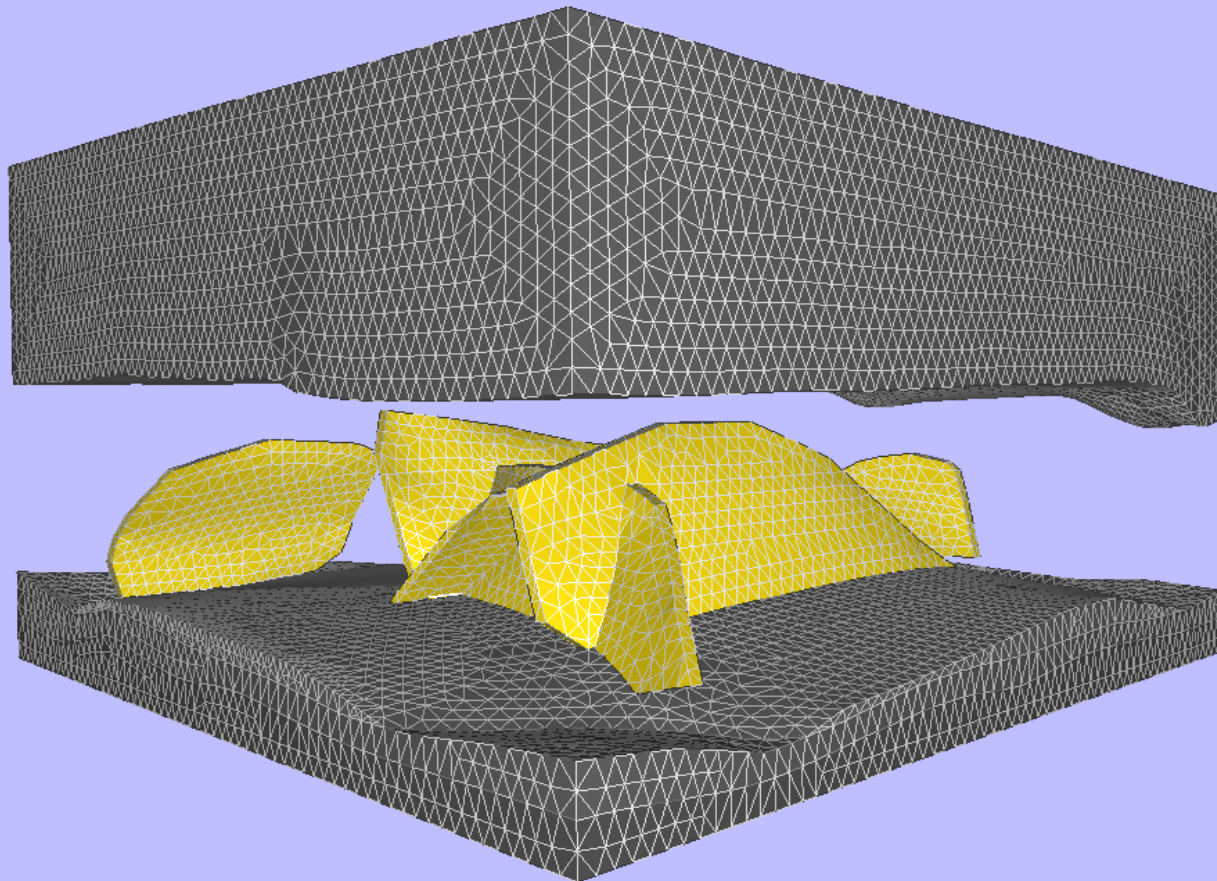
Mtool3D – Subsurface modeling

Modelo complexo sem superfícies fictícias para decomposição de domínios – malhas de tetraedros.



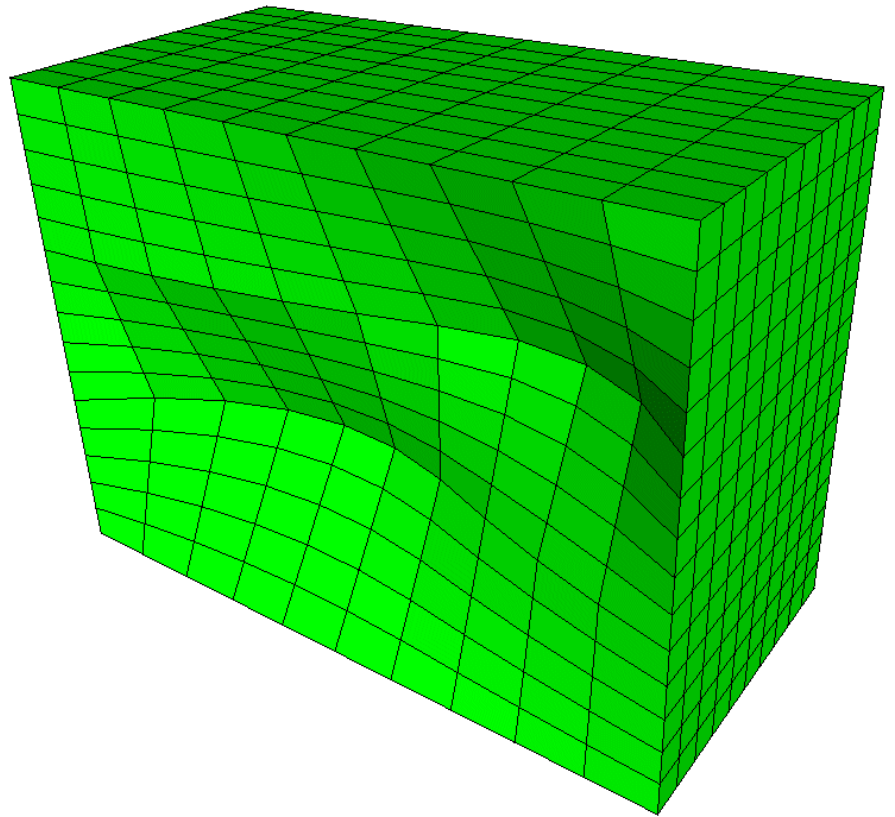
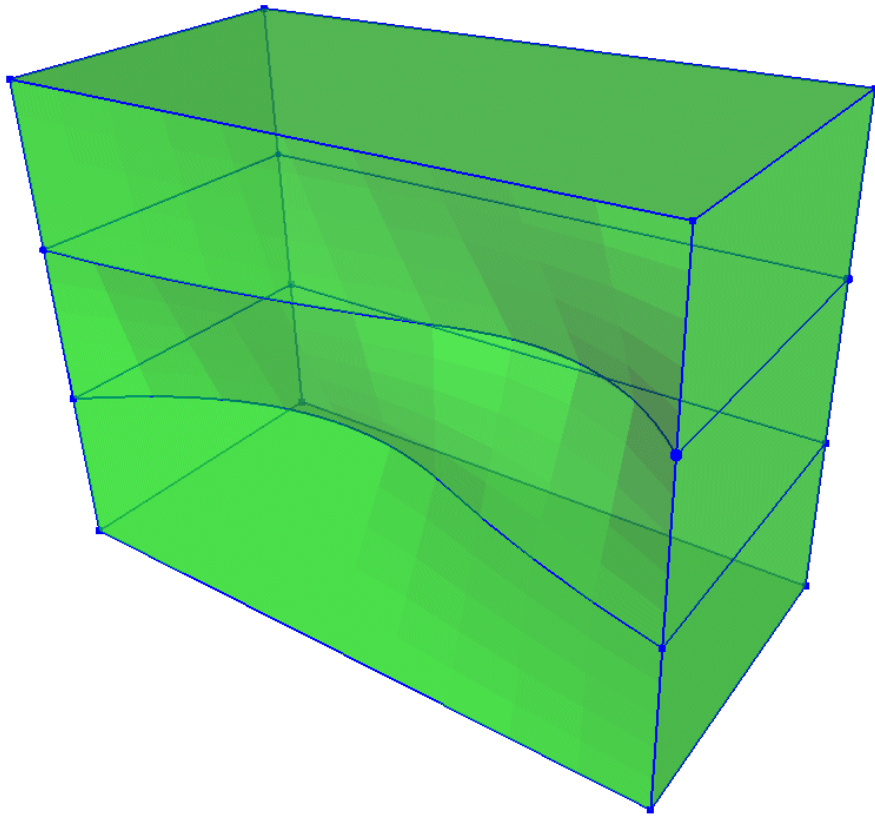
Mtool3D – Subsurface modeling

Modelo complexo sem superfícies fictícias para decomposição de domínios – malhas de tetraedros.



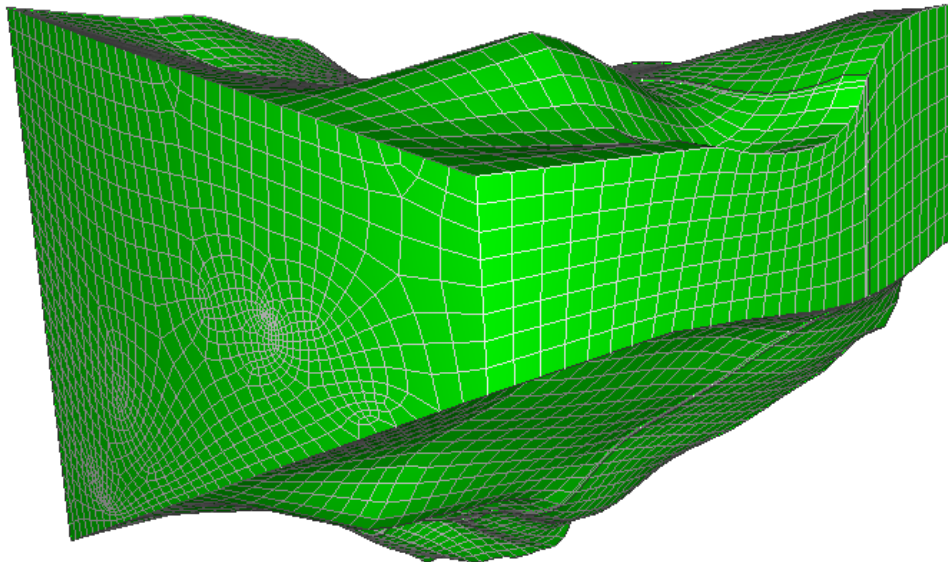
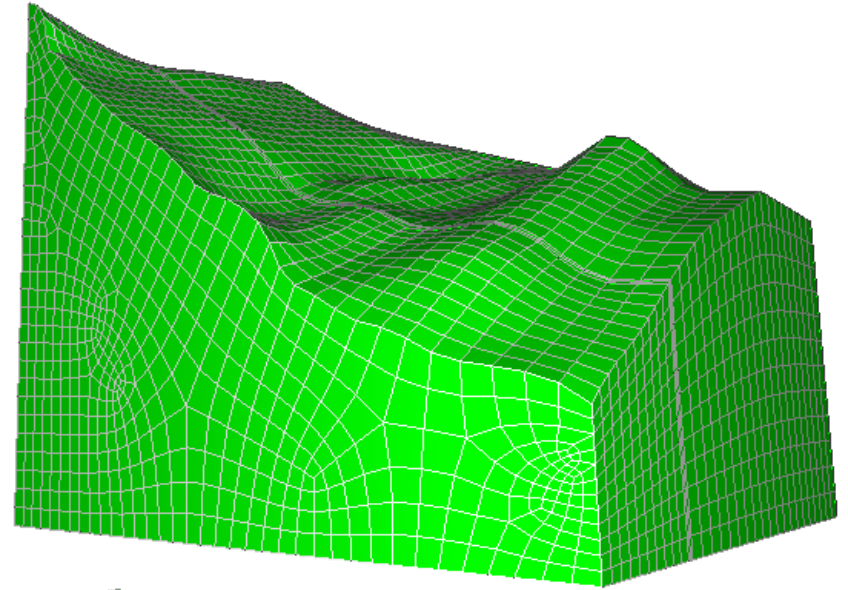
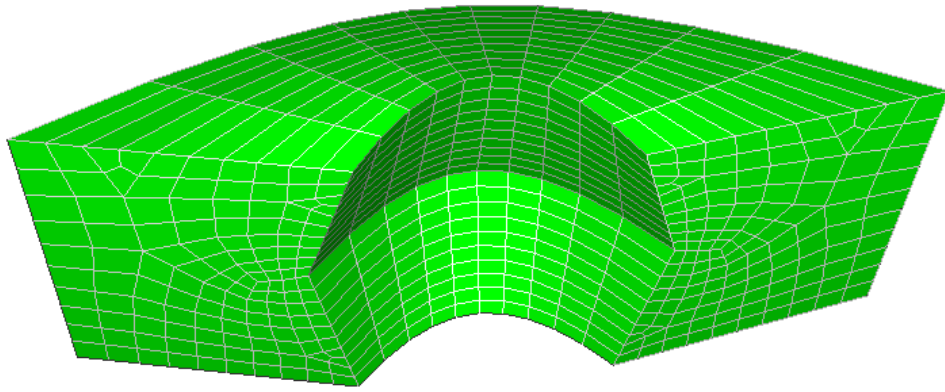
Mtool3D – Solid mesh generation

- 3D discrete transfinite mapping:
 - Multiple surfaces on volume boundary
 - Convex or concave domain



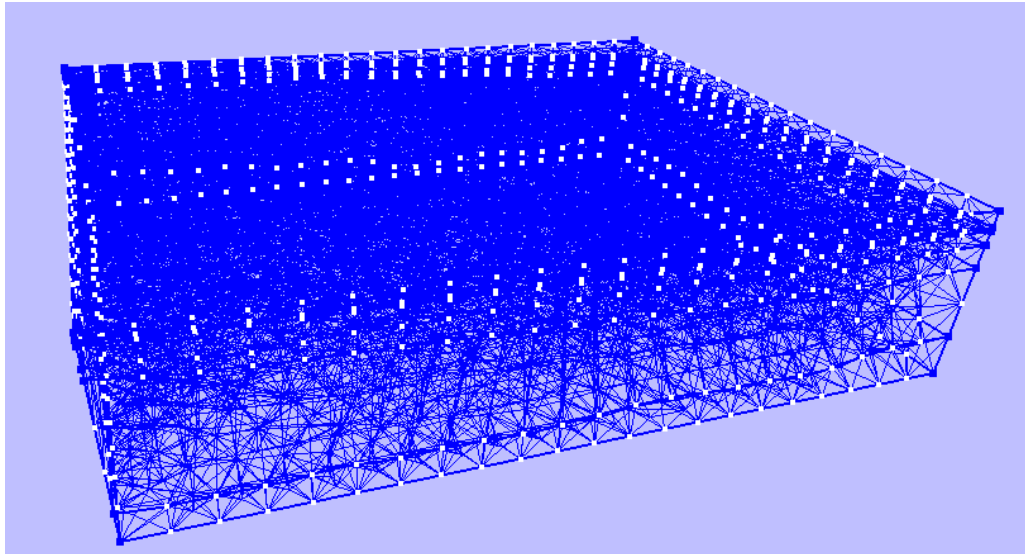
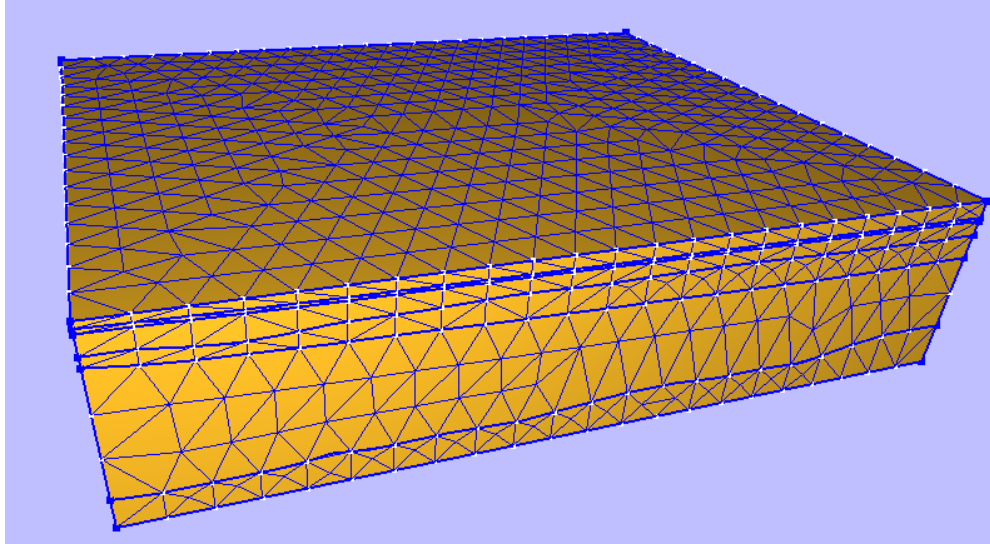
Mtool3D – Solid mesh generation

- *Sweeping:*



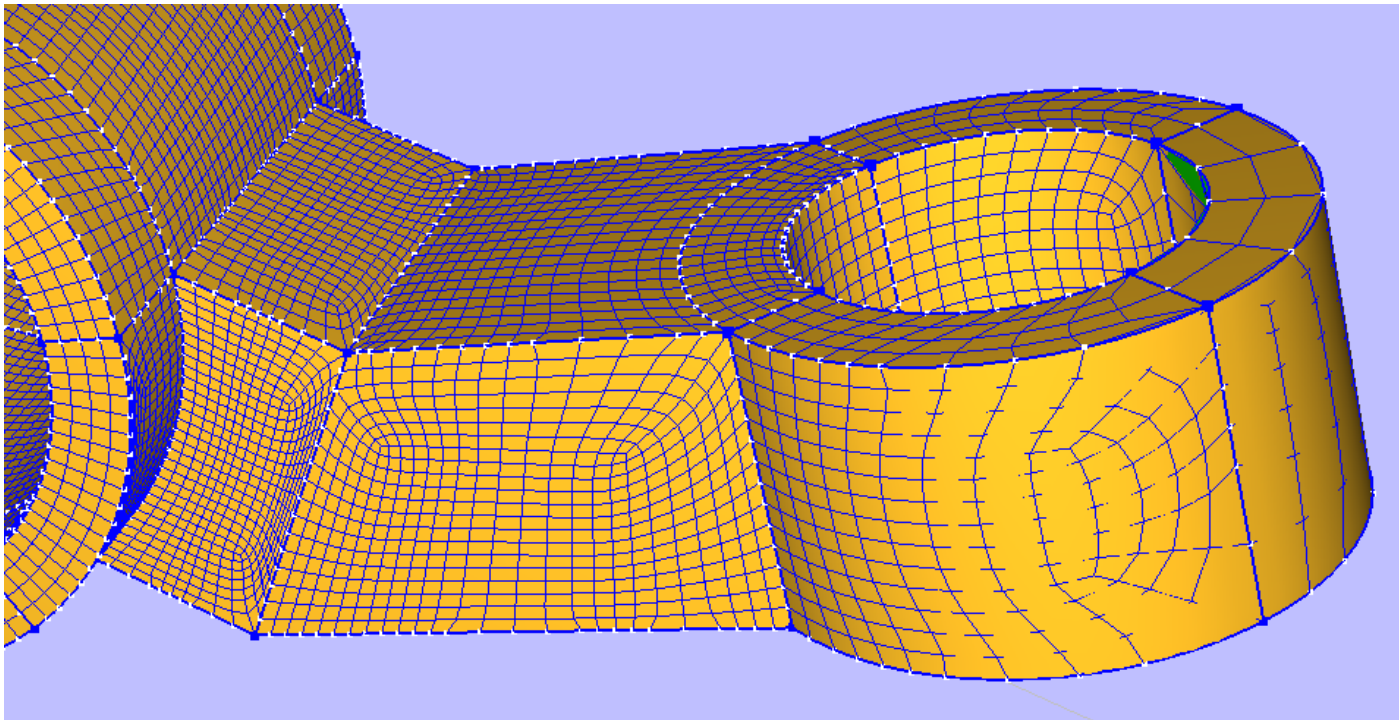
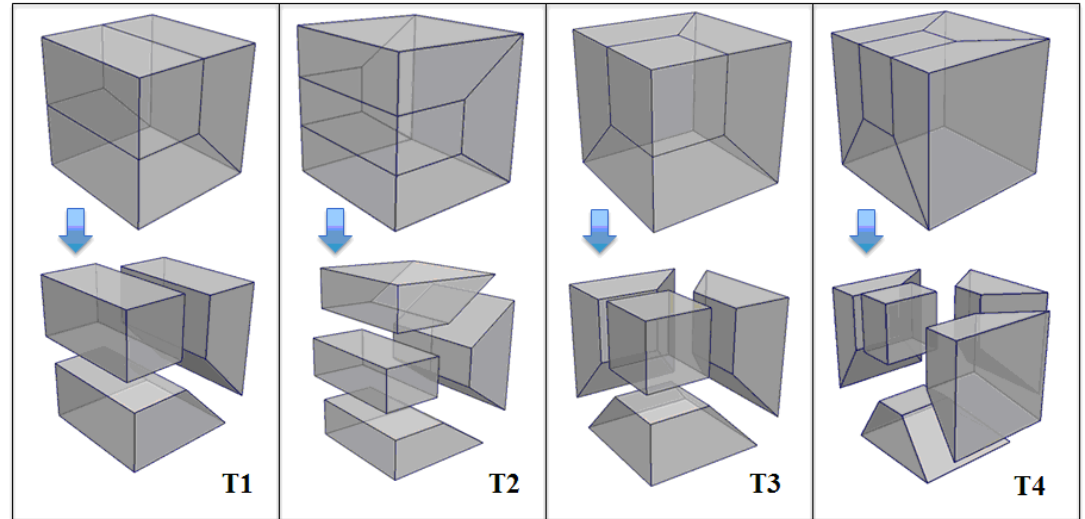
Mtool3D – Solid mesh generation

- Tetrahedral mesh in arbitrary domains (Jmesh):

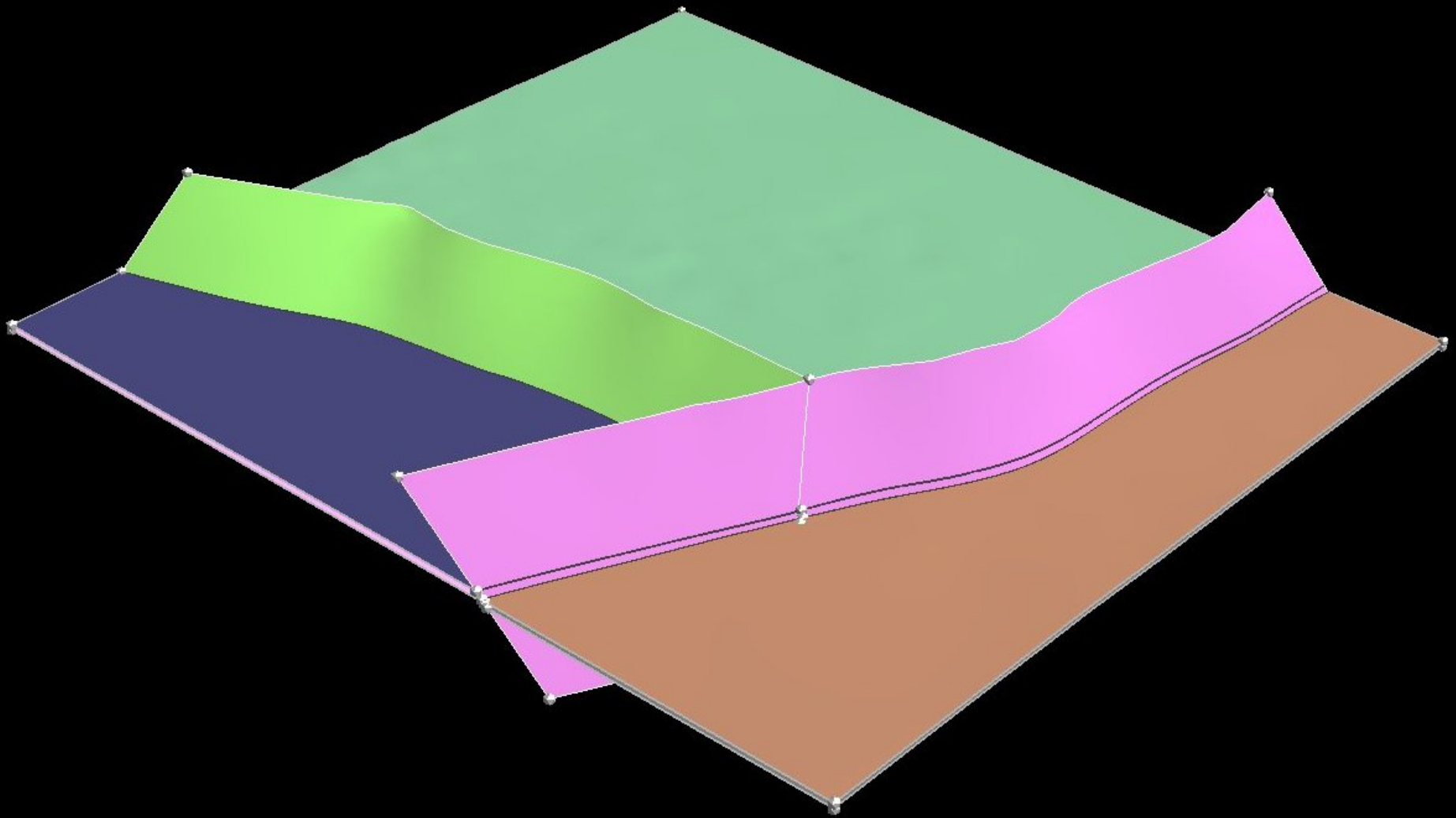


Mtool3D – Solid mesh generation

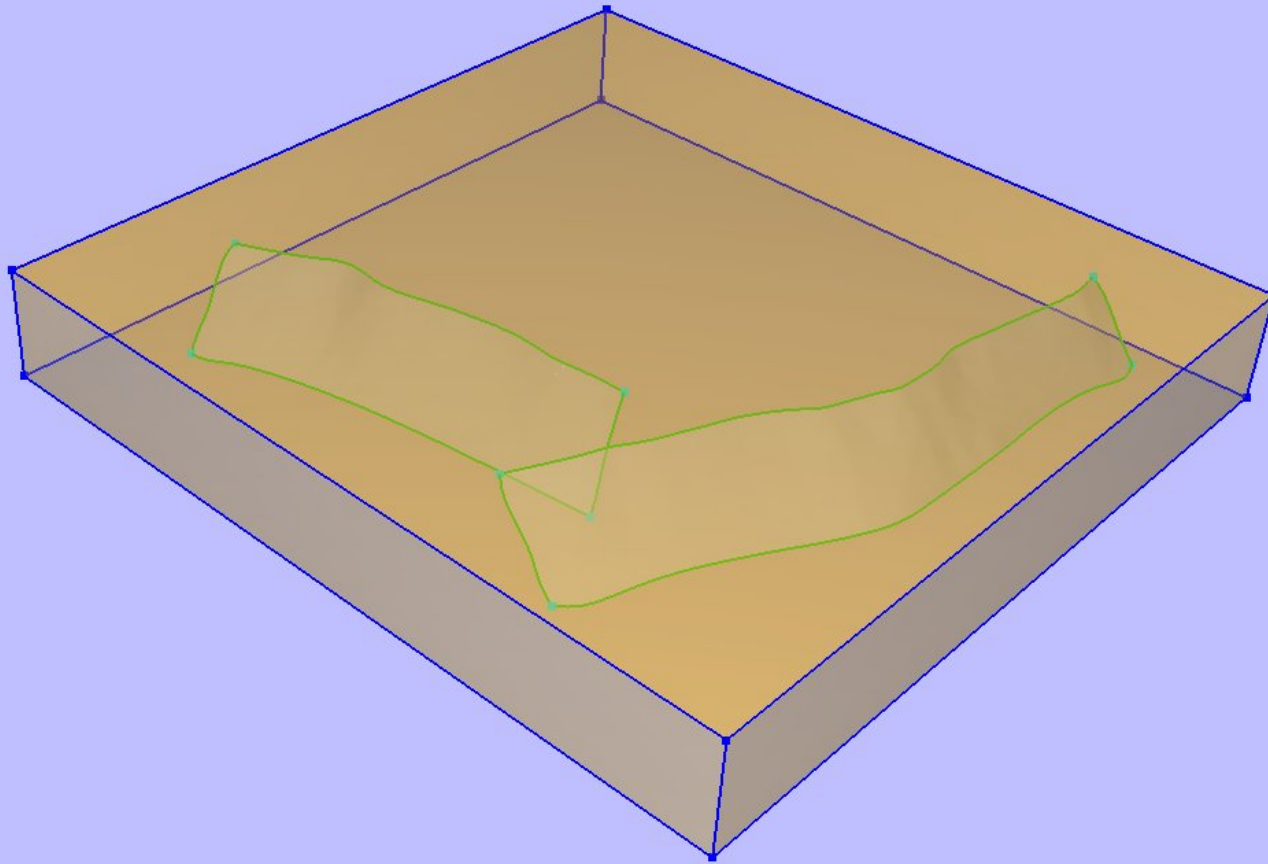
- Under development: hexahedral-template
- Automatic domain decomposition



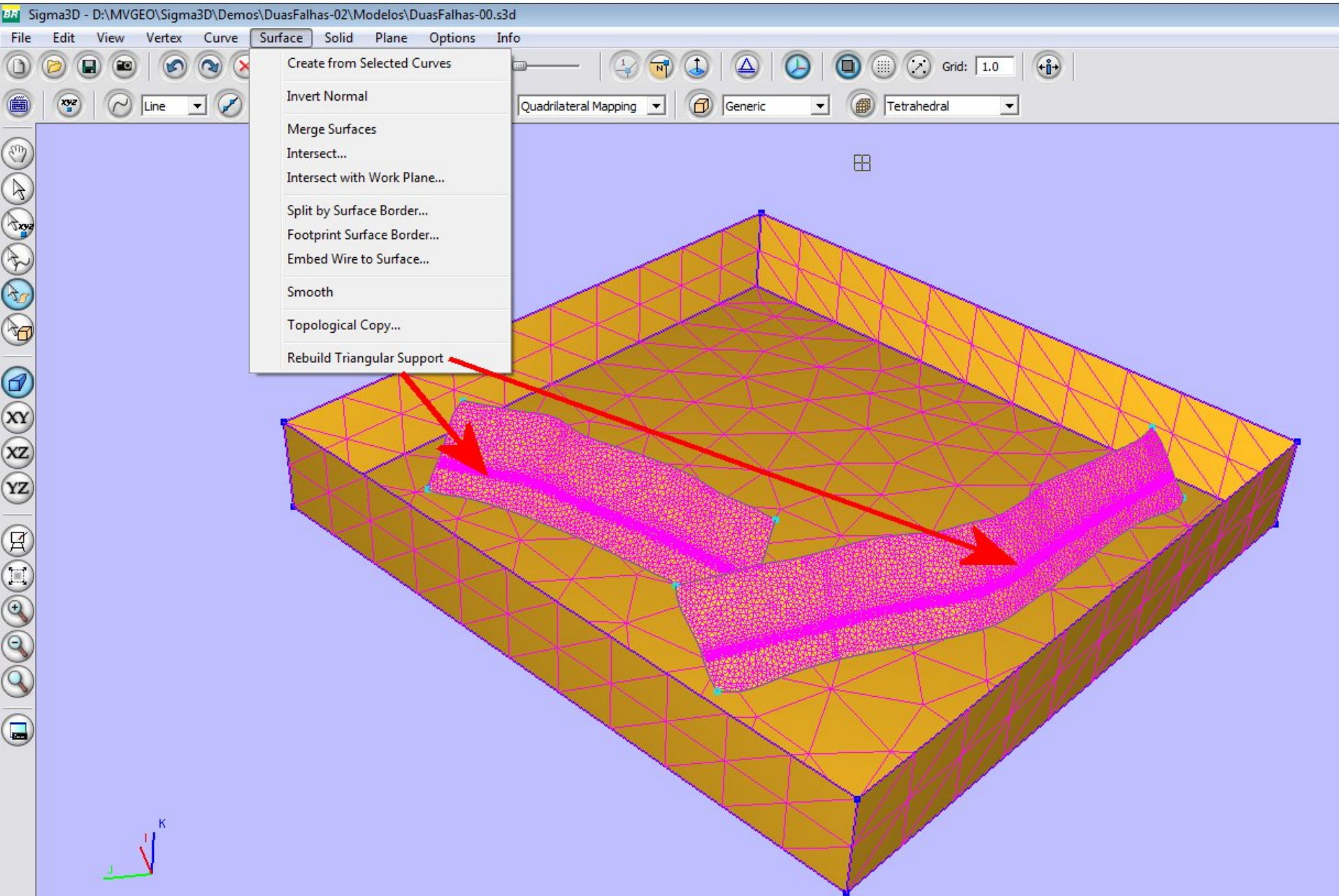
Case study: subsurface model with two faults



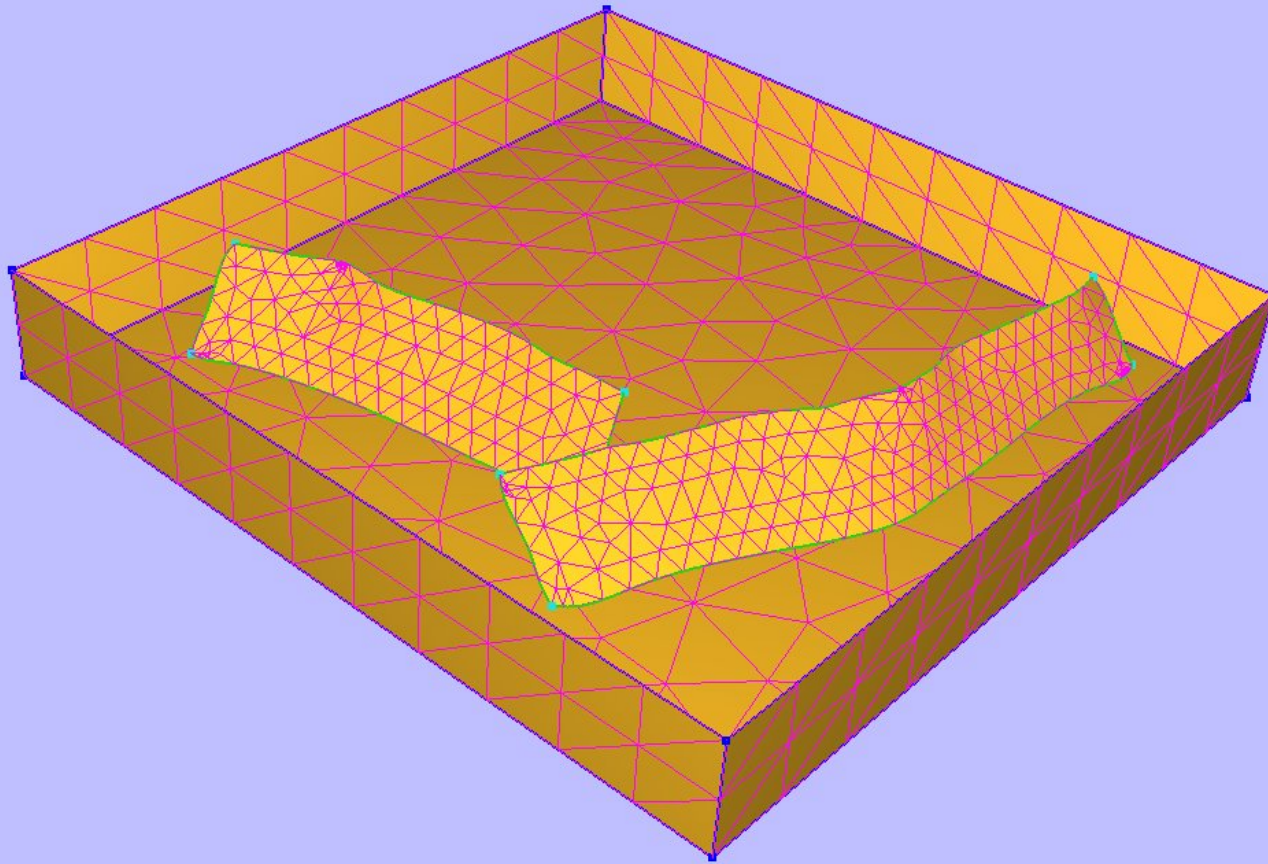
Original geological faults and bounding box



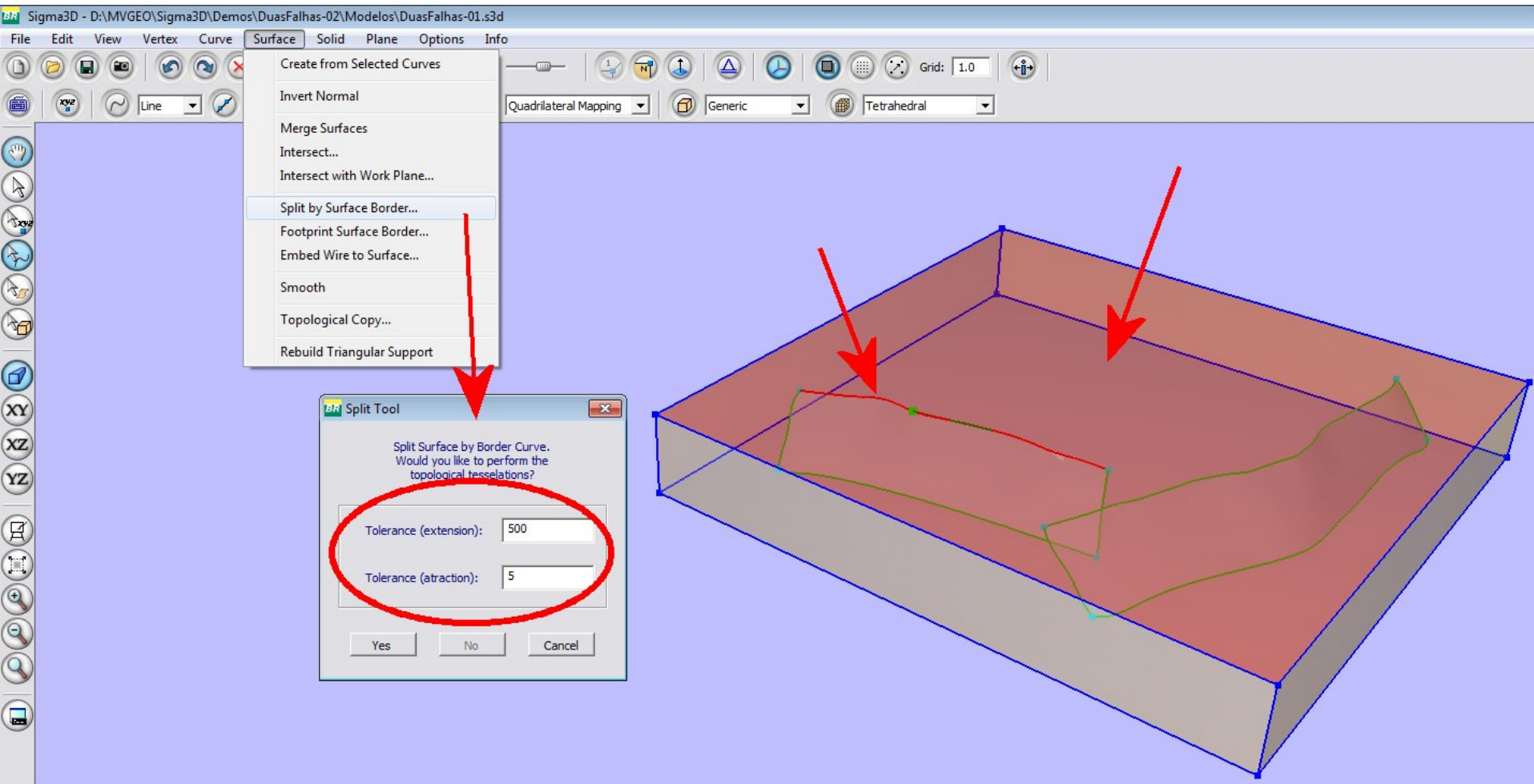
Reconstruction of support triangulation



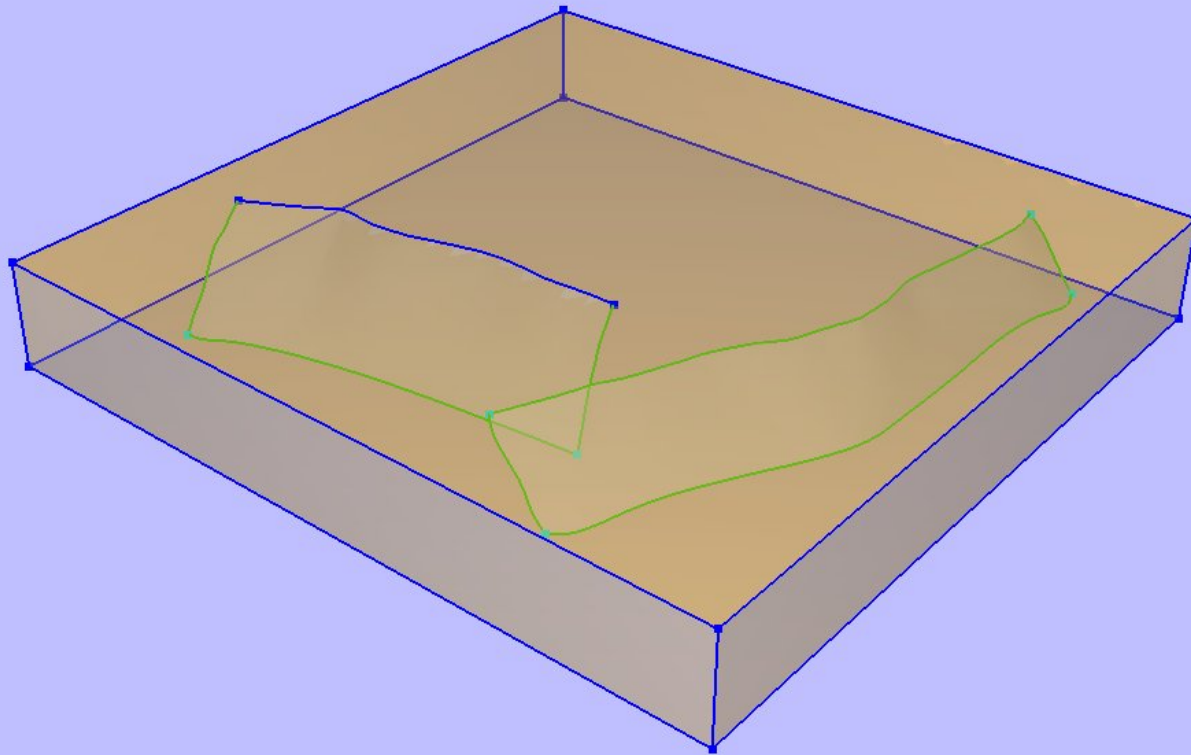
Reconstruction of support triangulation



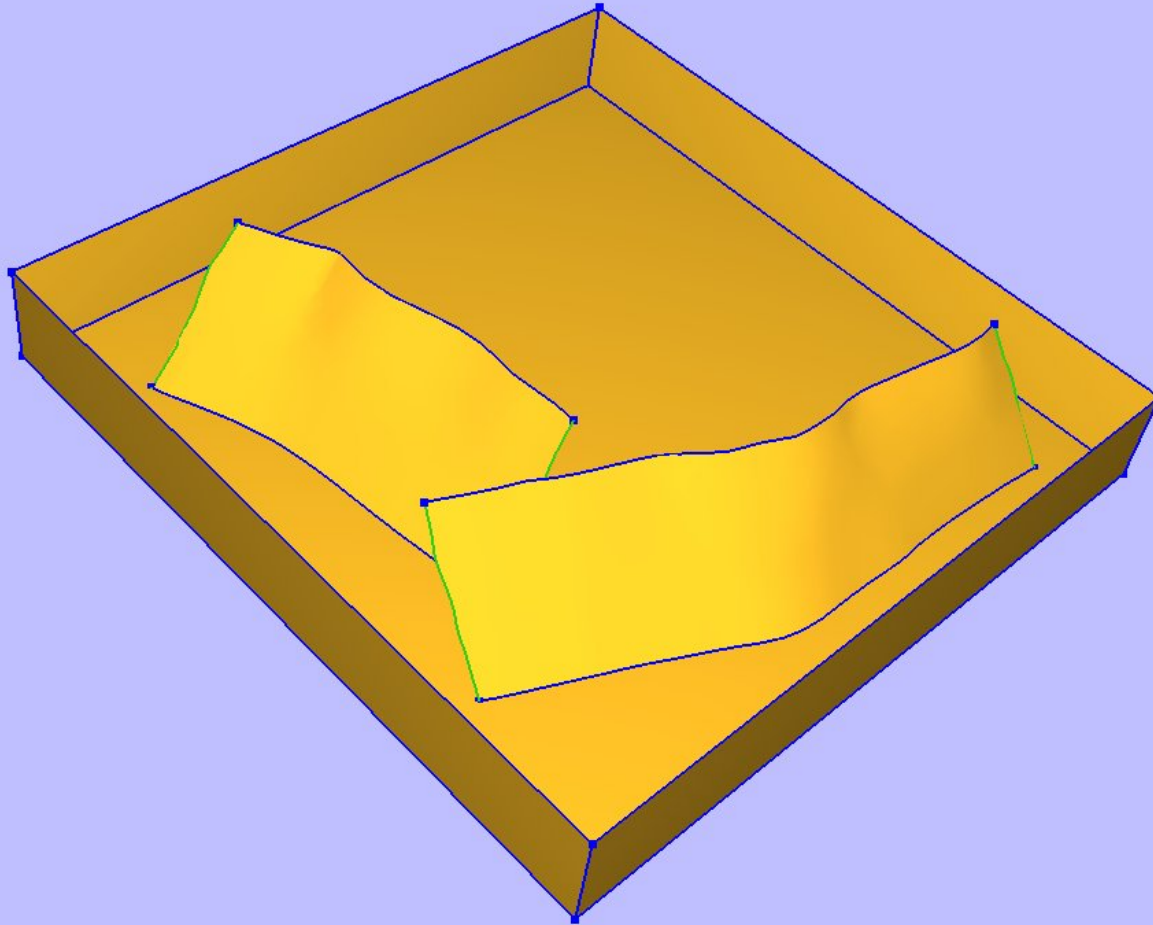
Split surface by surface border



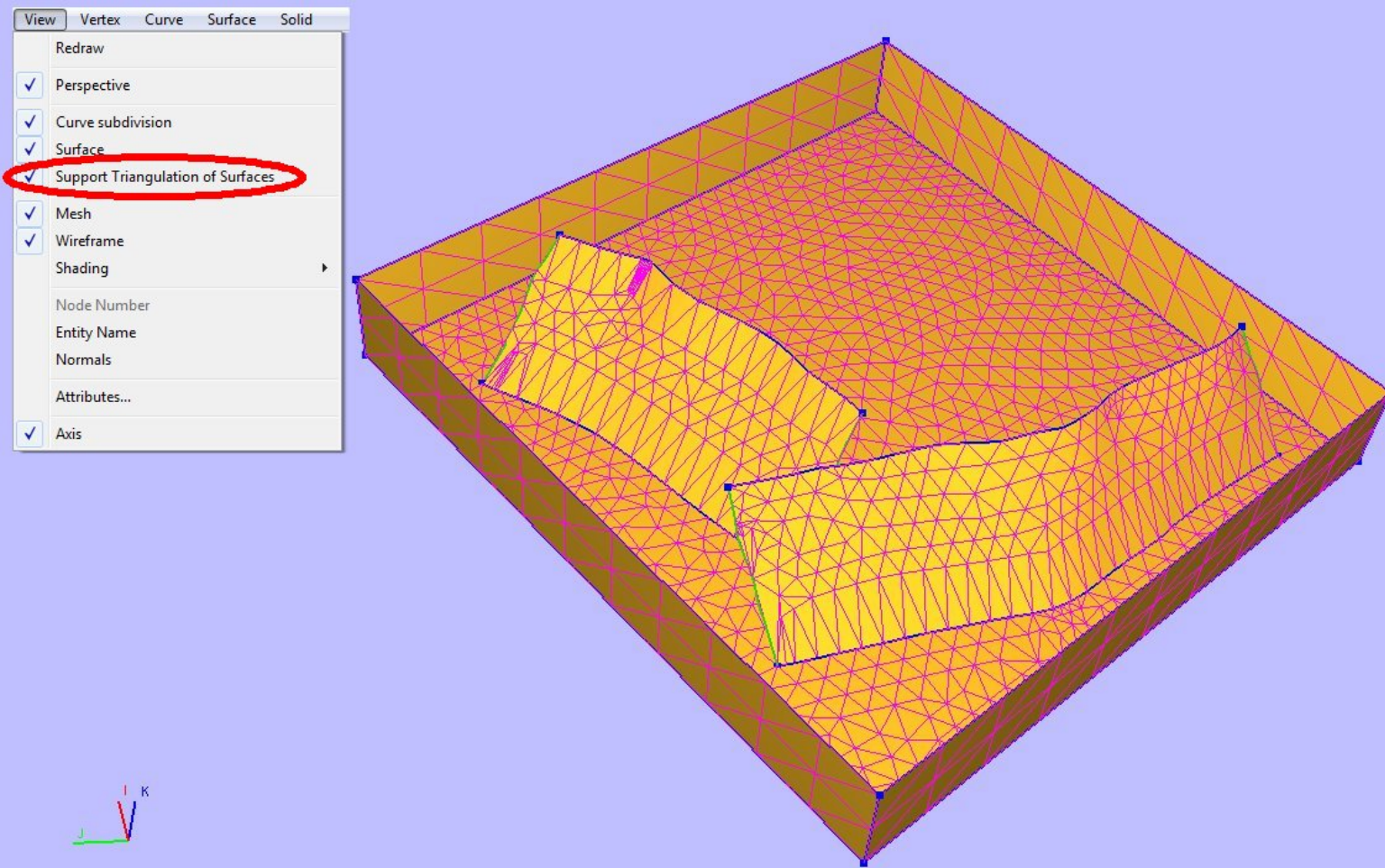
Surface split by extended surface border



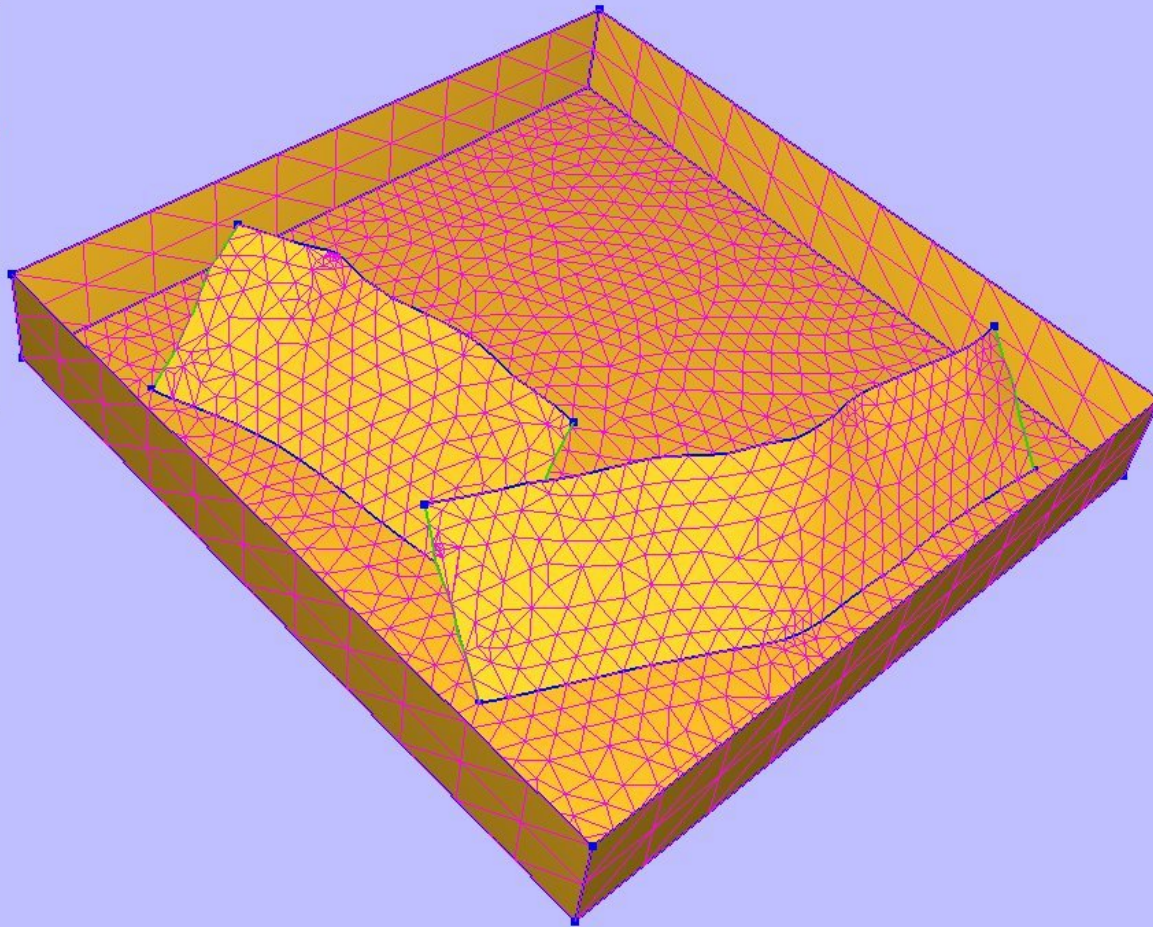
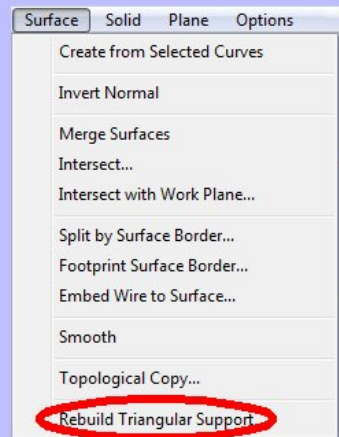
Split by surface border: fault extensions



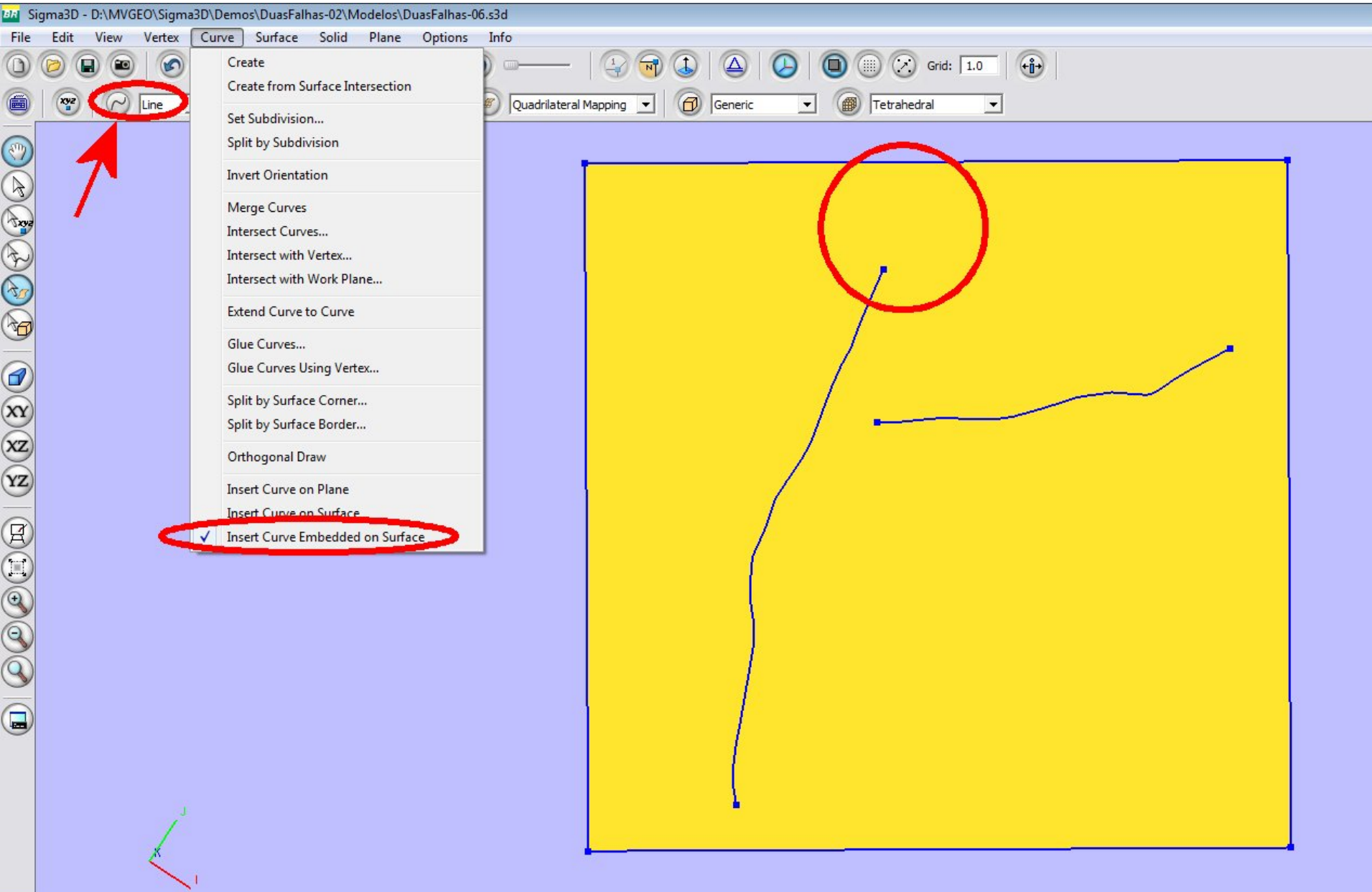
Support triangulation of extended faults



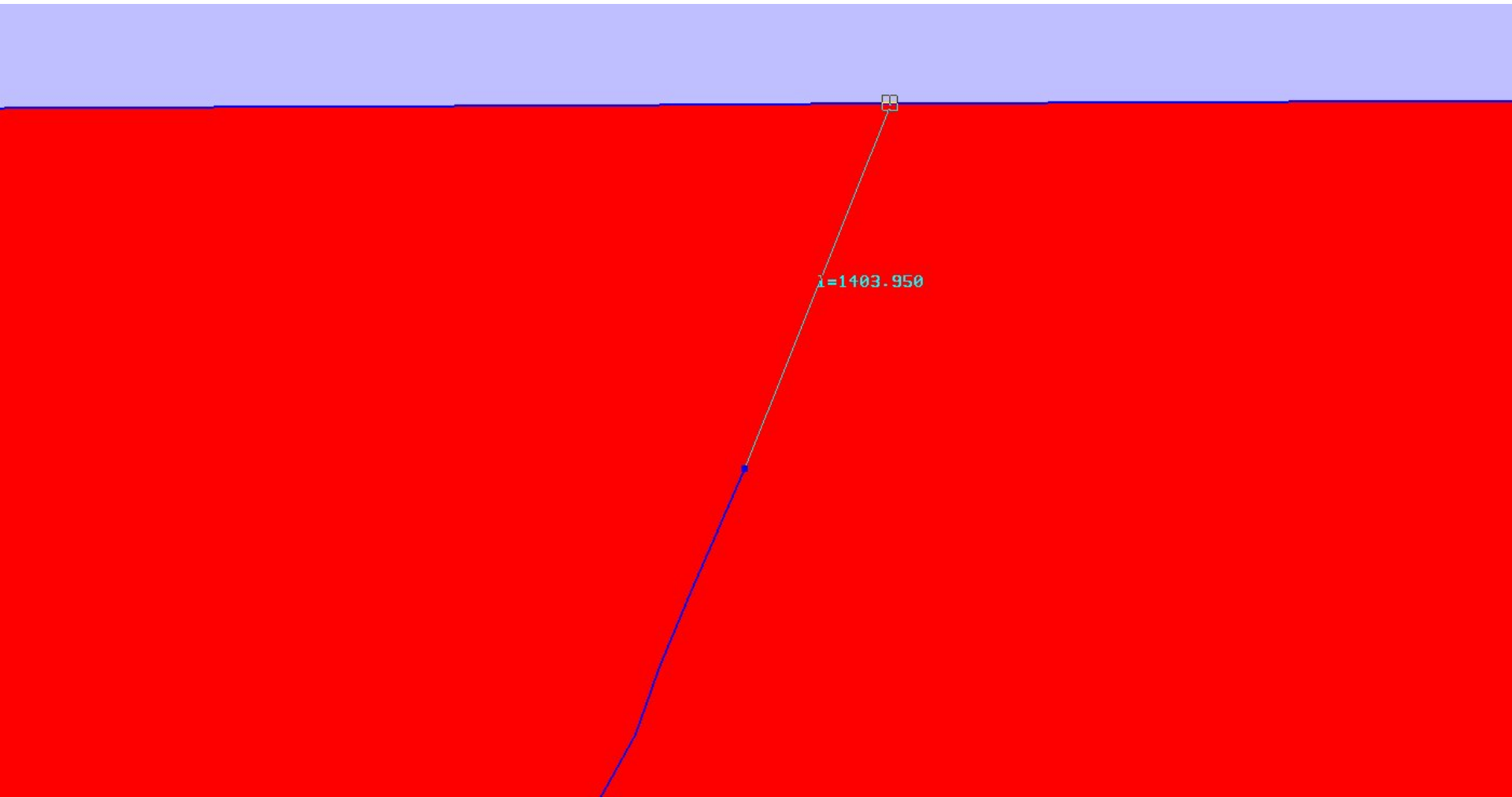
Reconstruction of support triangulation



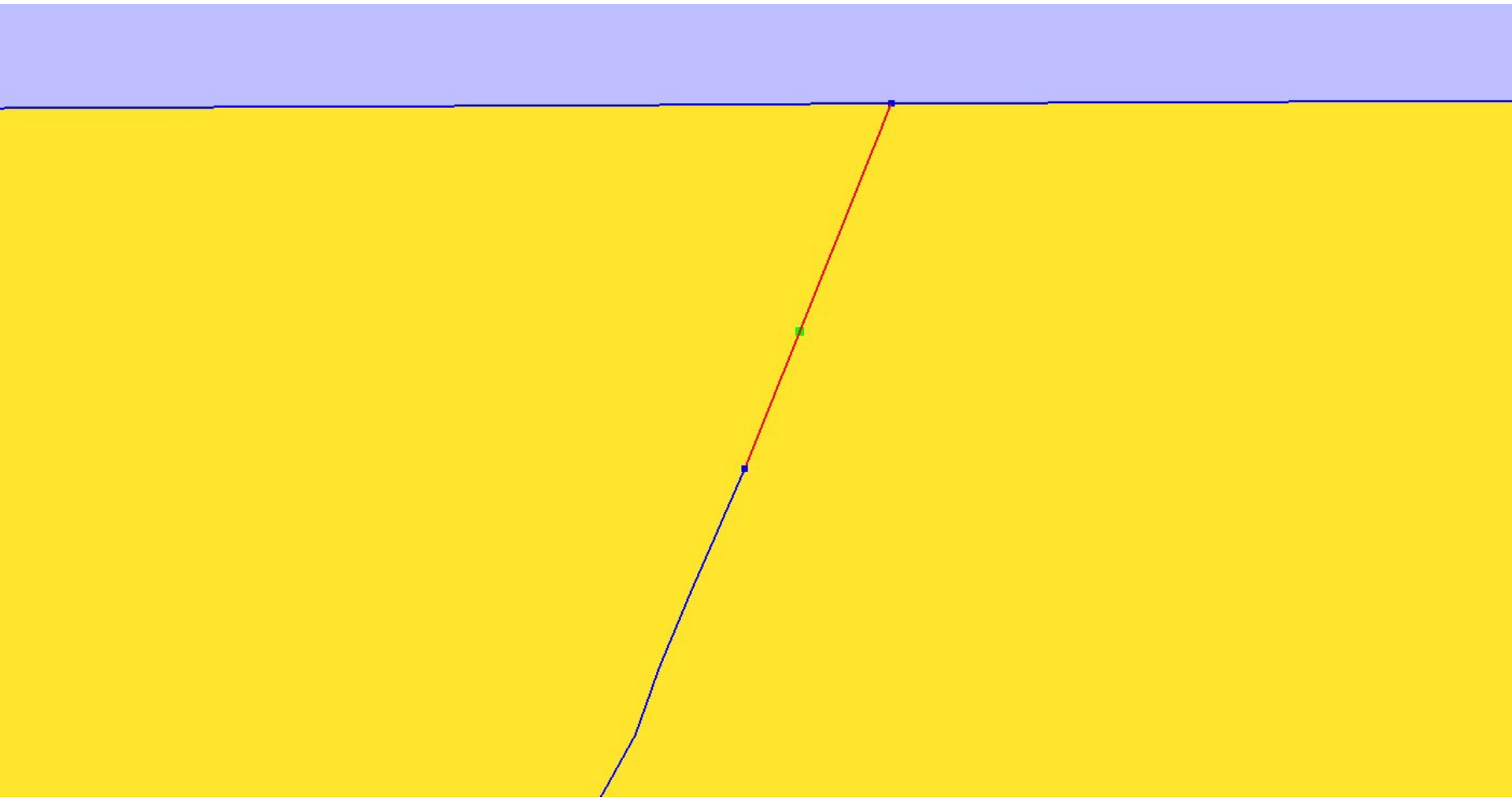
Curve insertion of surface



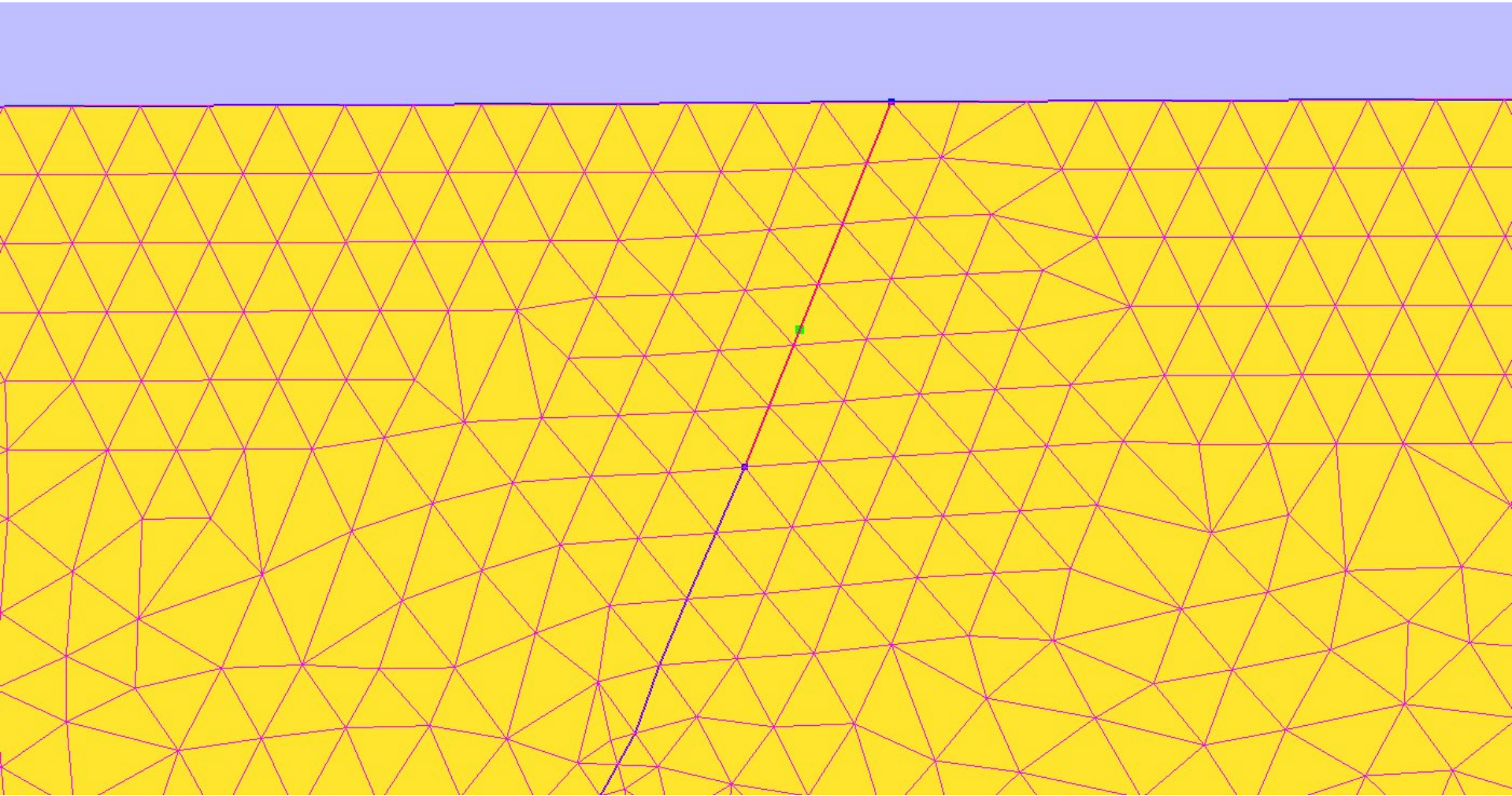
Curve insertion of surface



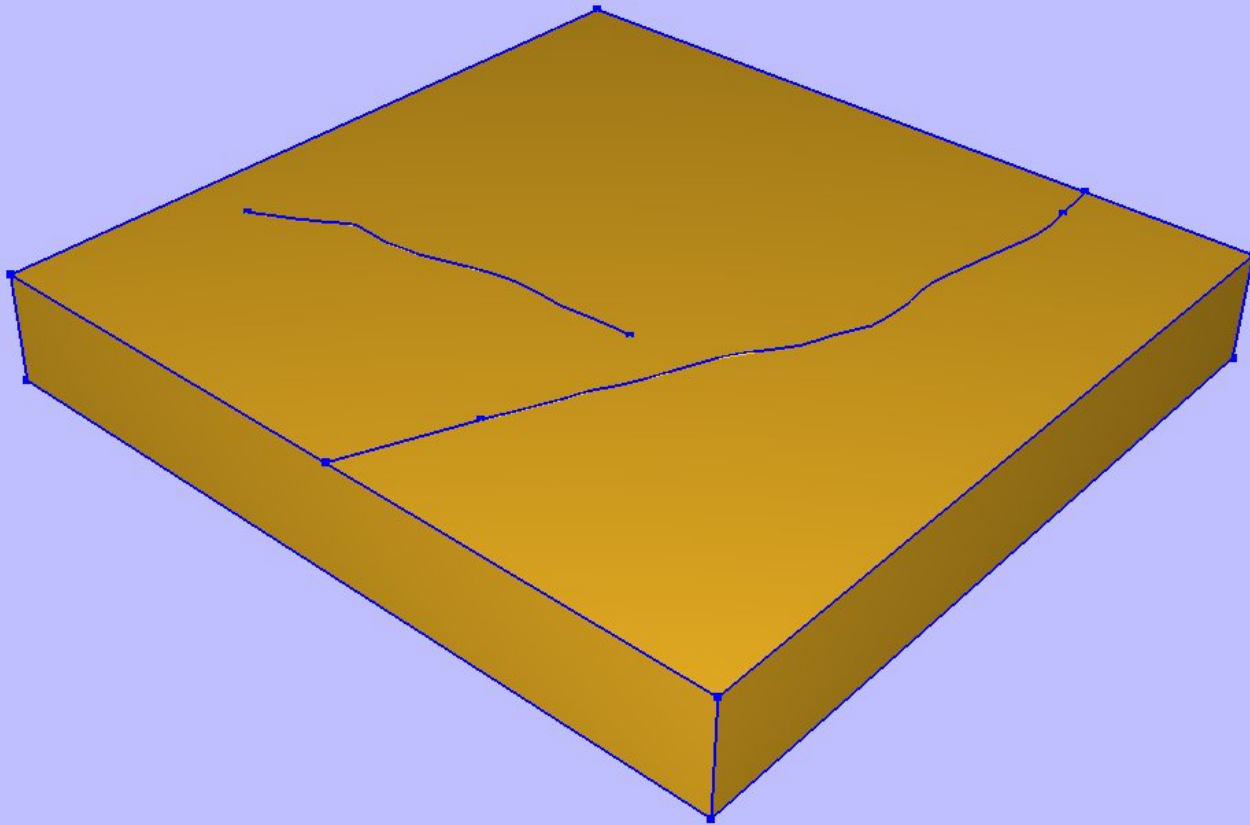
Curve insertion of surface



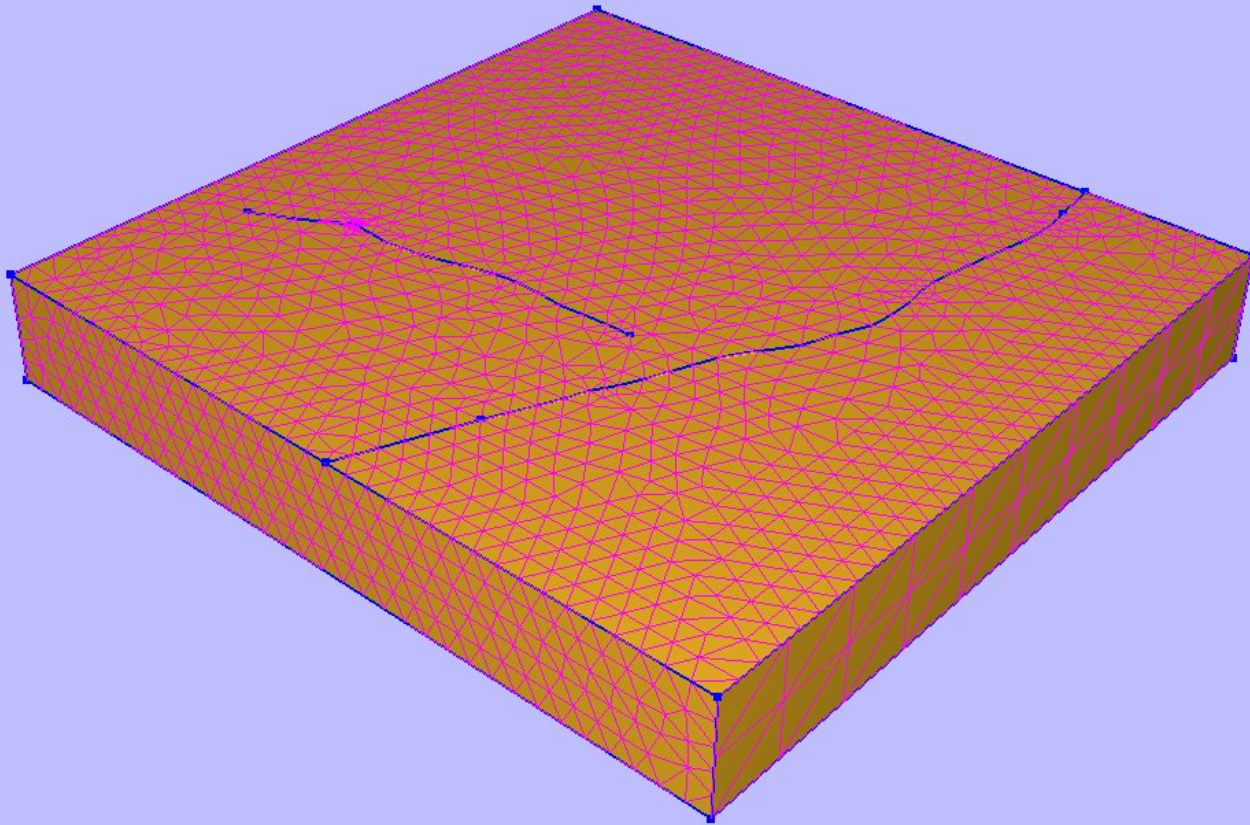
Reconstruction of support triangulation



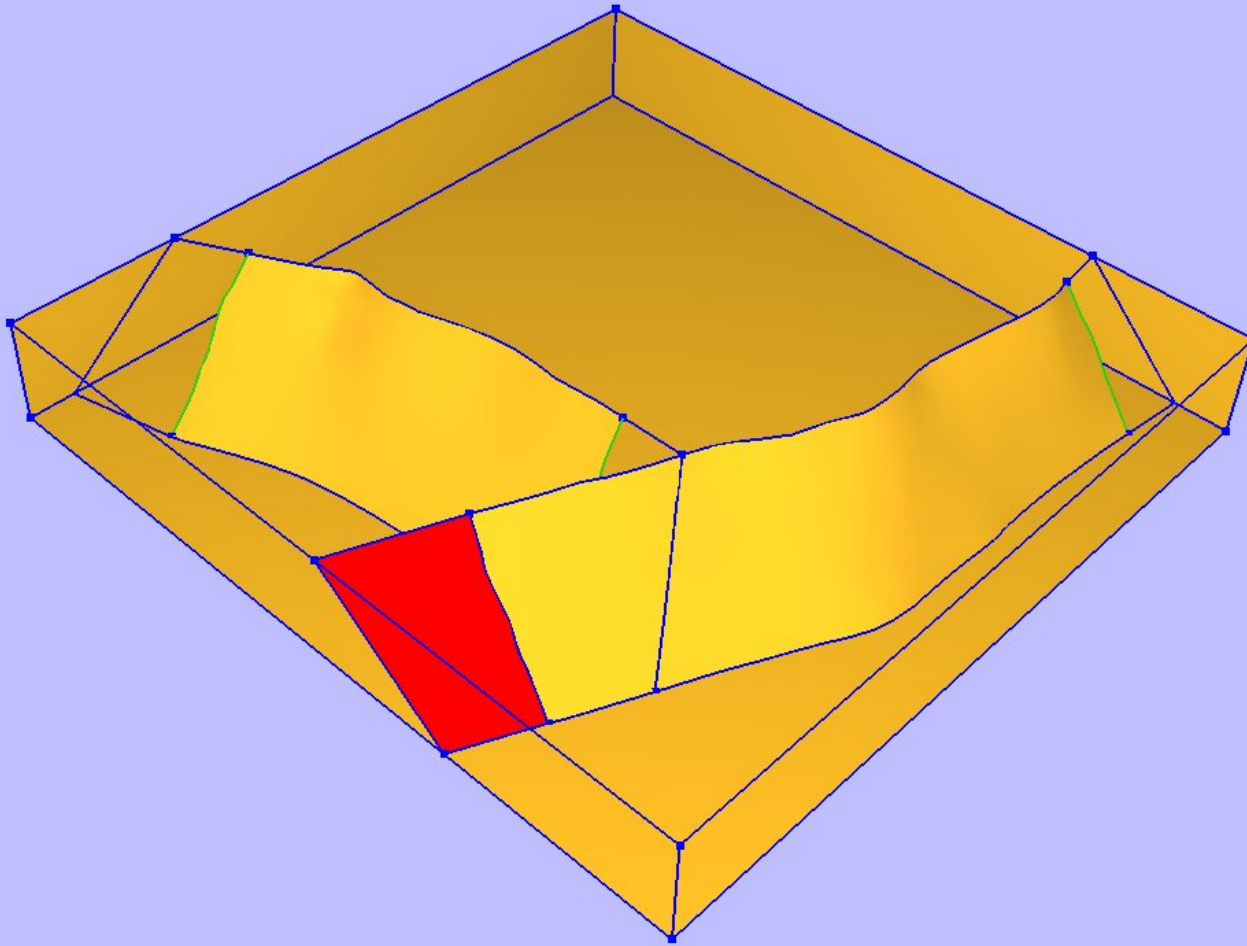
Curve insertion of surface



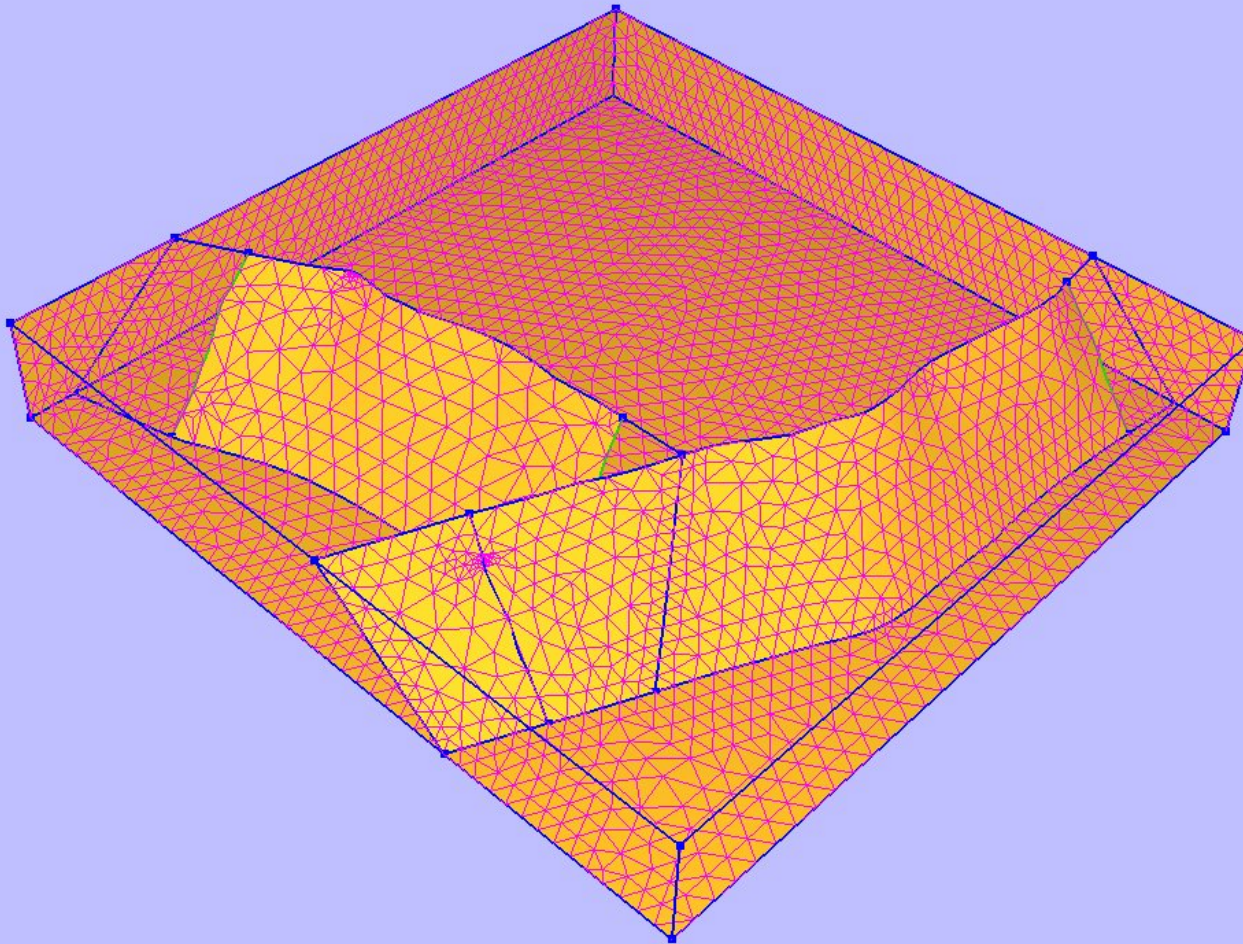
Reconstruction of support triangulation



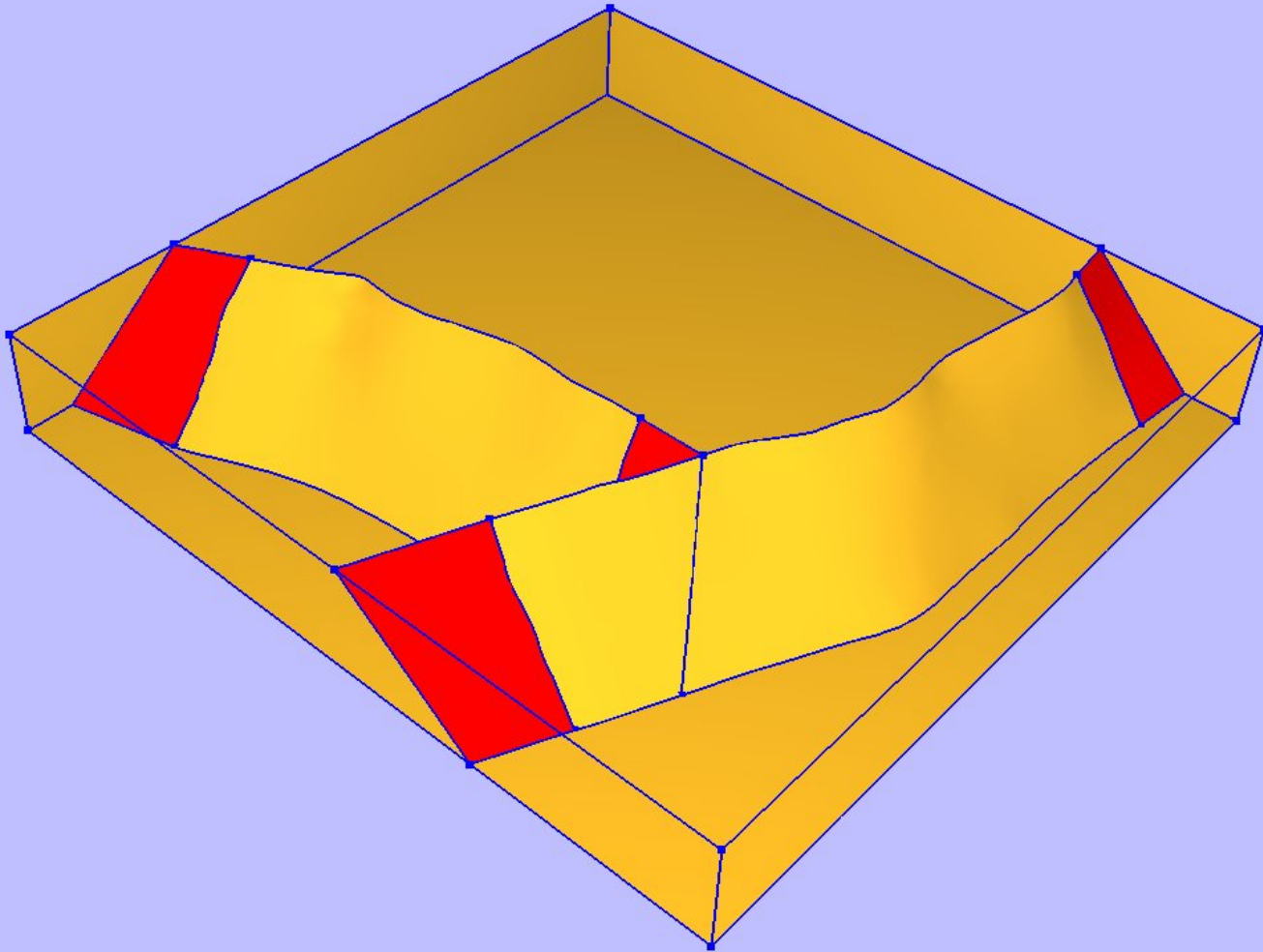
Creation of a surface patch



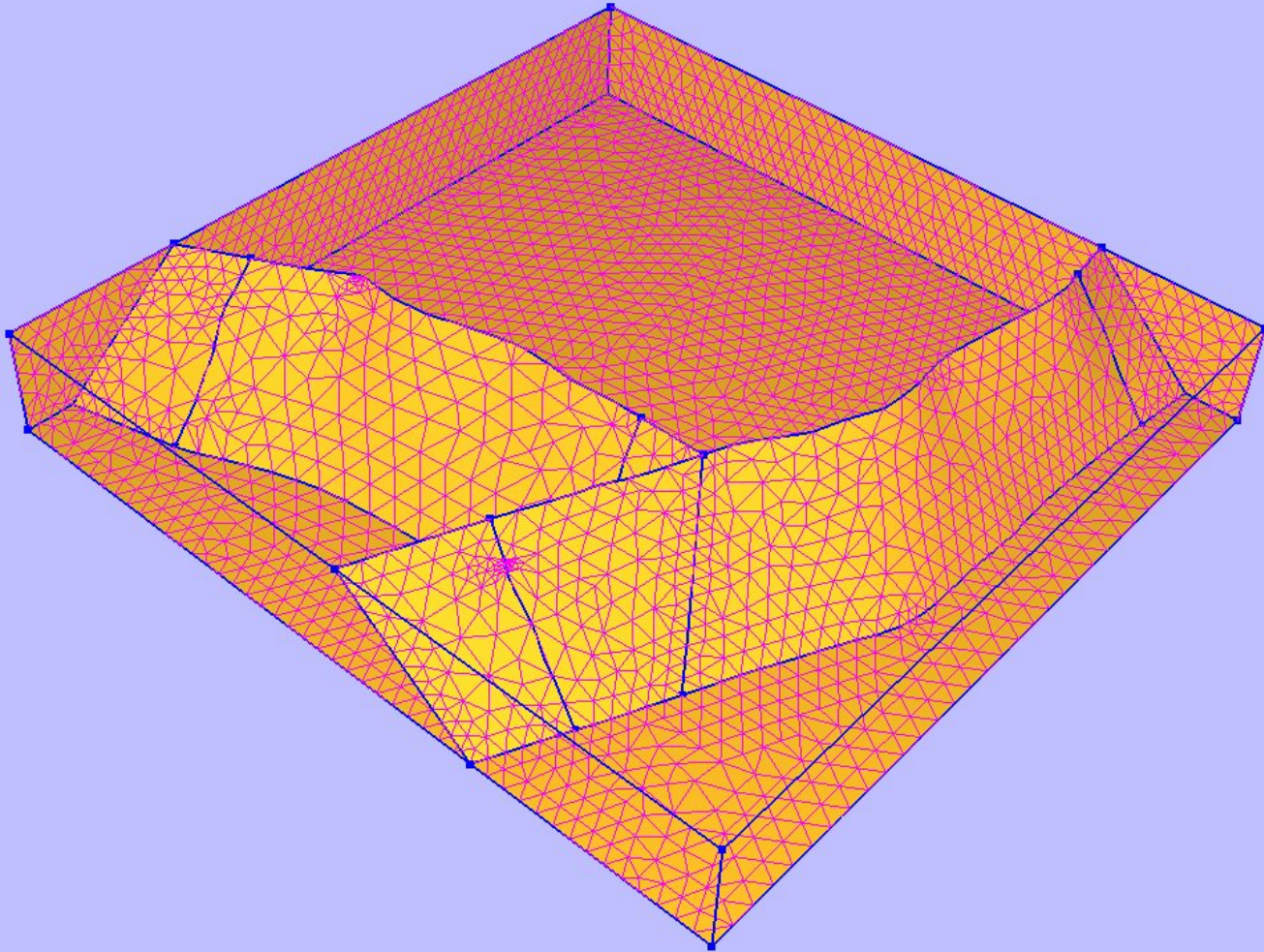
Support triangulation of new patch



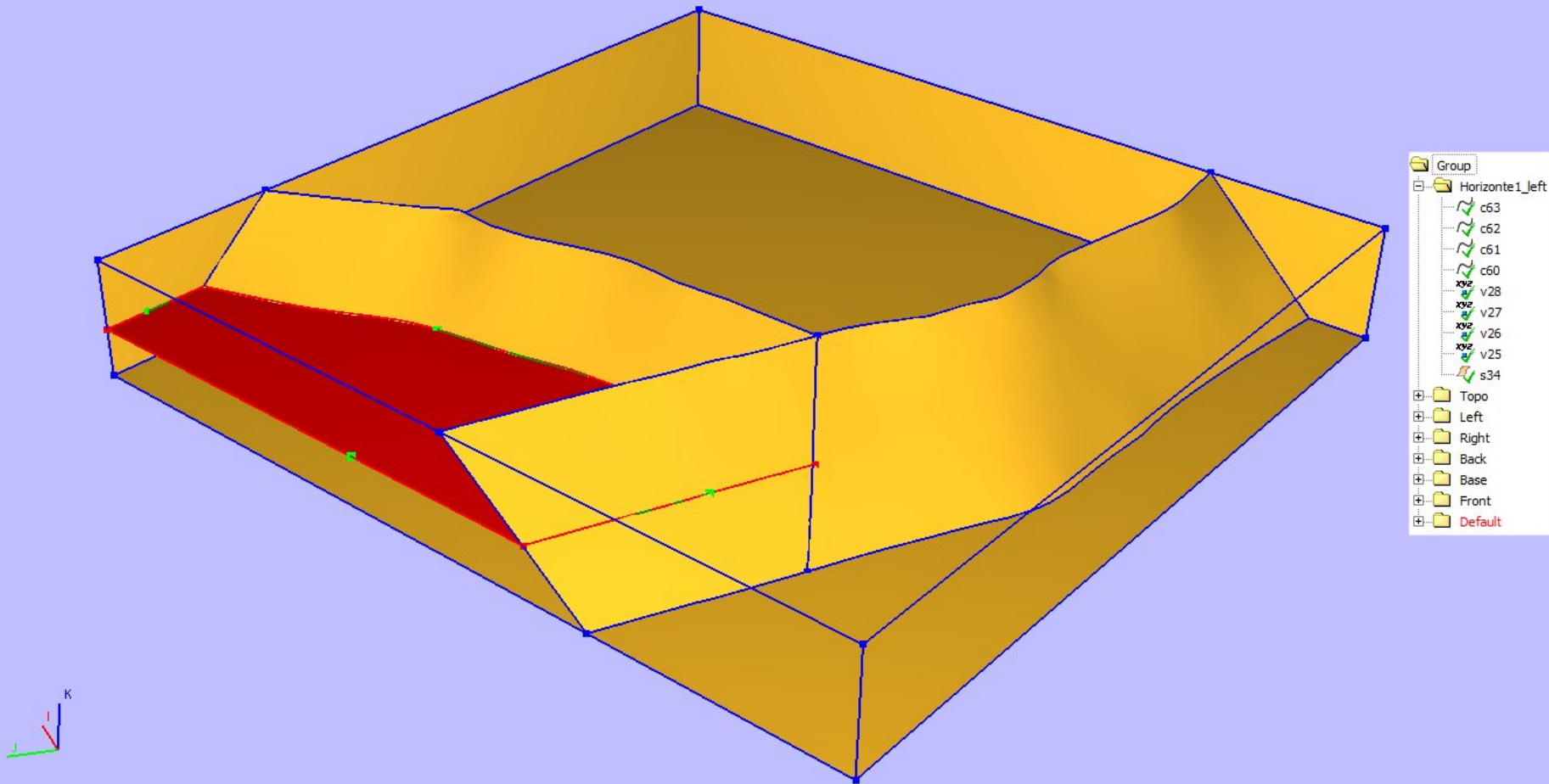
New surface patches



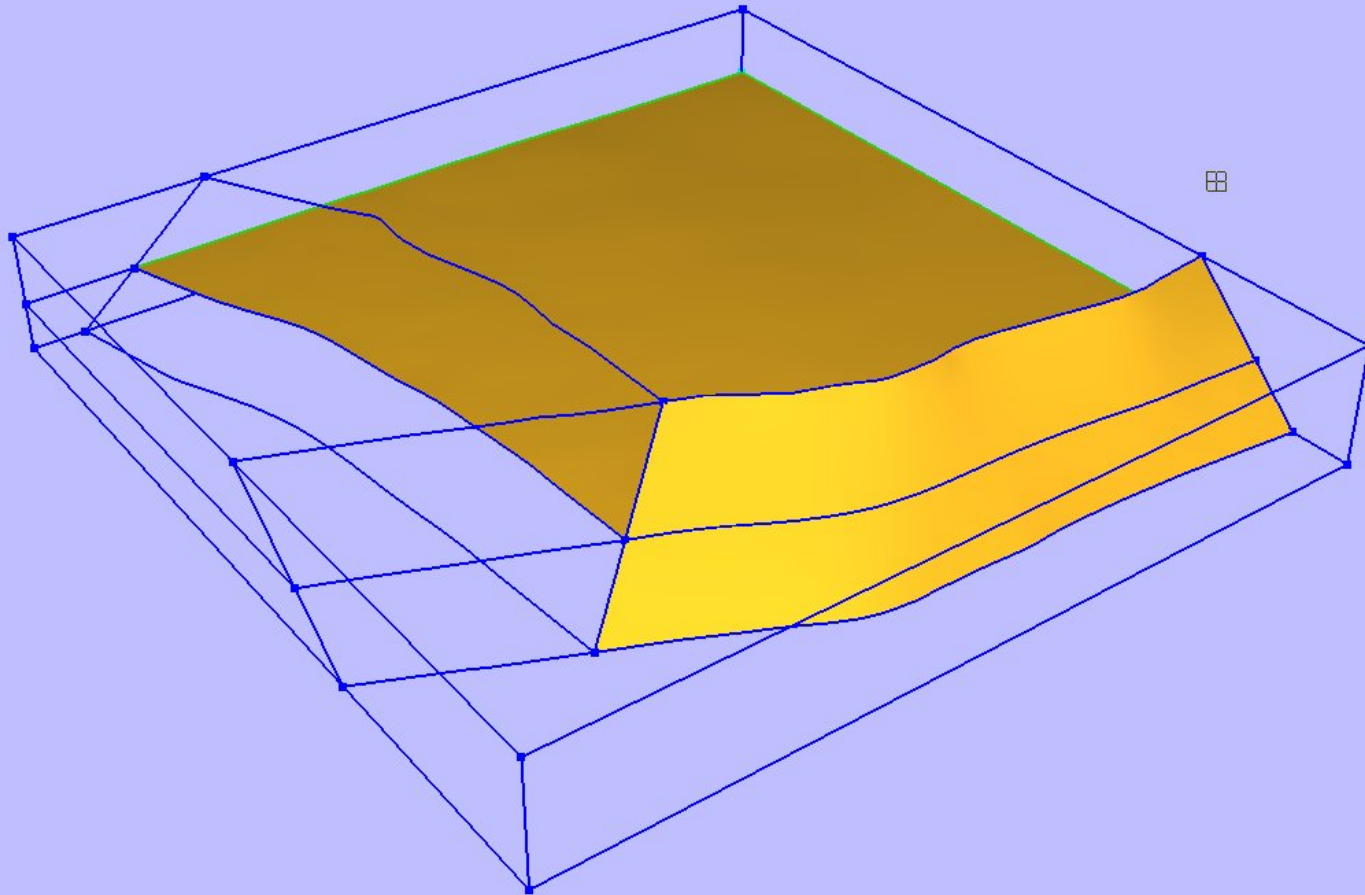
Support triangulations



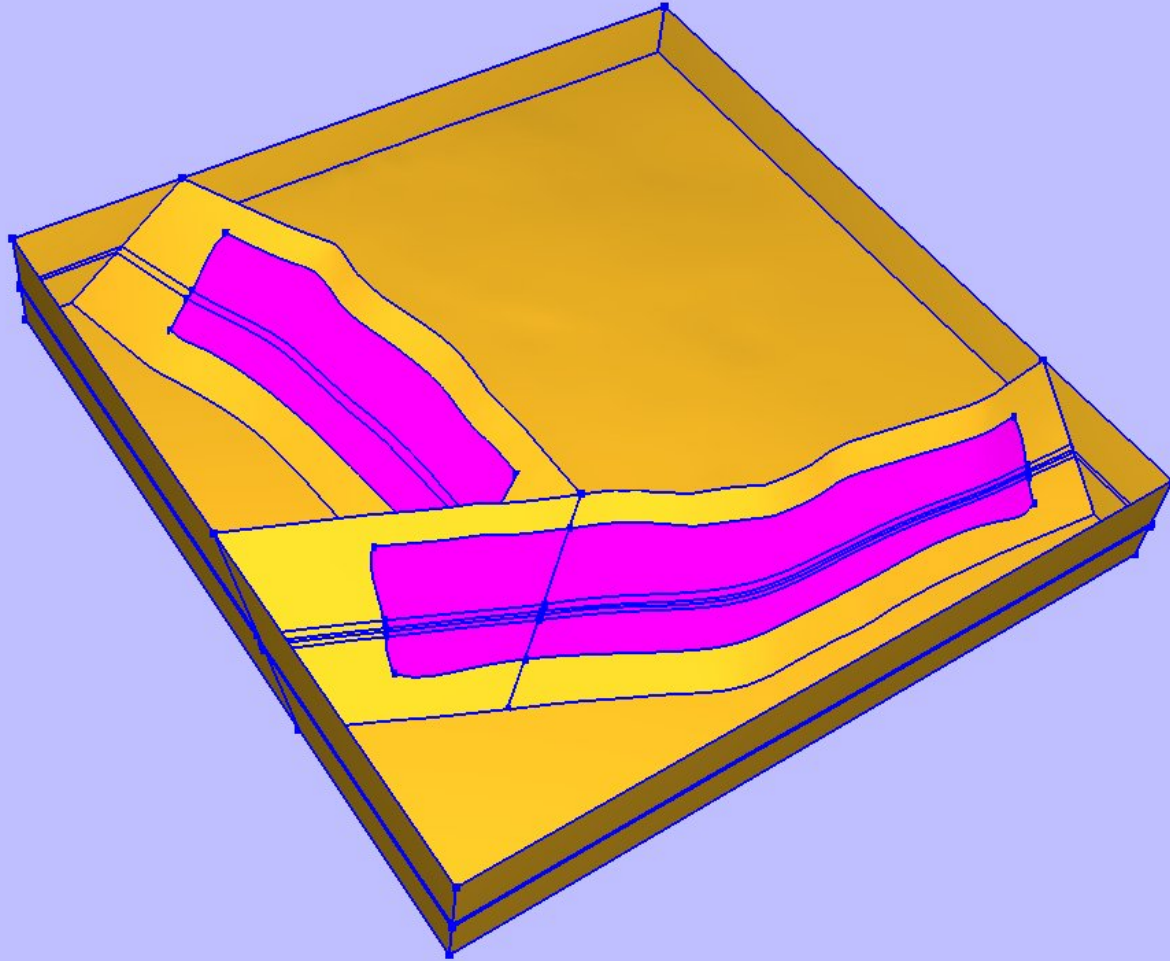
Adjustments of geological horizon surface



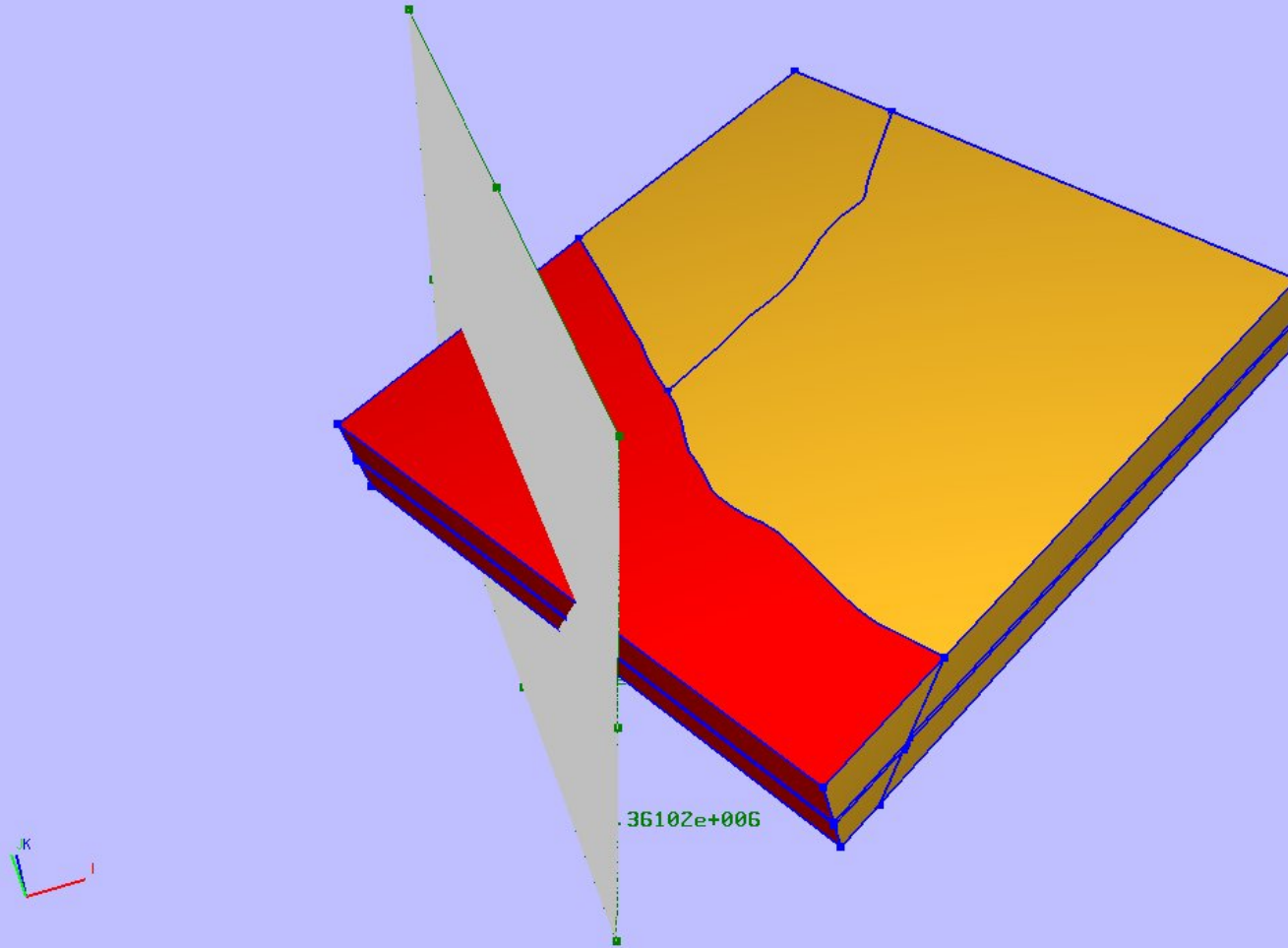
Treatment of other geological horizon surfaces



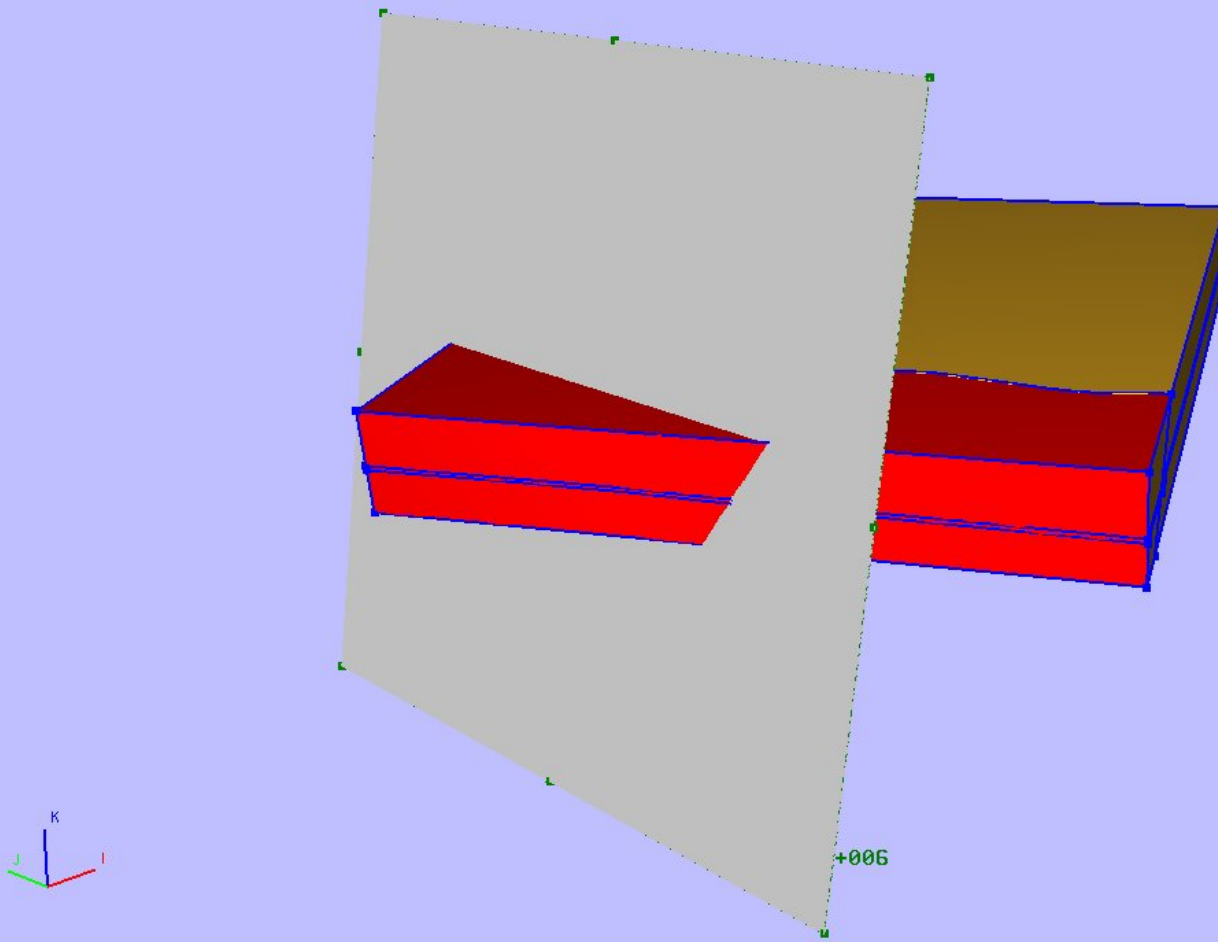
Recovery of original fault surfaces



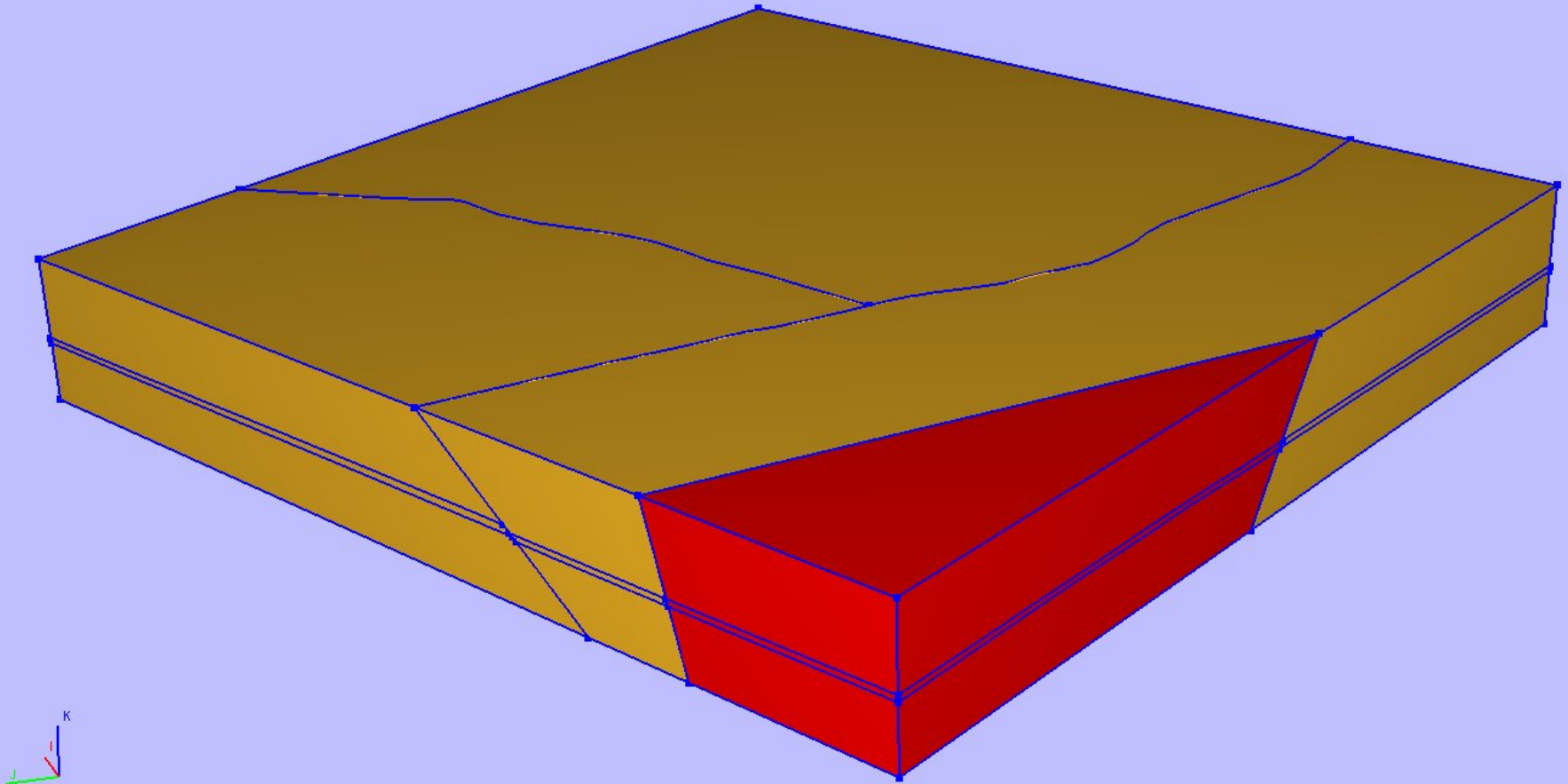
Domain decomposition for solid mesh generation



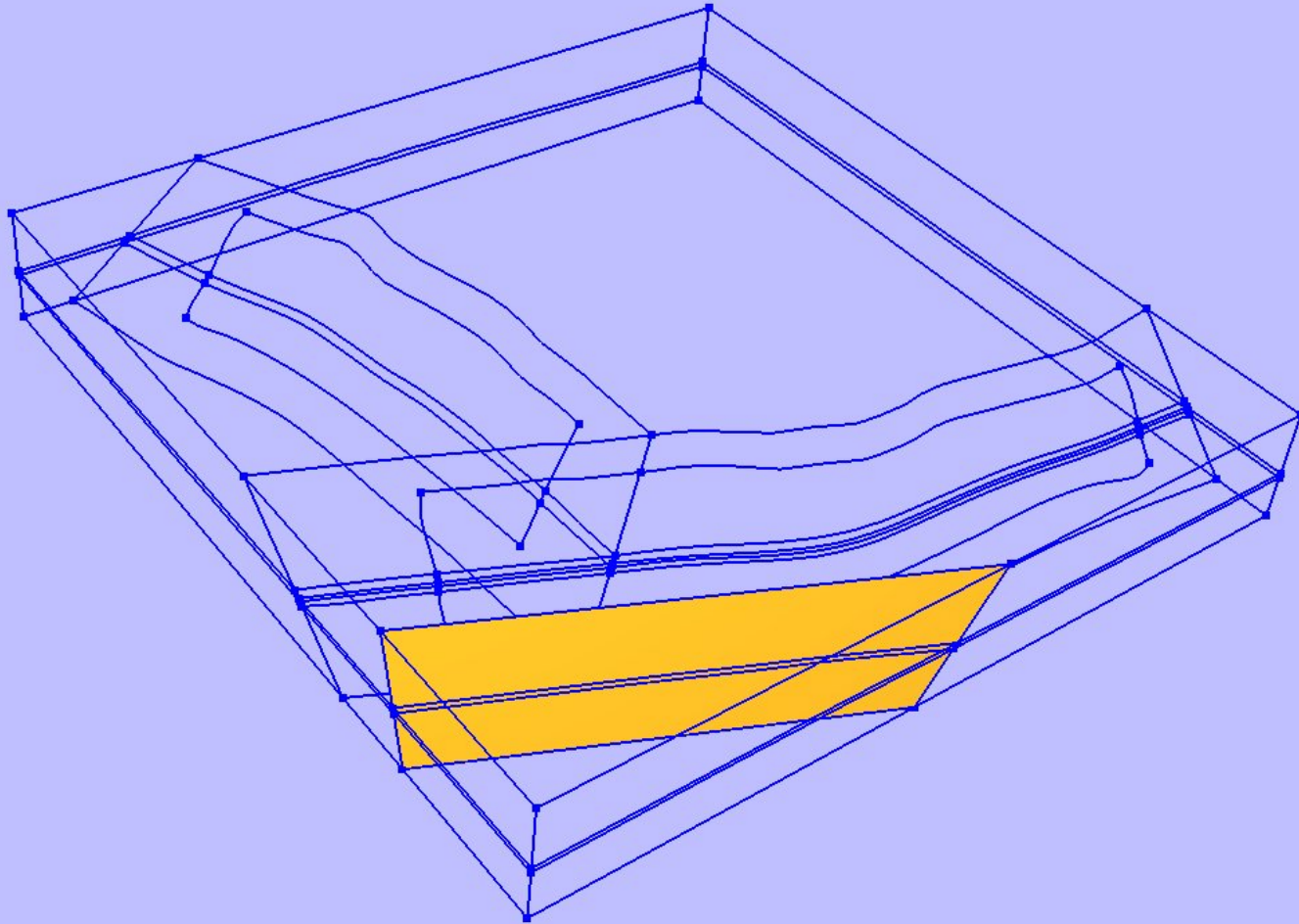
Domain decomposition for solid mesh generation



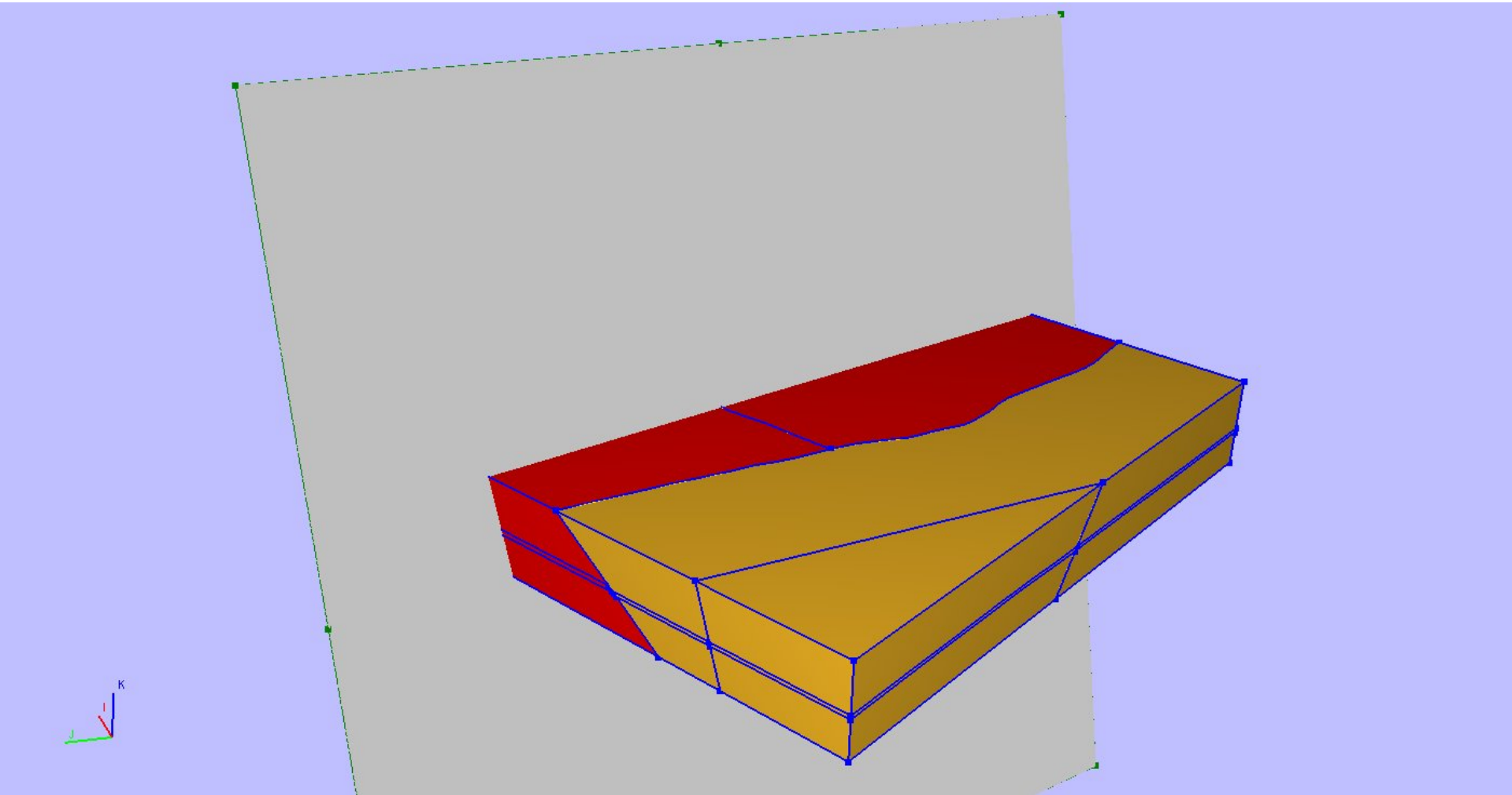
Domain decomposition for solid mesh generation



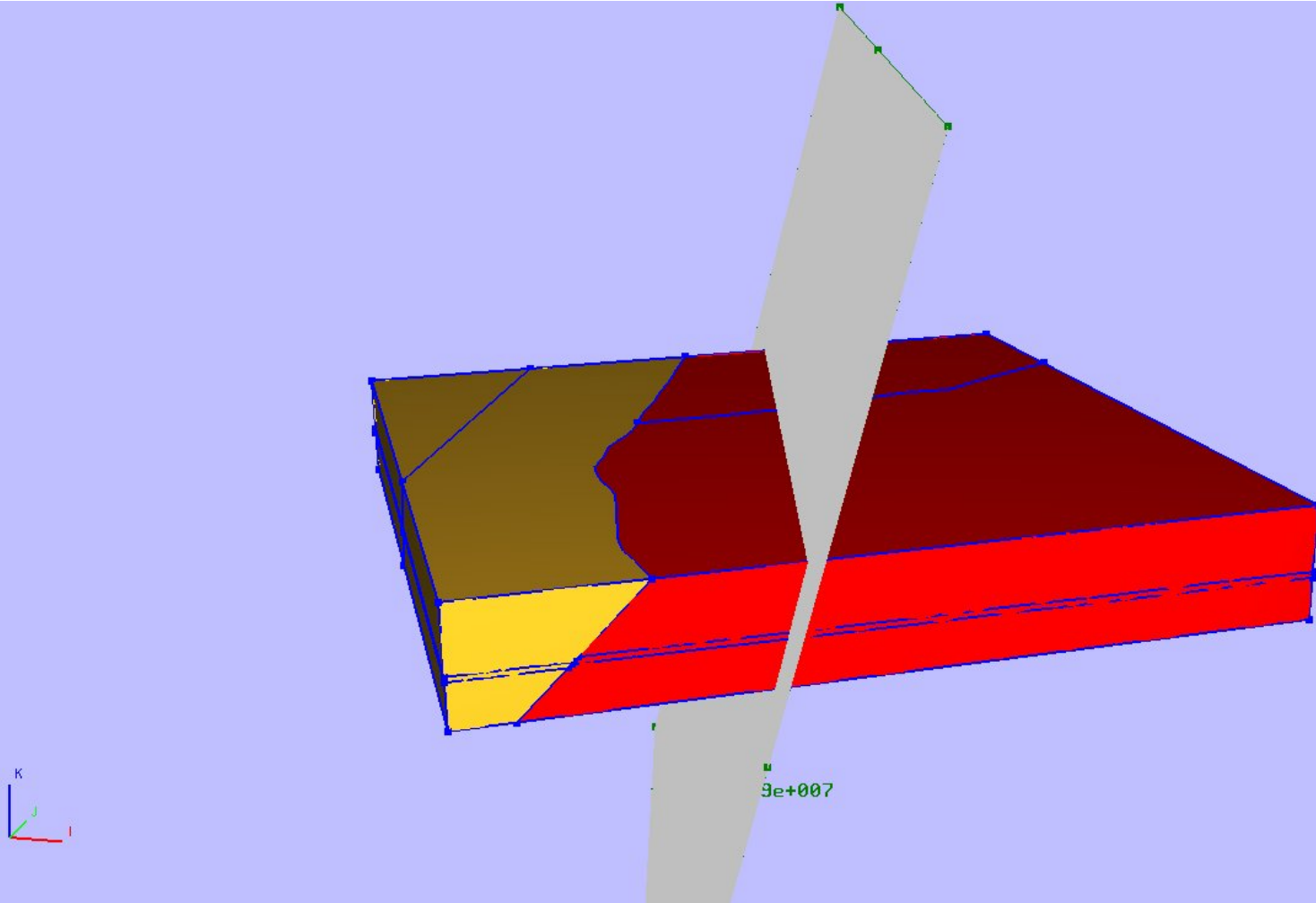
Domain decomposition for solid mesh generation



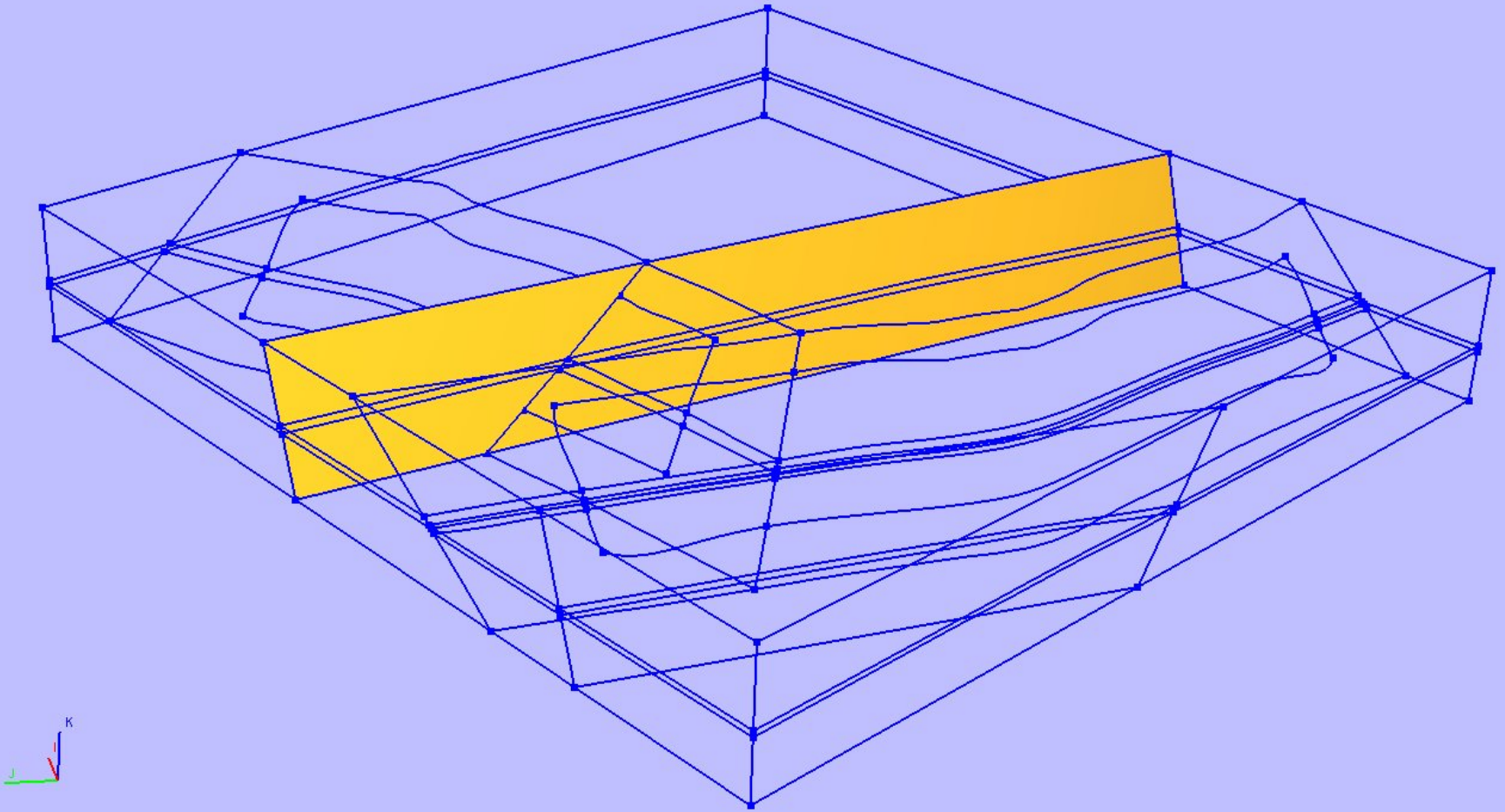
Domain decomposition for solid mesh generation



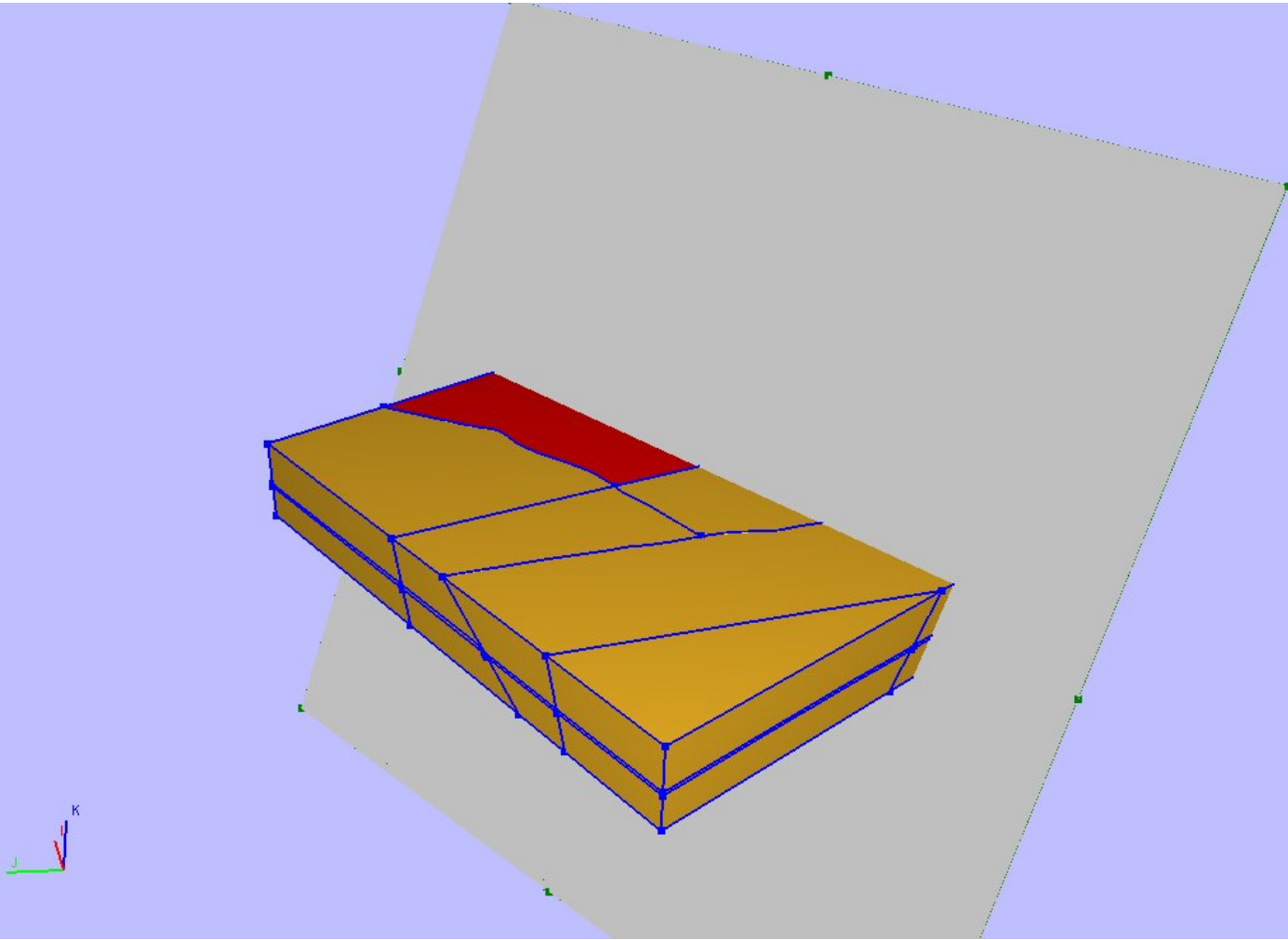
Domain decomposition for solid mesh generation



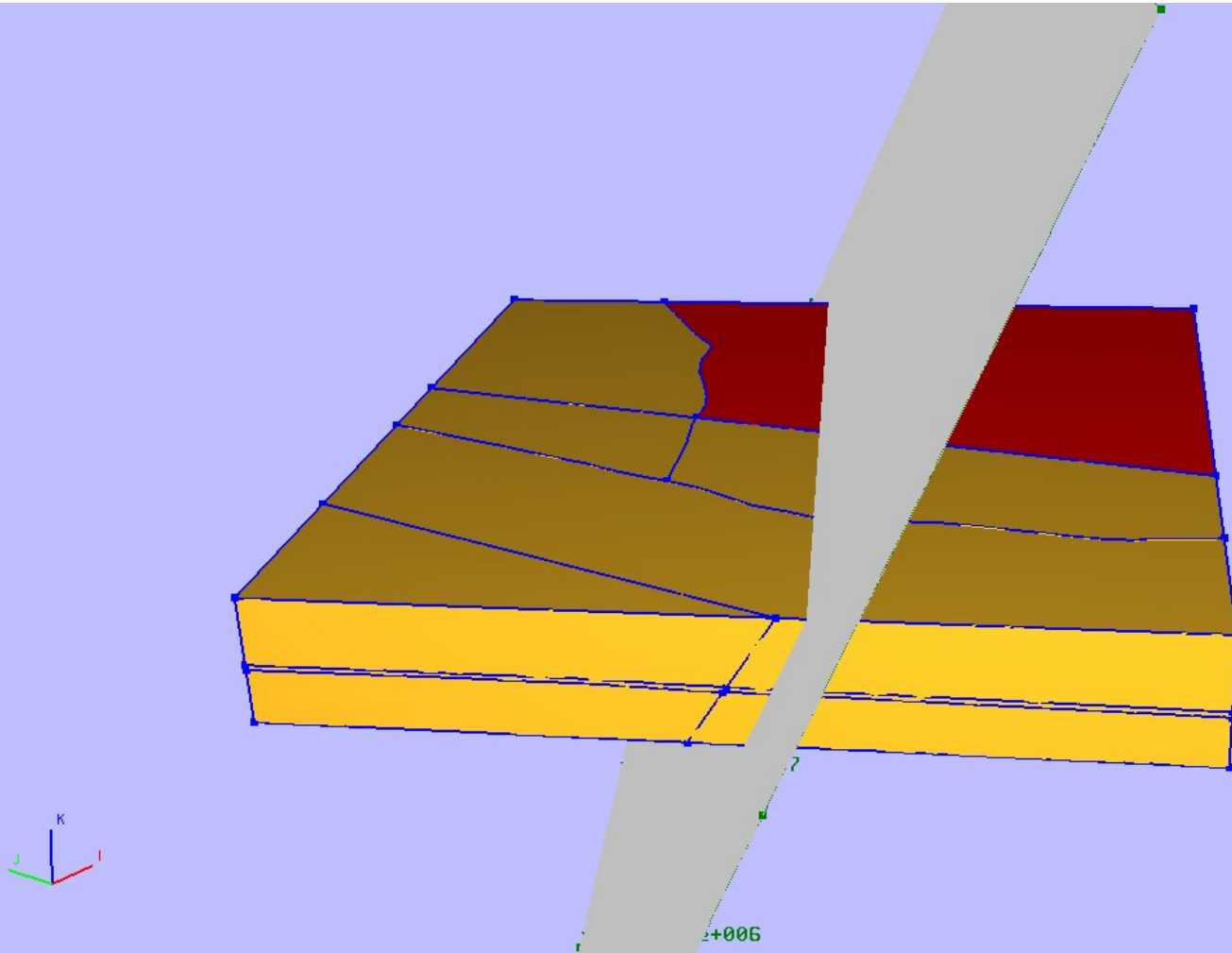
Domain decomposition for solid mesh generation



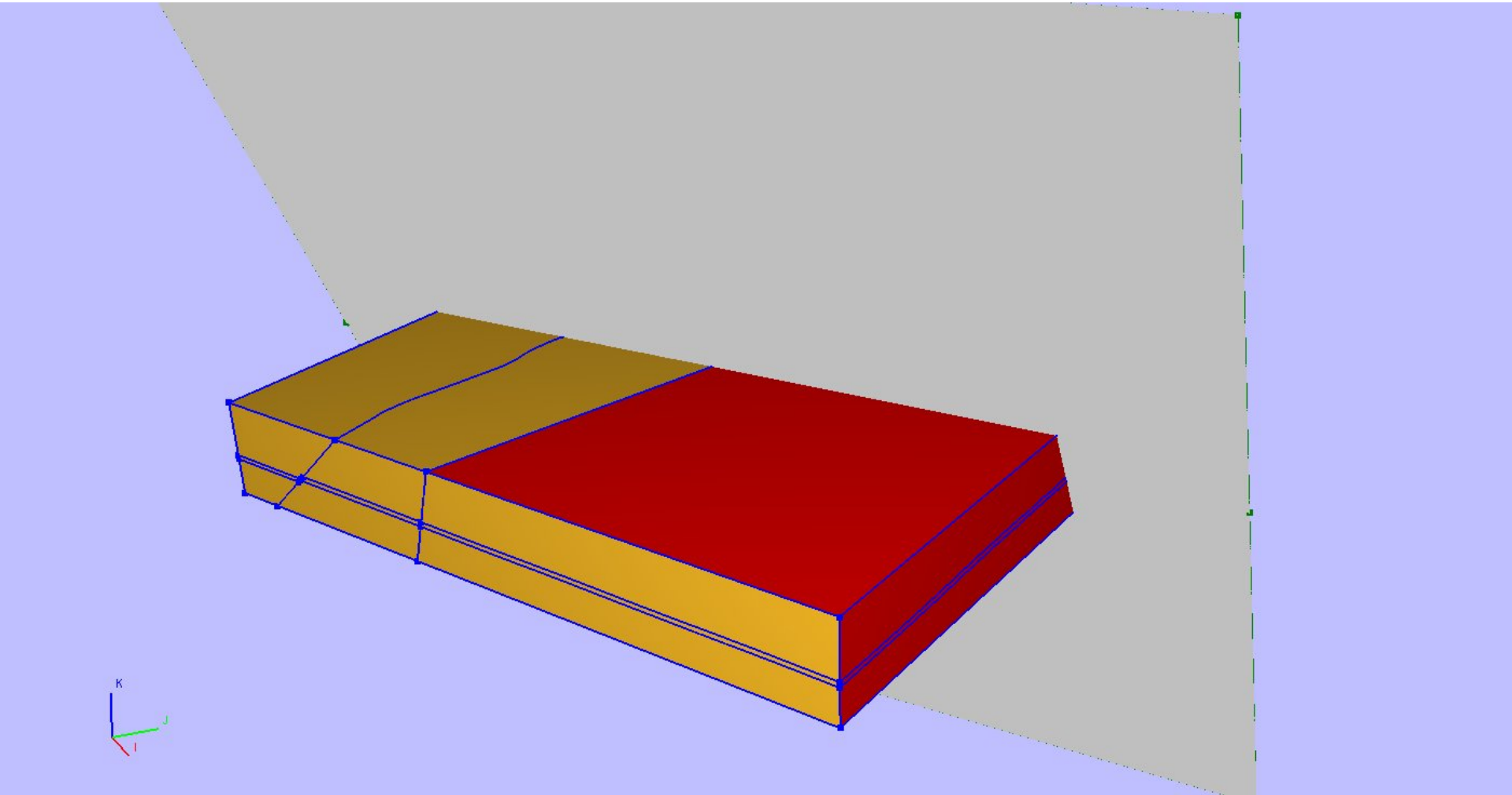
Domain decomposition for solid mesh generation



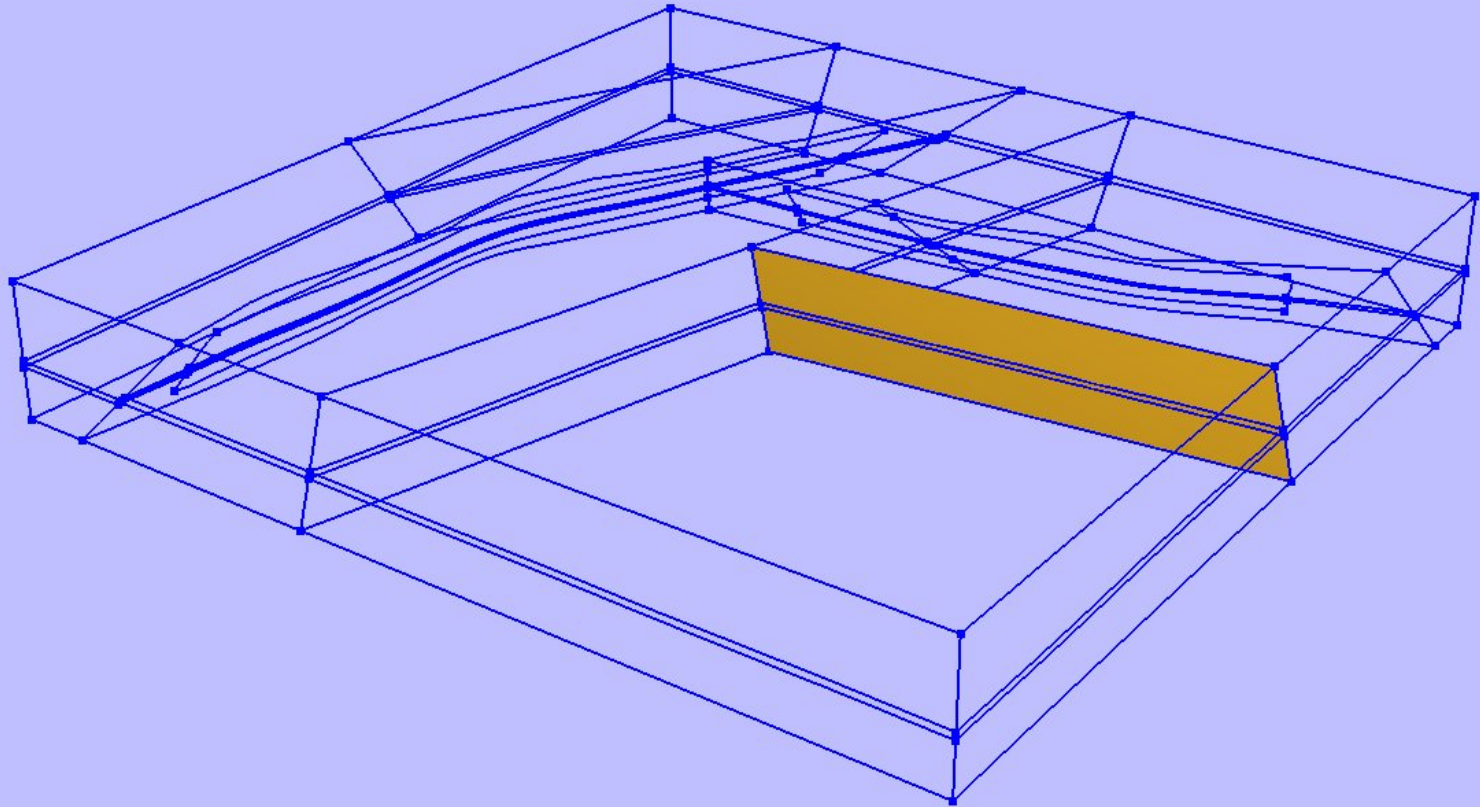
Domain decomposition for solid mesh generation



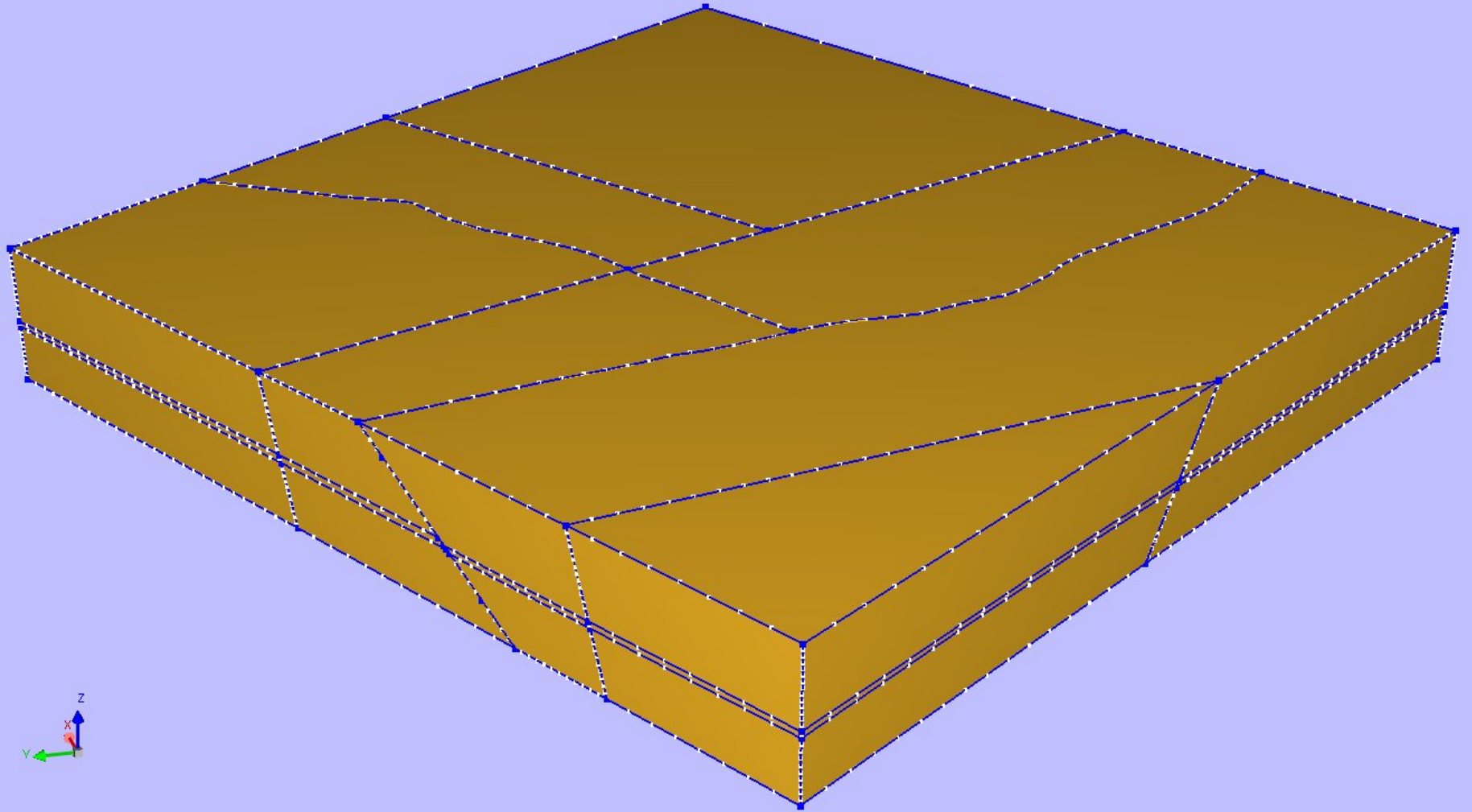
Domain decomposition for solid mesh generation



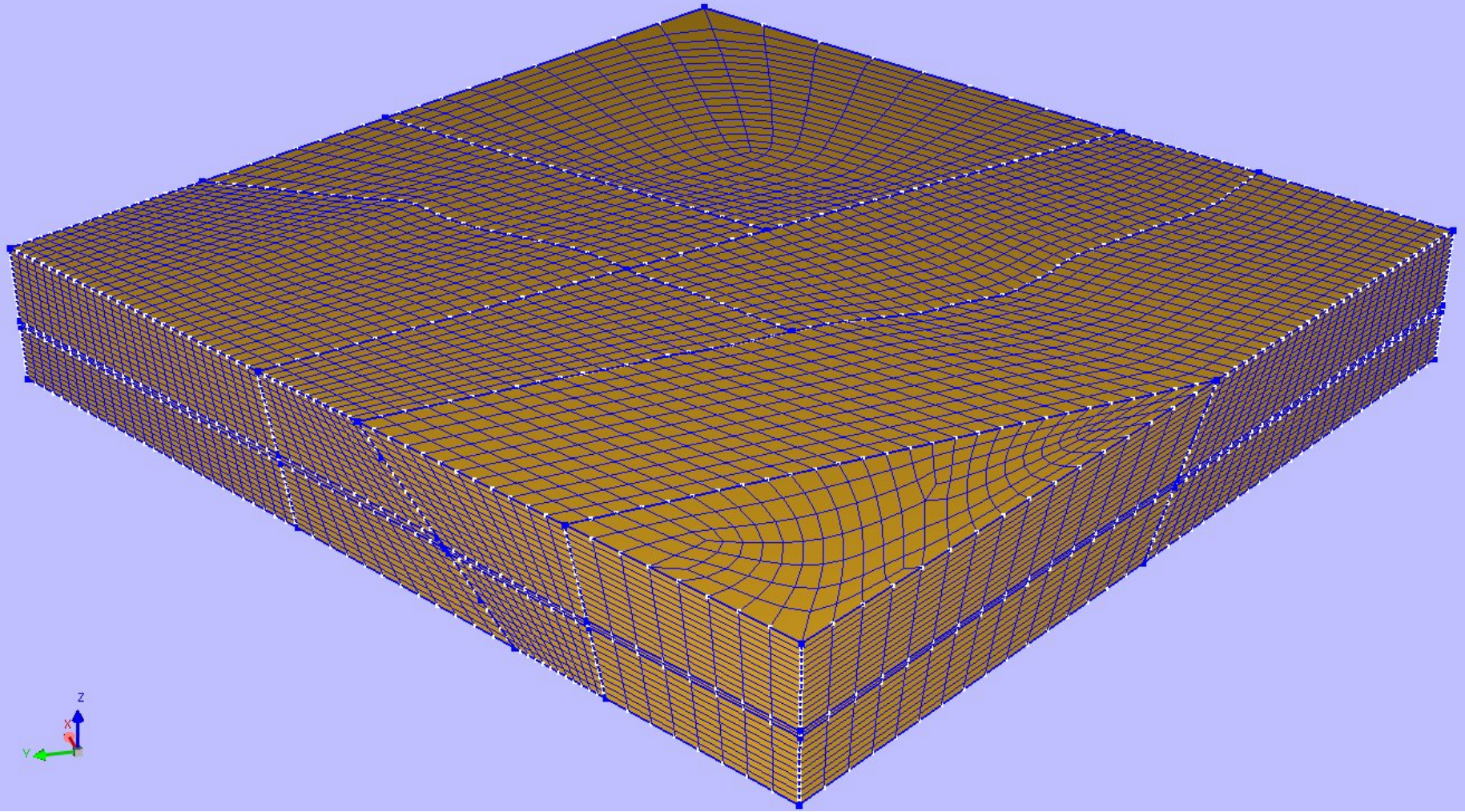
Domain decomposition for solid mesh generation



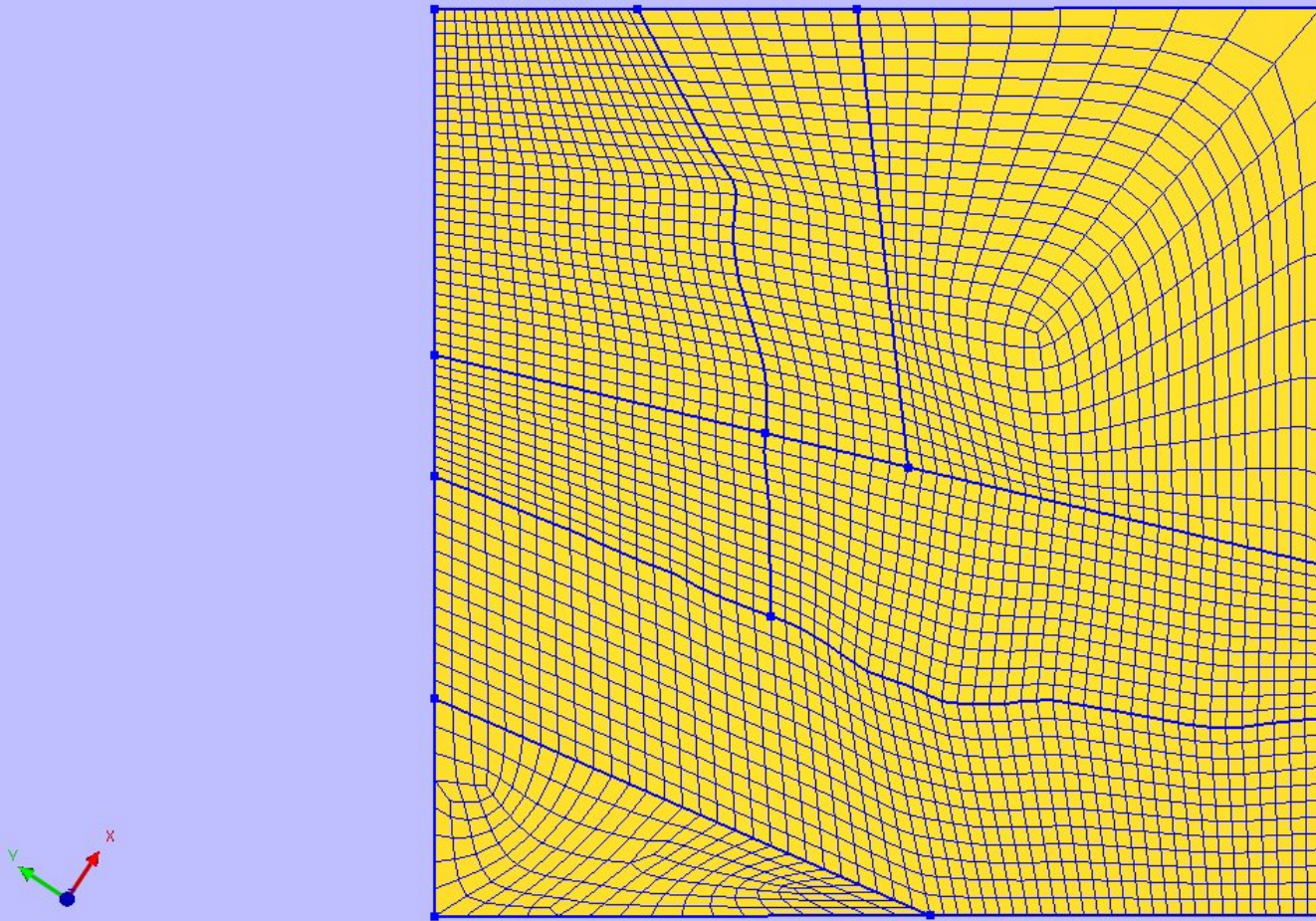
Curve subdivision



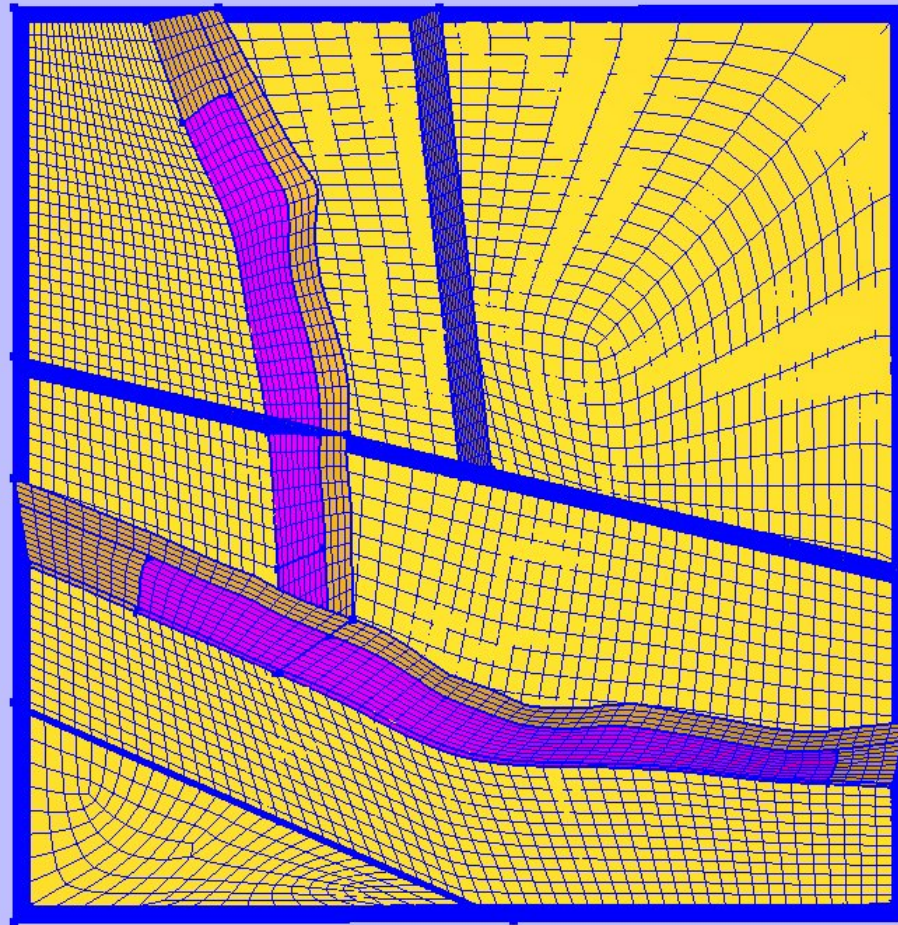
Surface mesh generation



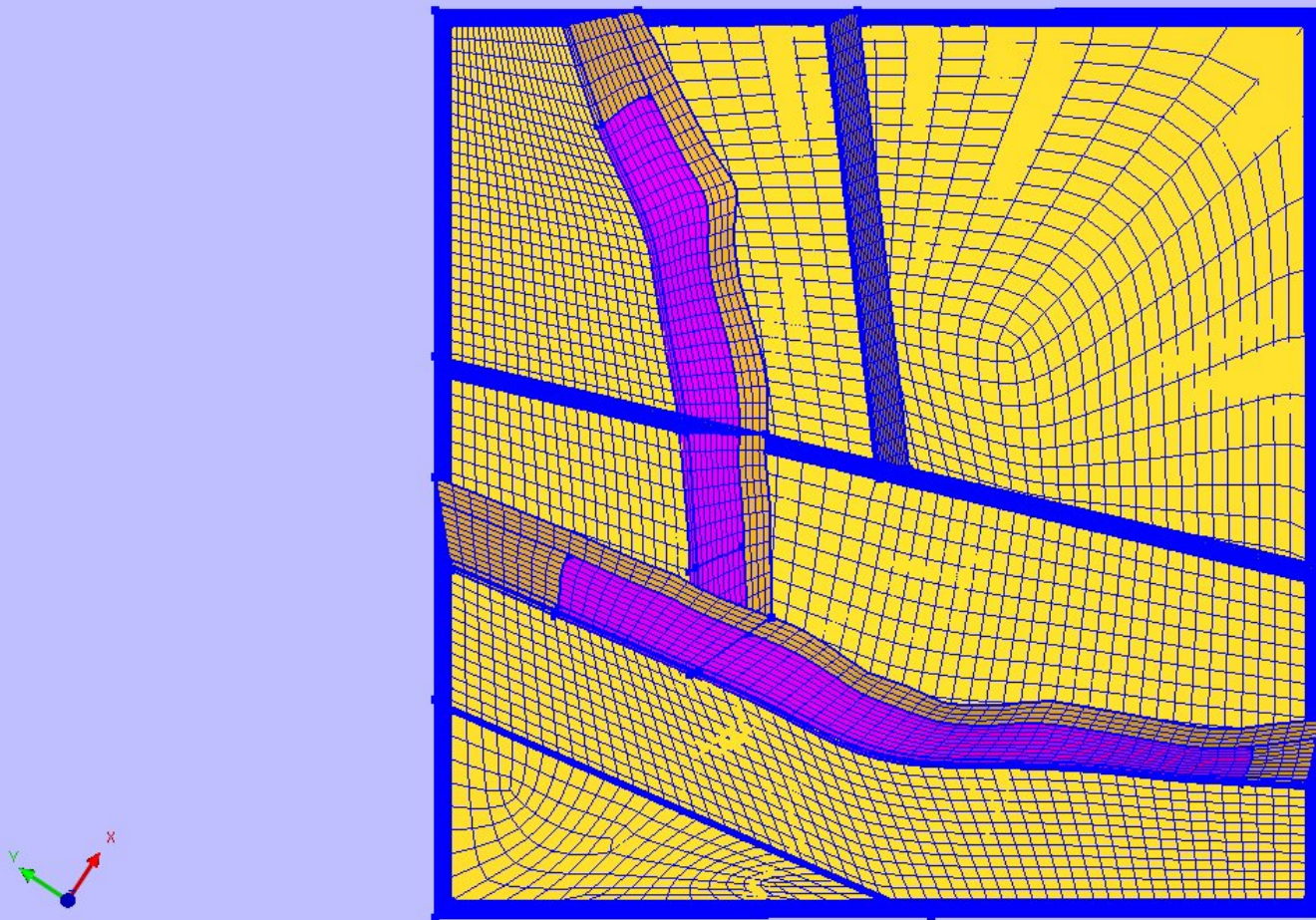
Surface mesh generation



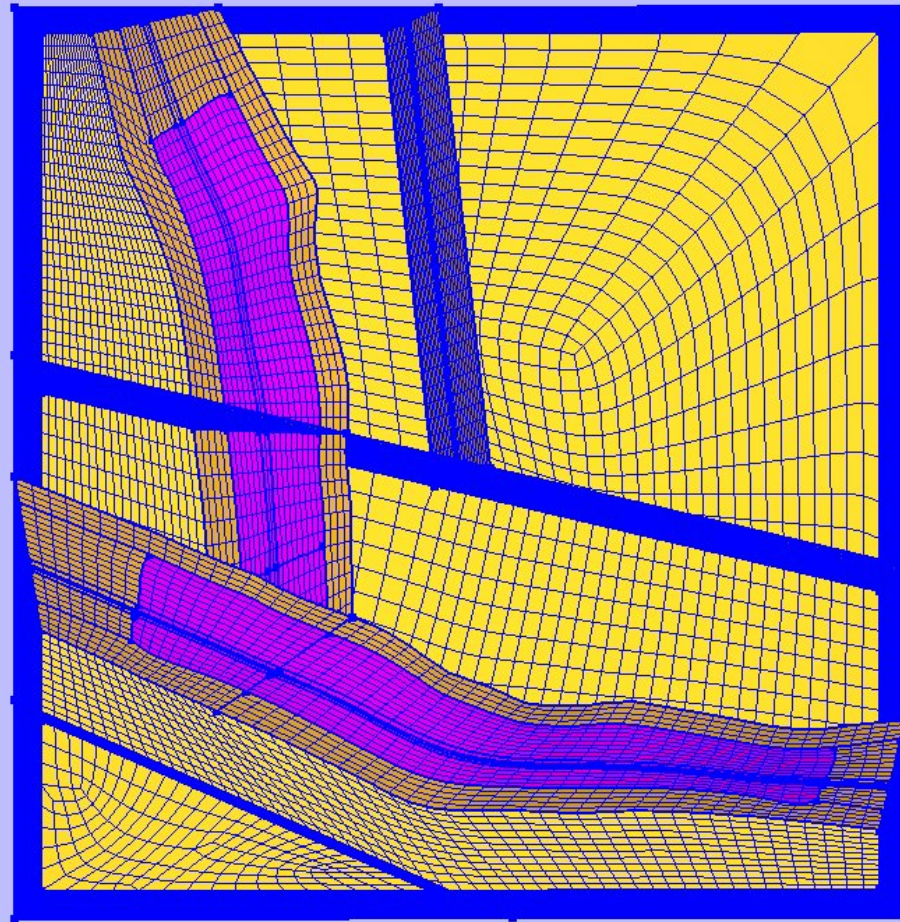
Surface mesh generation



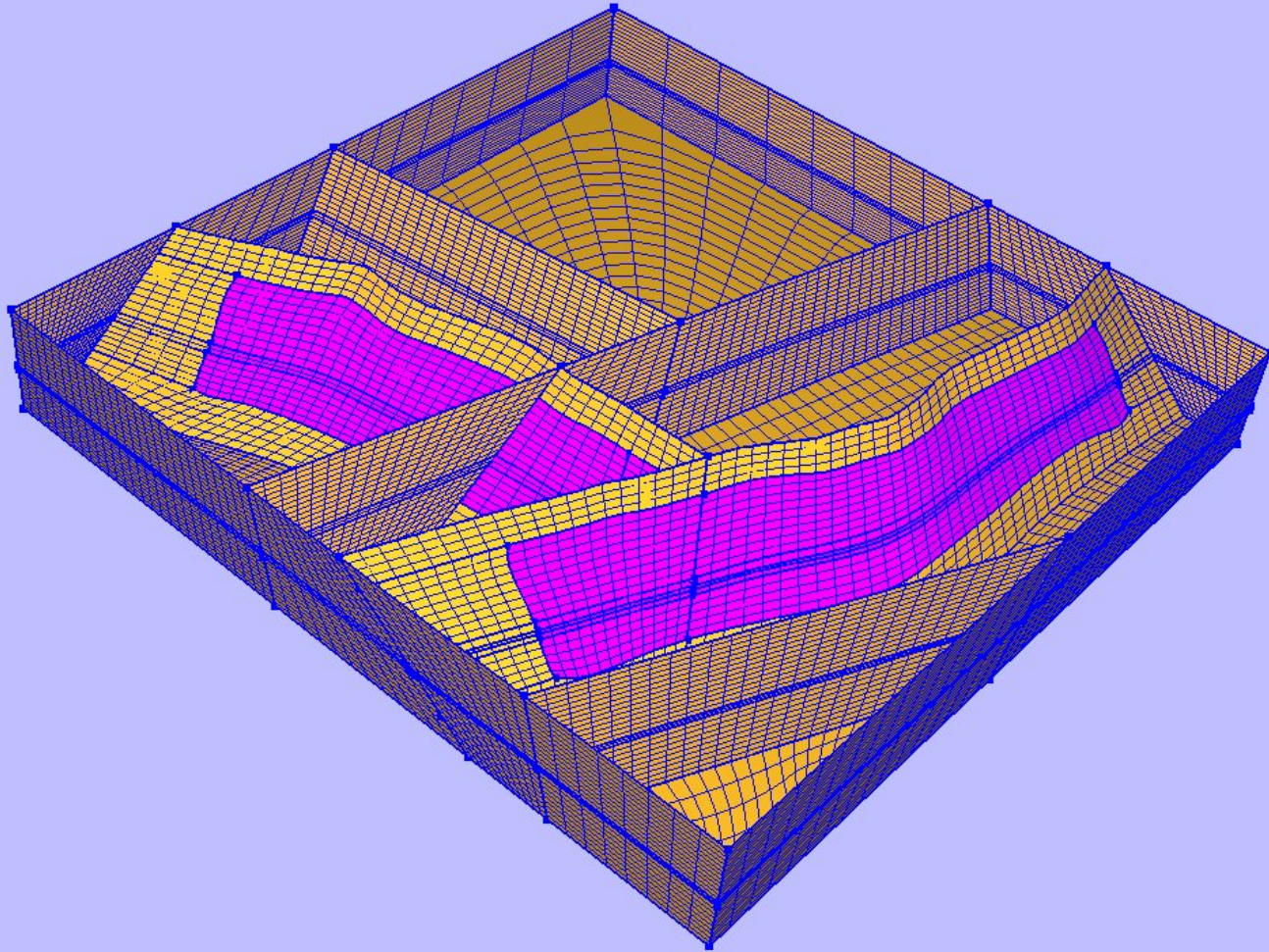
Surface mesh generation



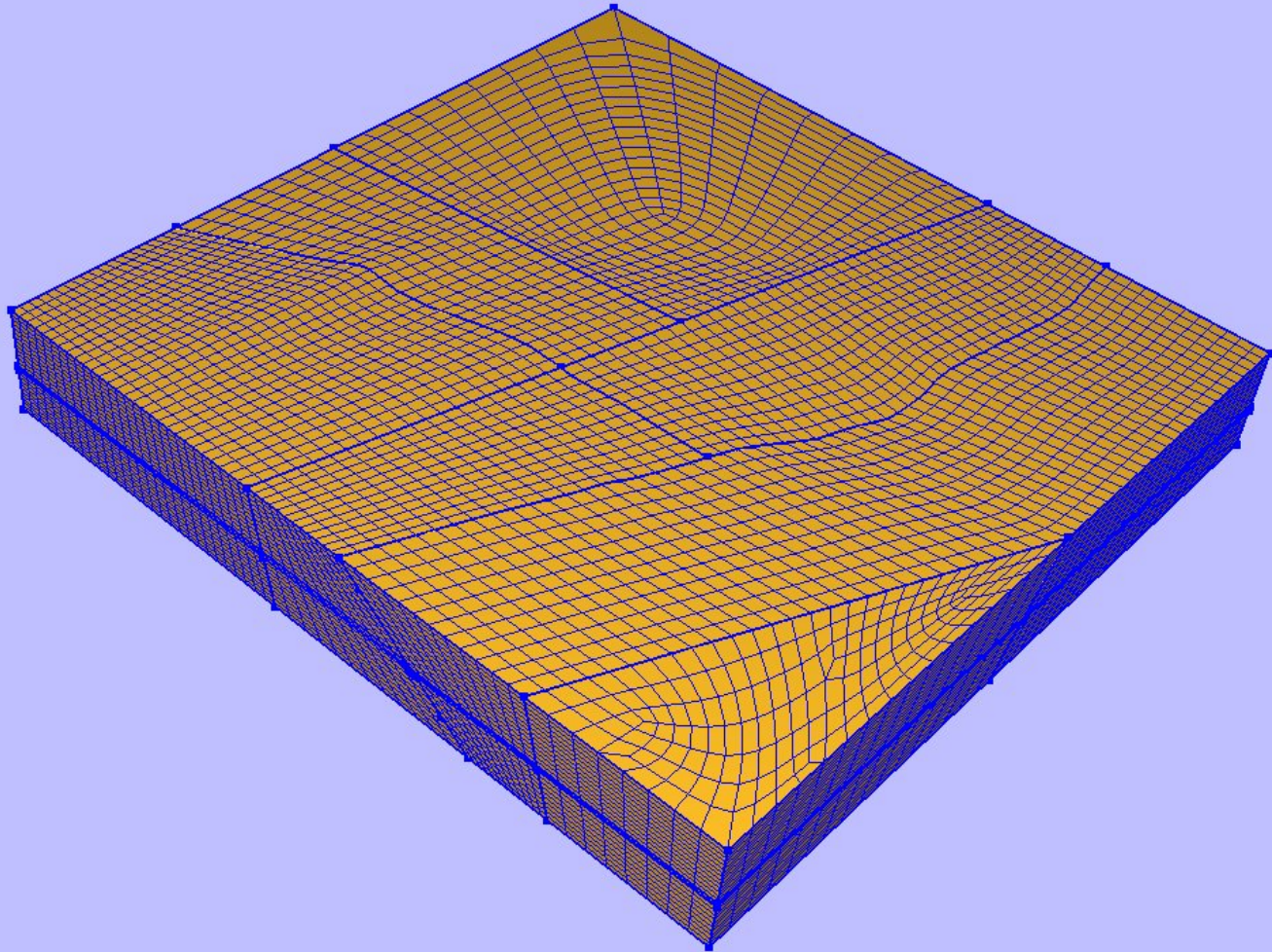
Surface mesh generation



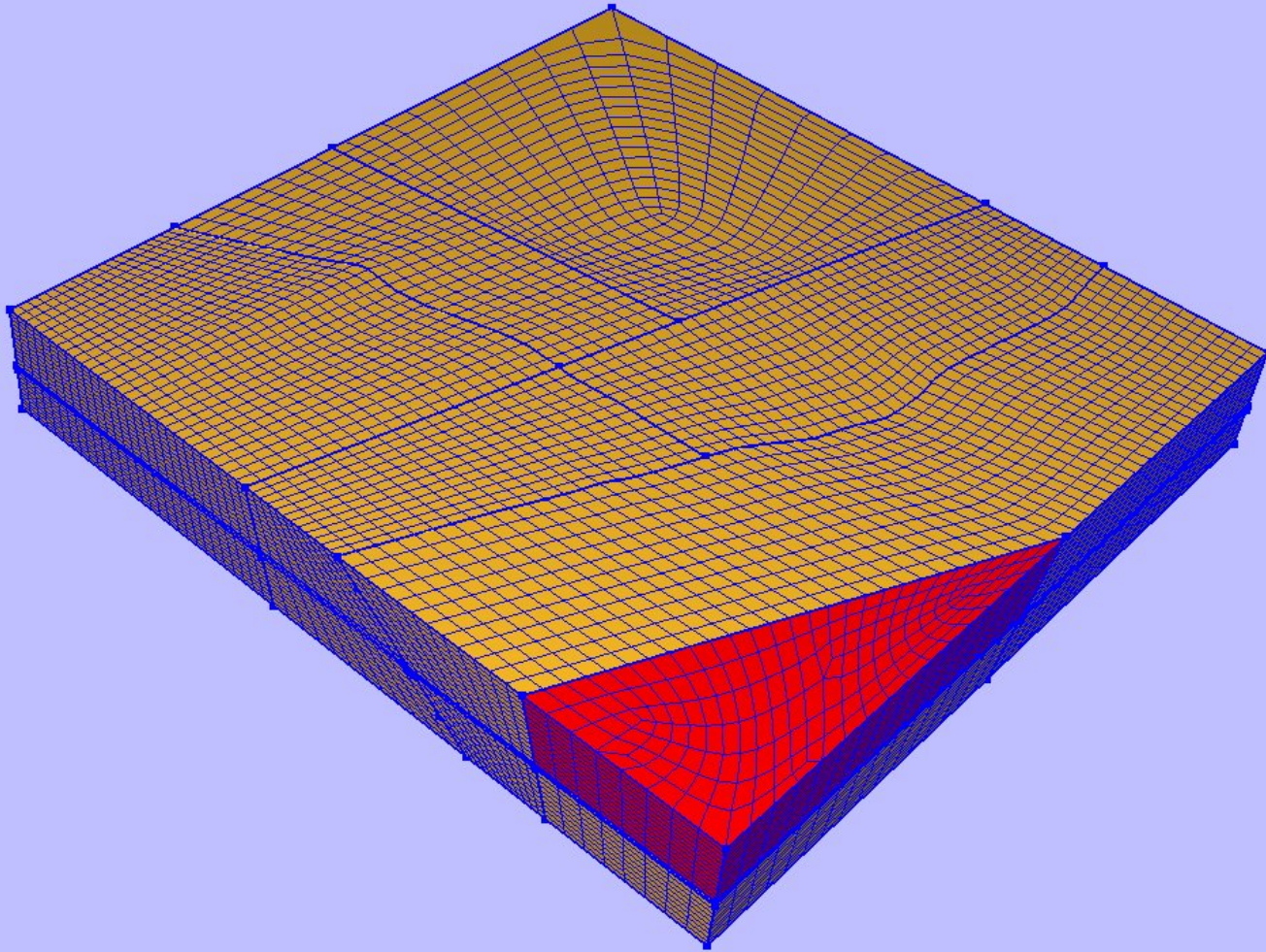
Surface mesh generation



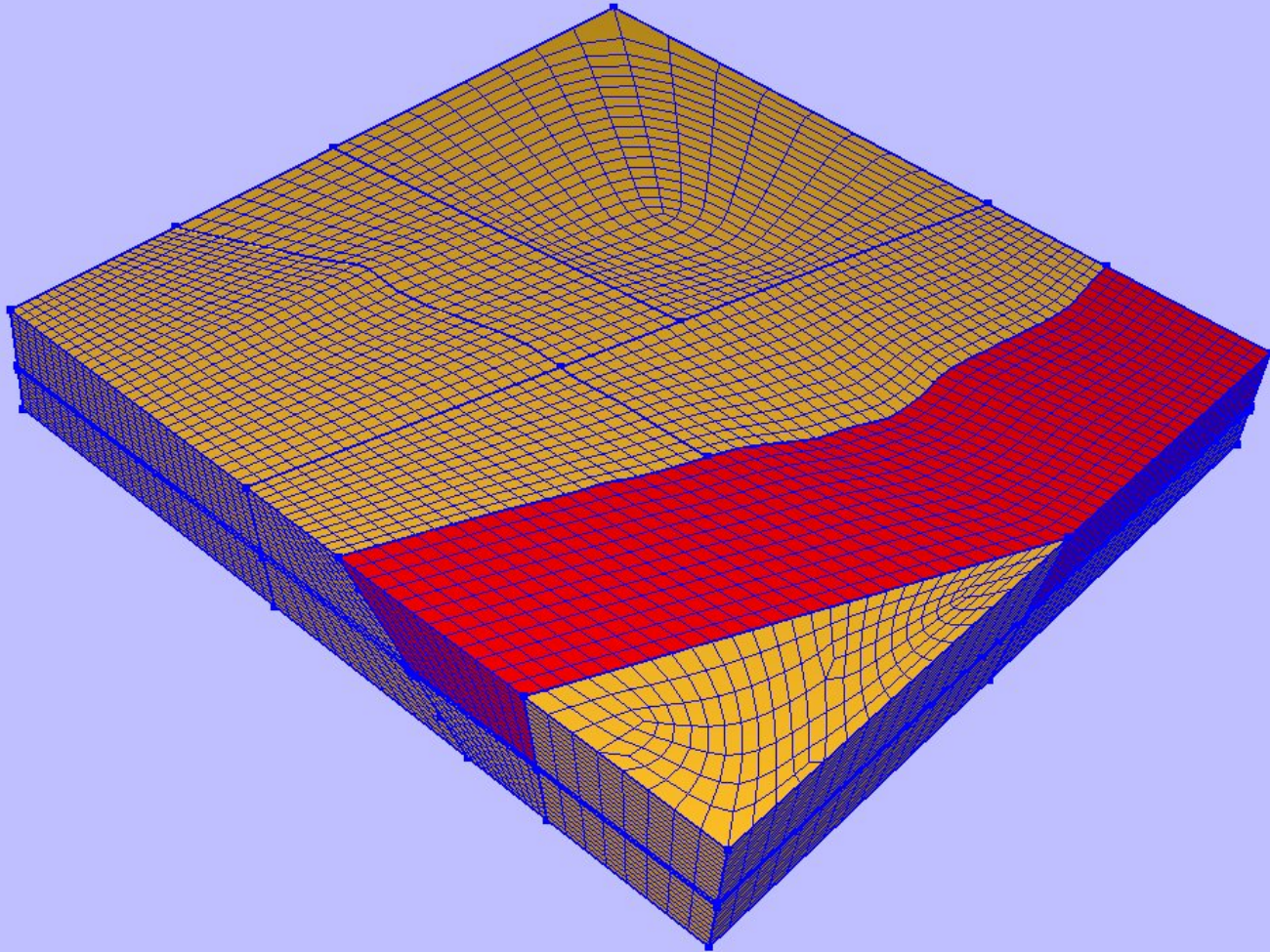
Surface mesh generation



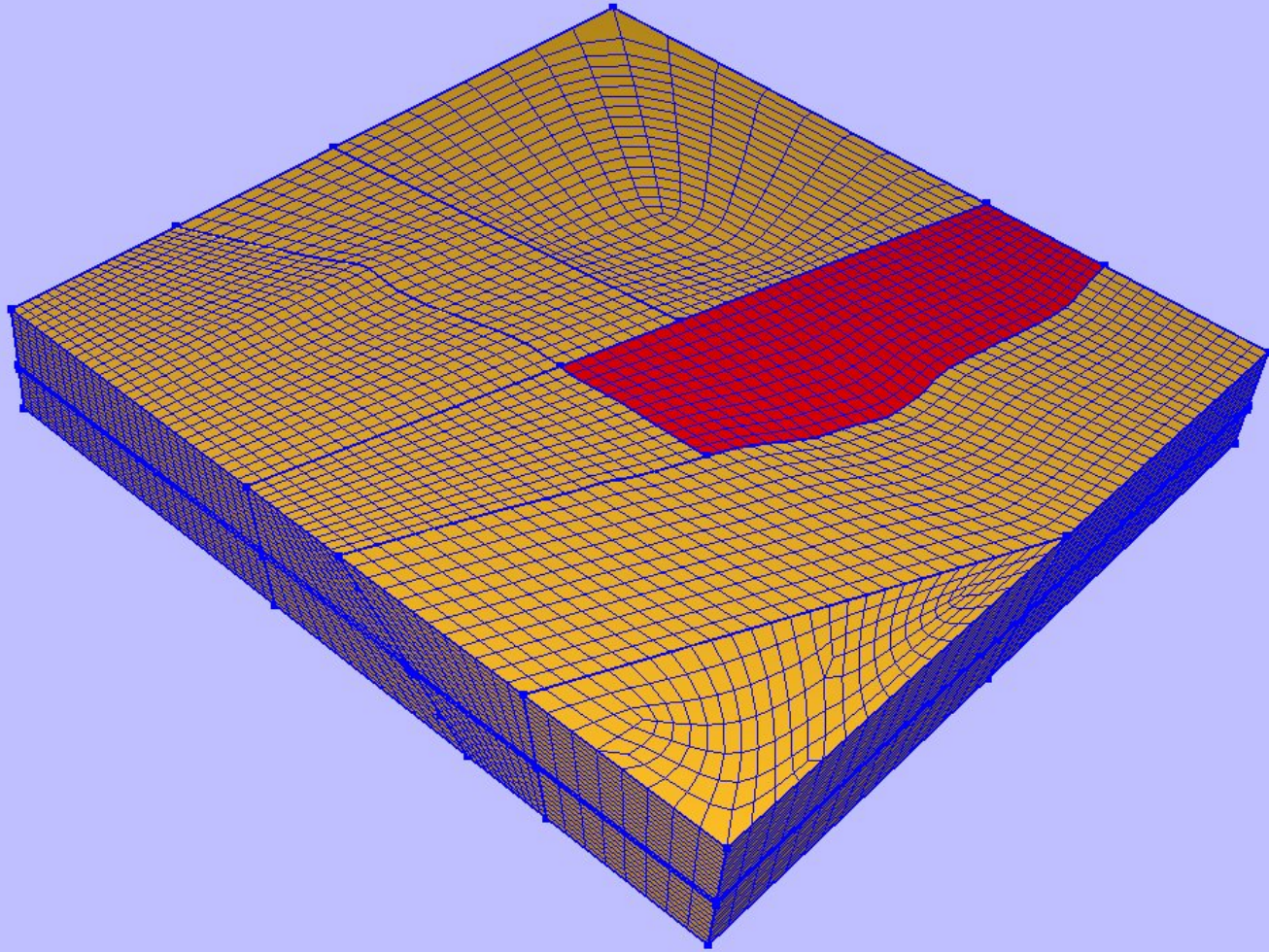
Automatic volume recognition



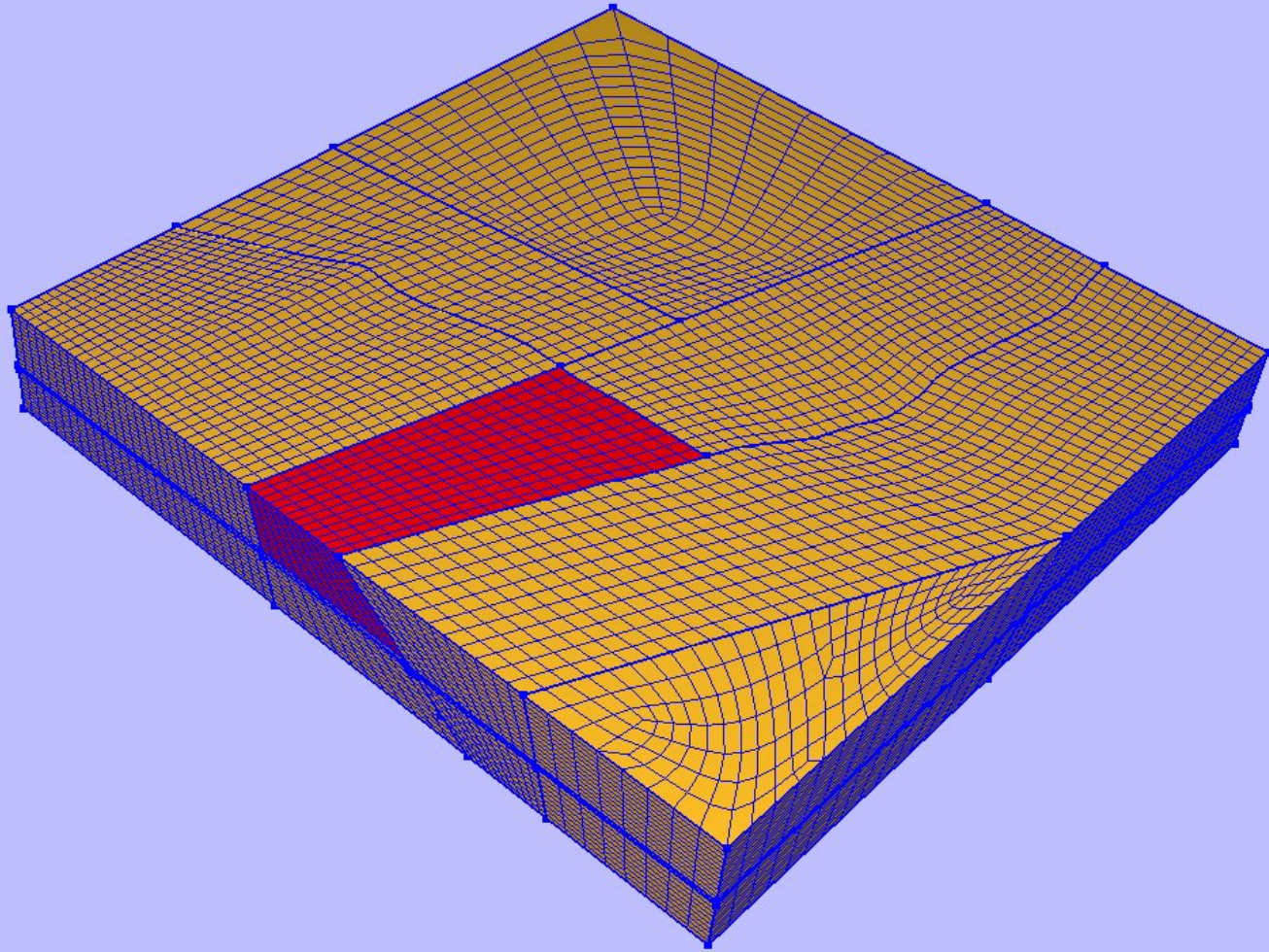
Automatic volume recognition



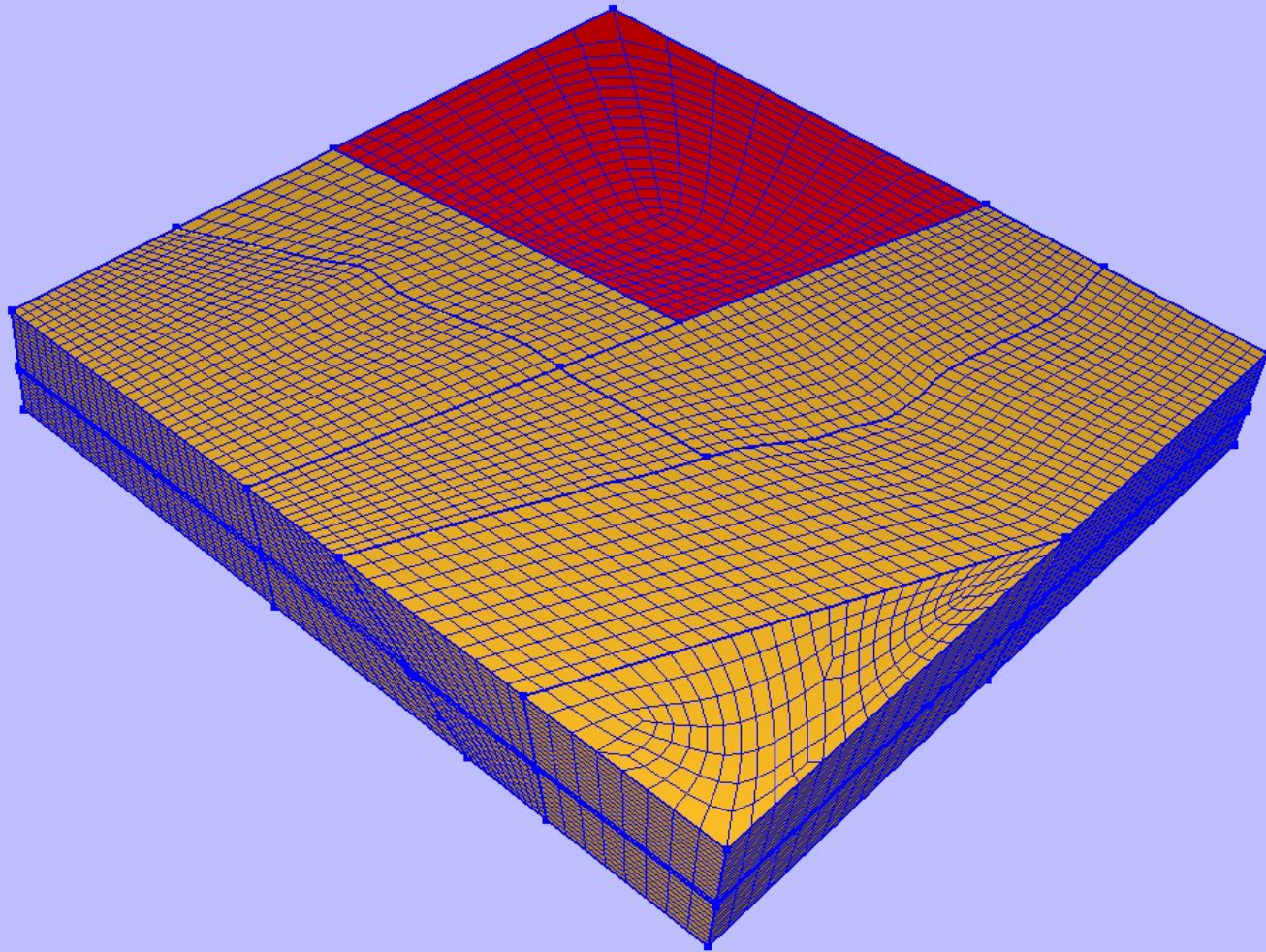
Automatic volume recognition



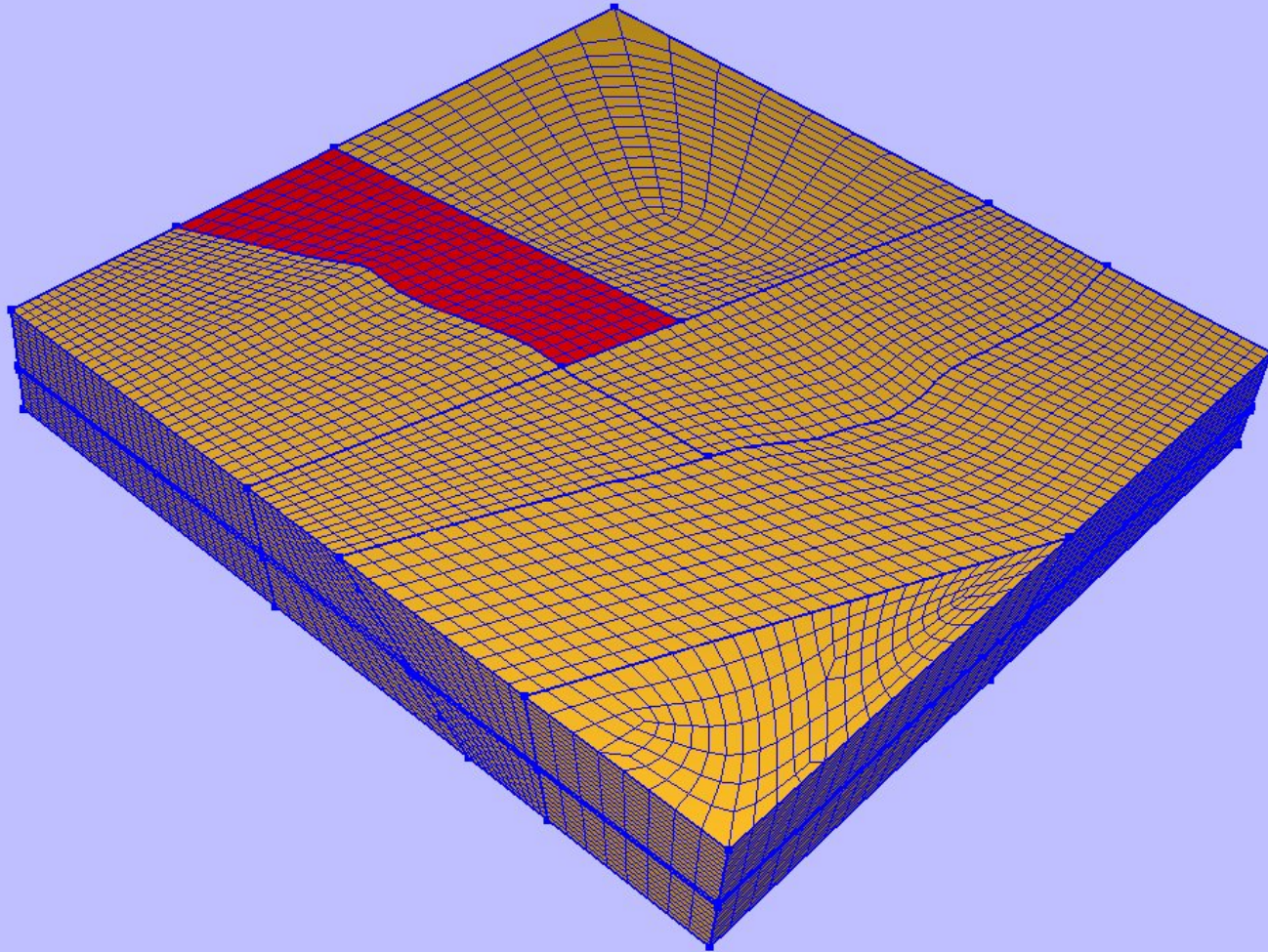
Automatic volume recognition



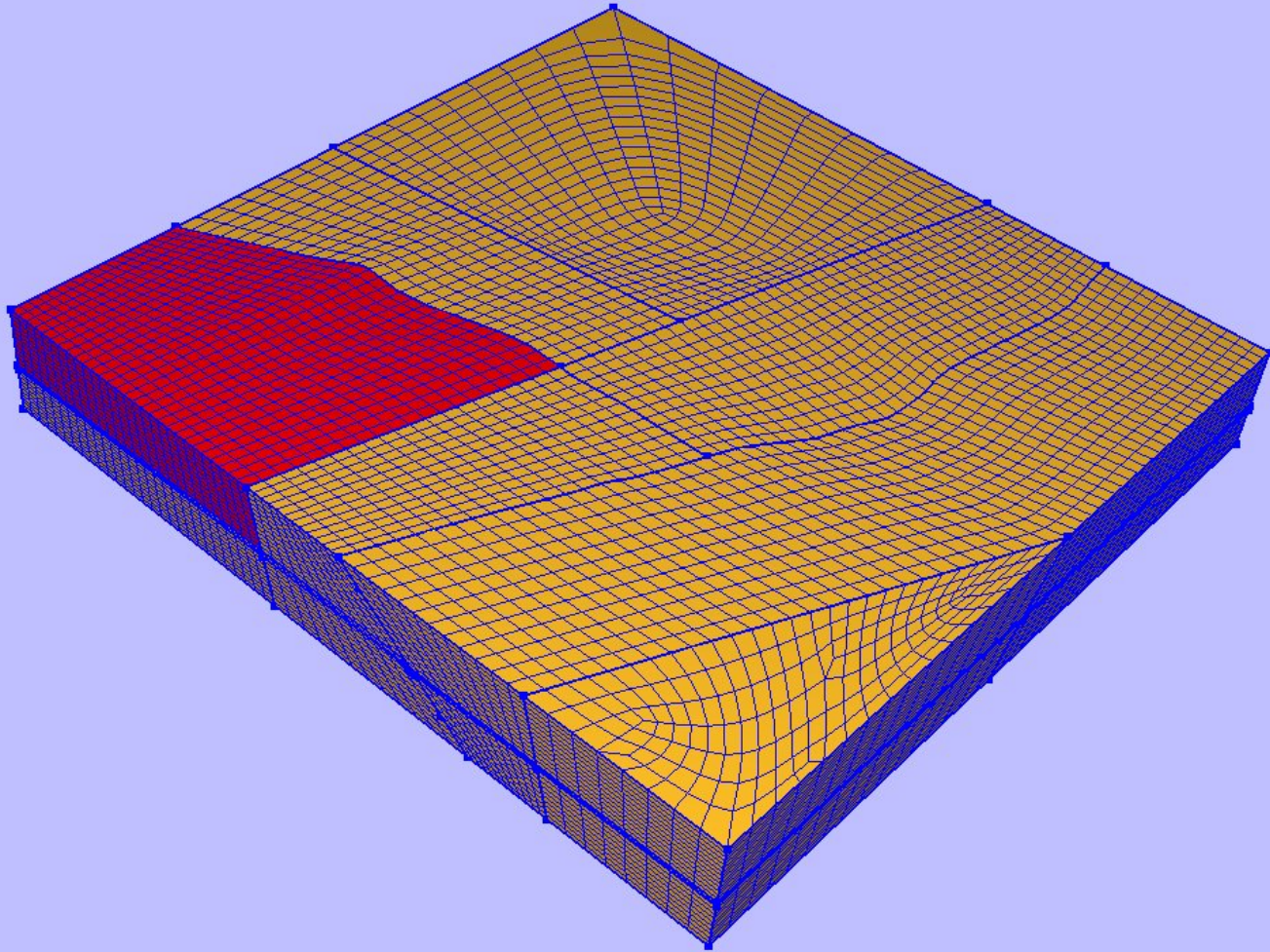
Automatic volume recognition



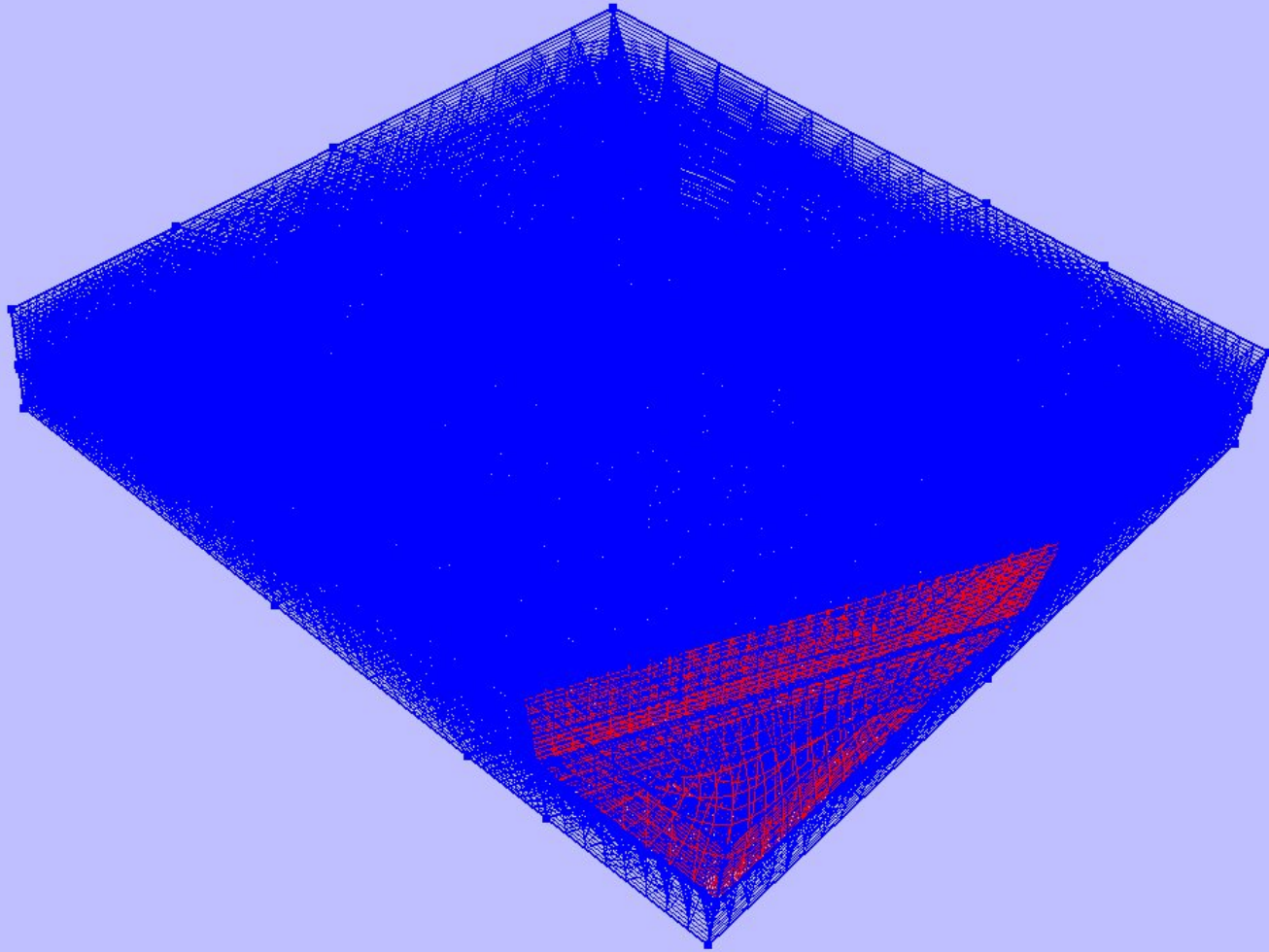
Automatic volume recognition



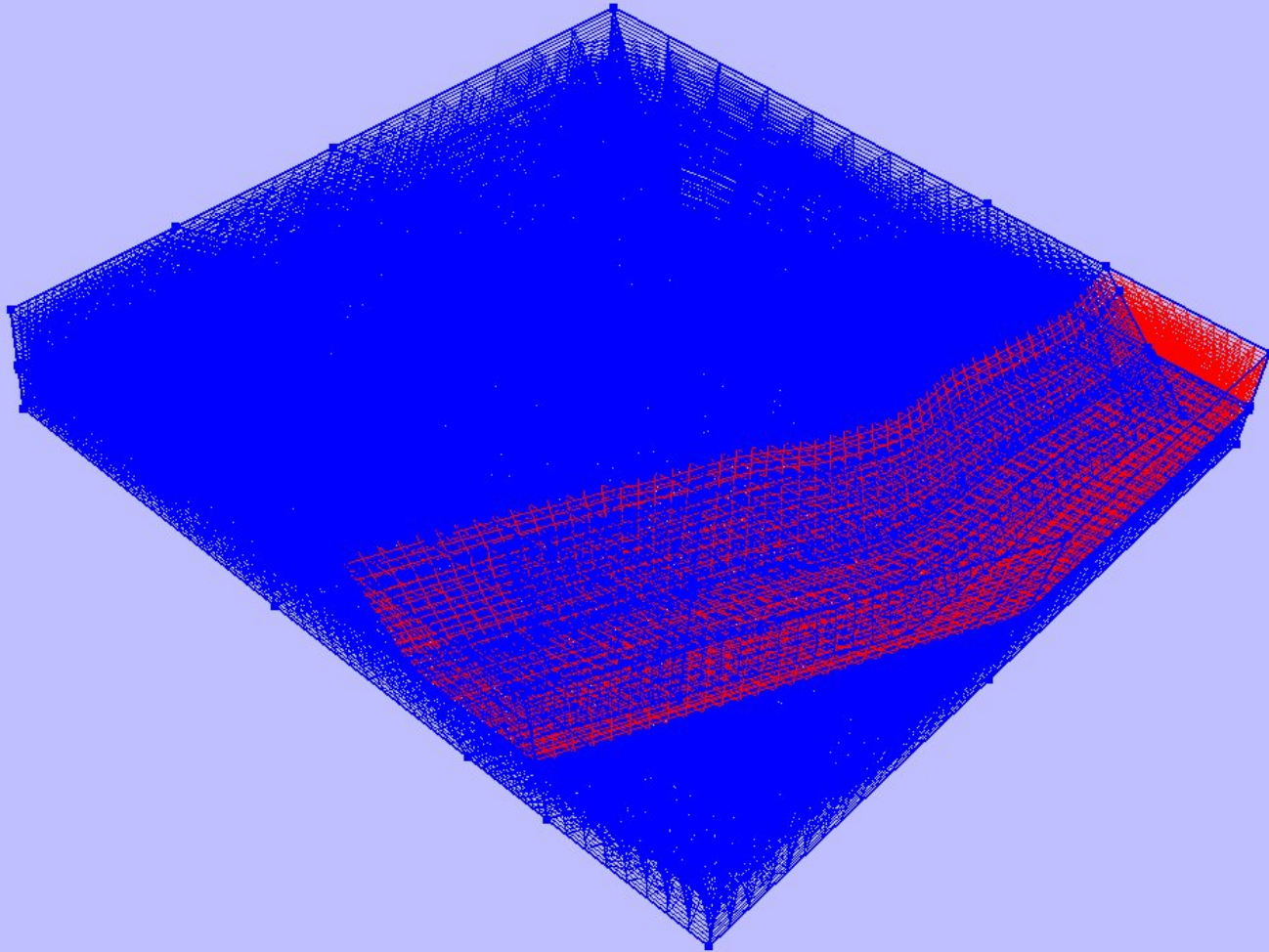
Automatic volume recognition



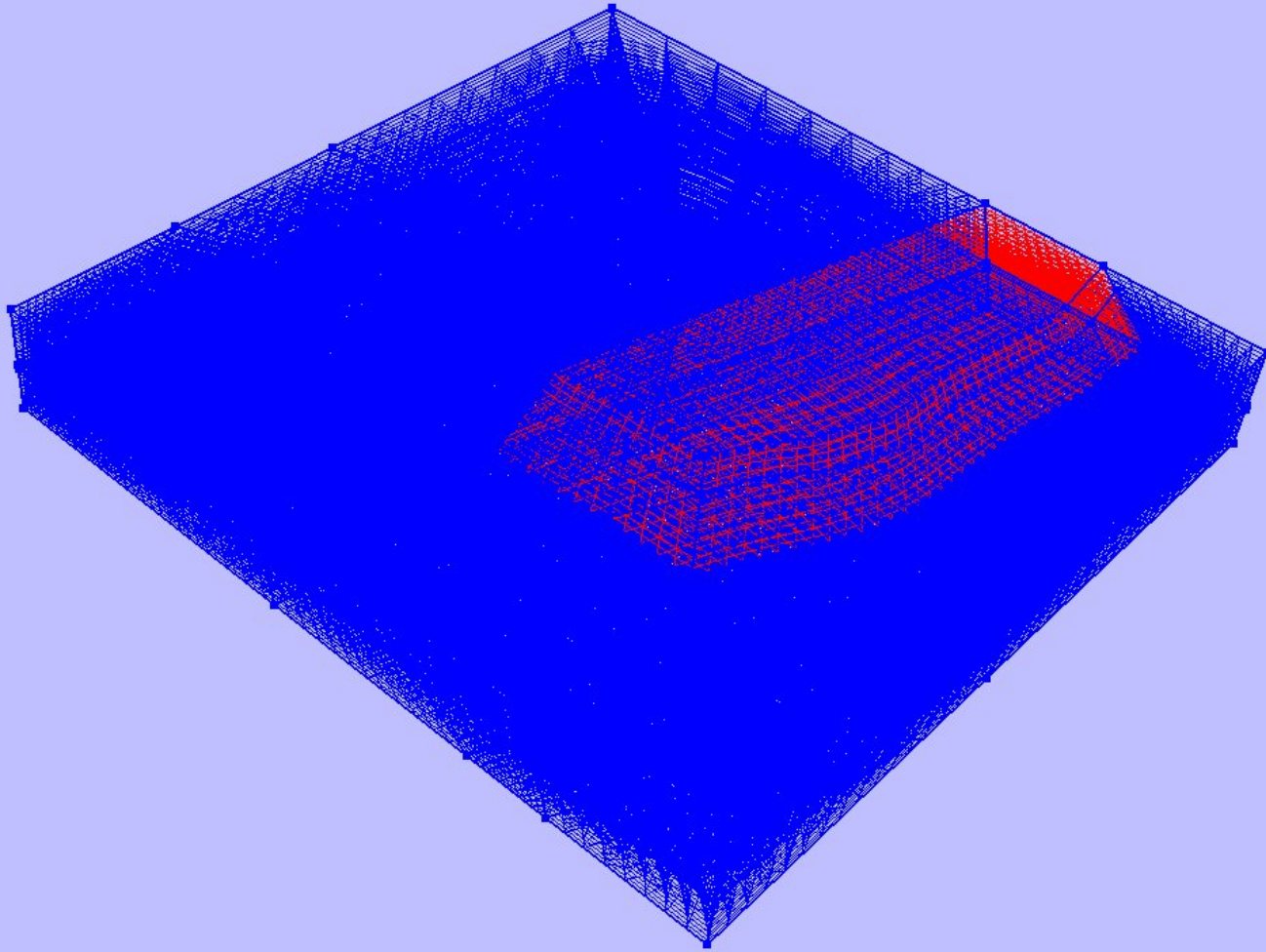
Generation of solid mesh by sweeping



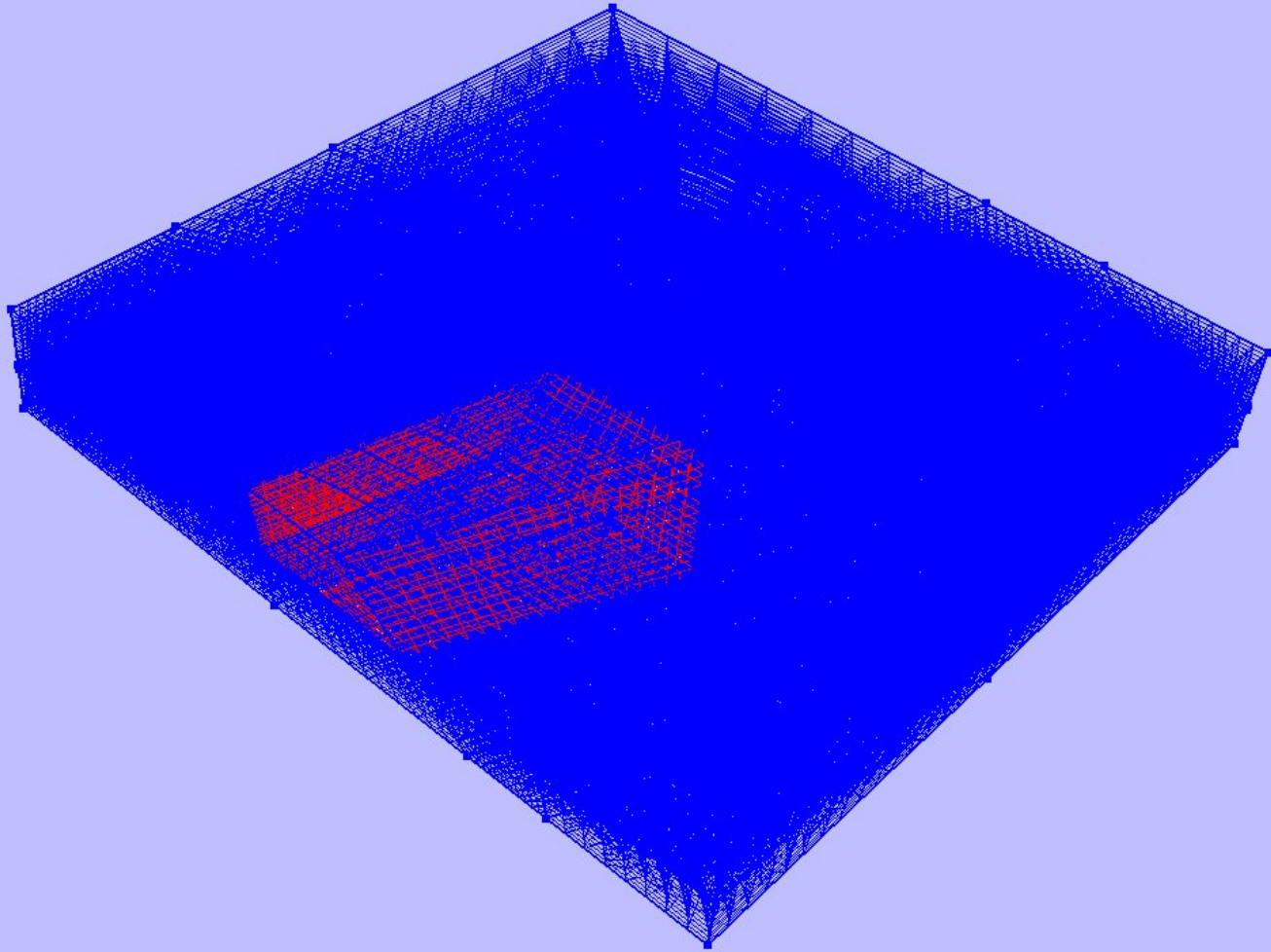
Generation of solid mesh by 3D mapping



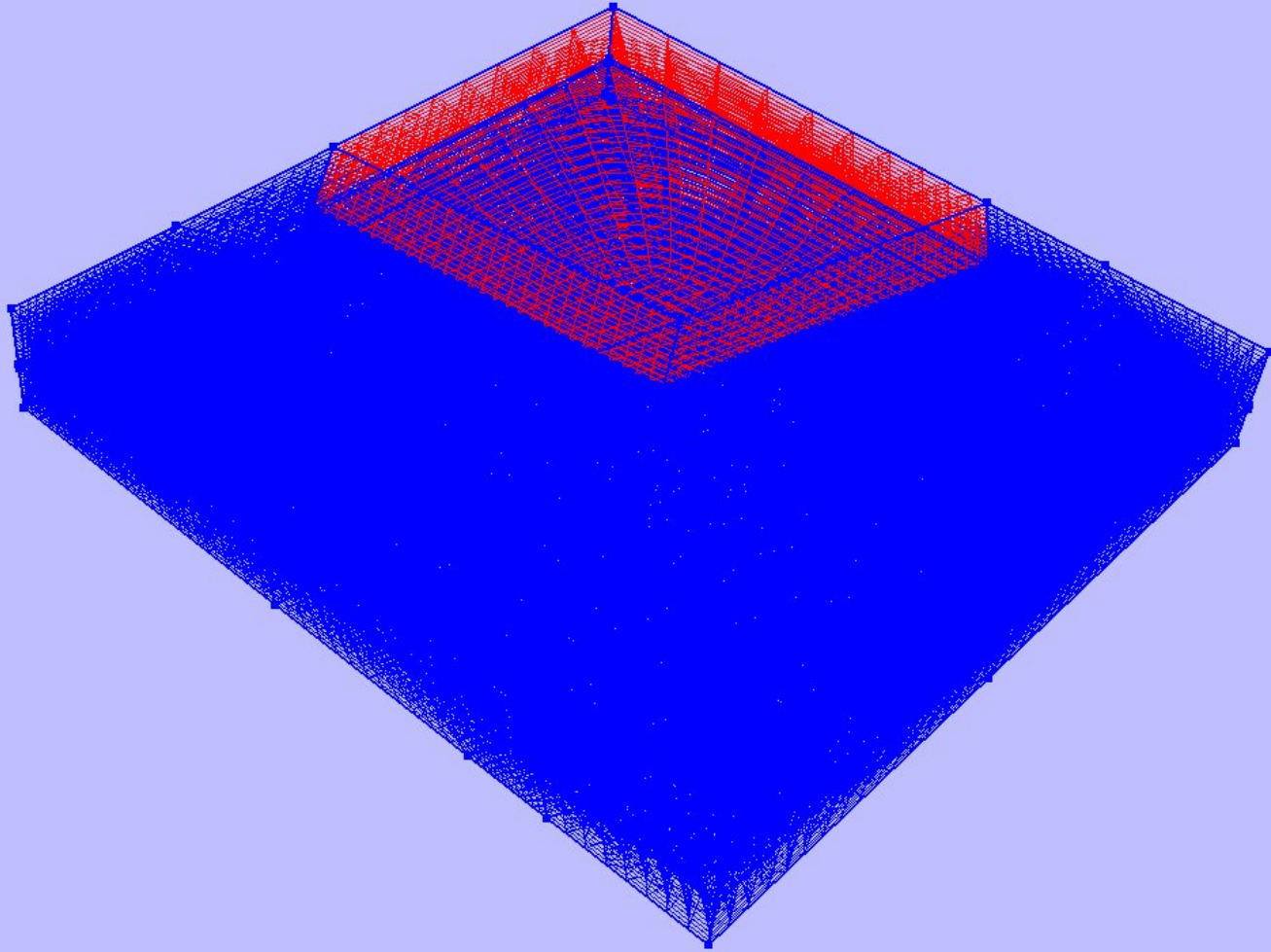
Generation of solid mesh by 3D mapping



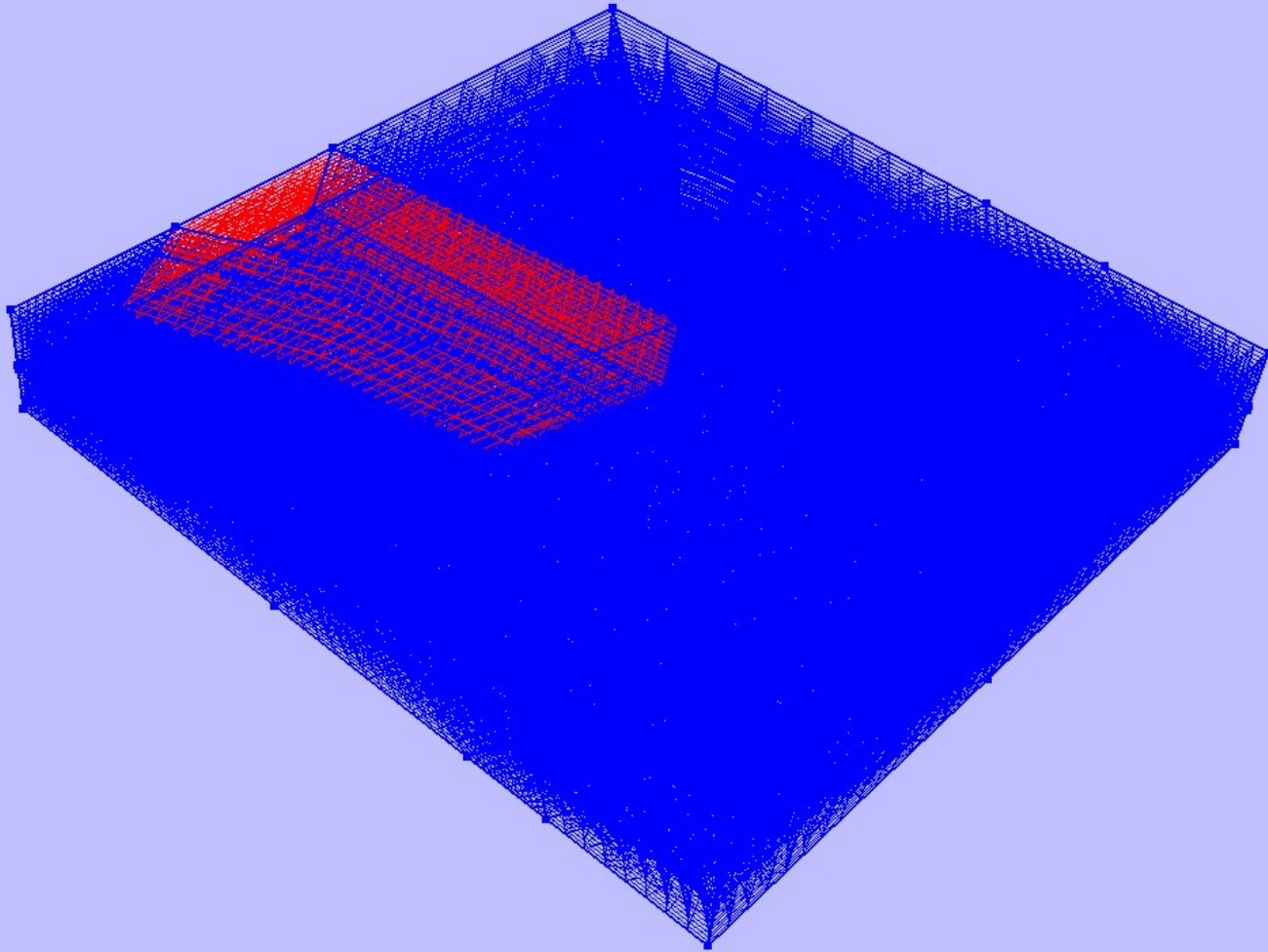
Generation of solid mesh by 3D mapping



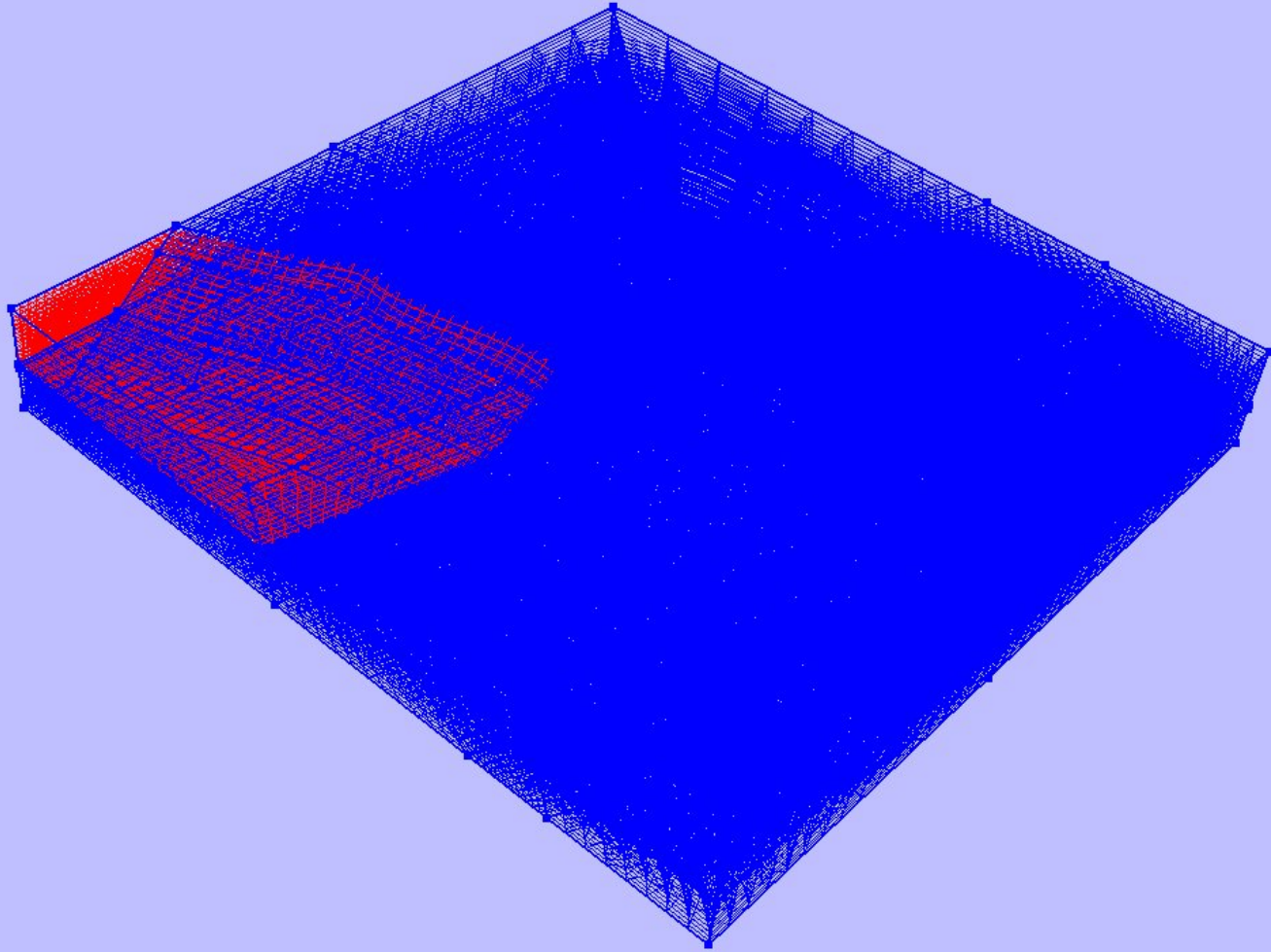
Generation of solid mesh by sweeping



Generation of solid mesh by 3D mapping



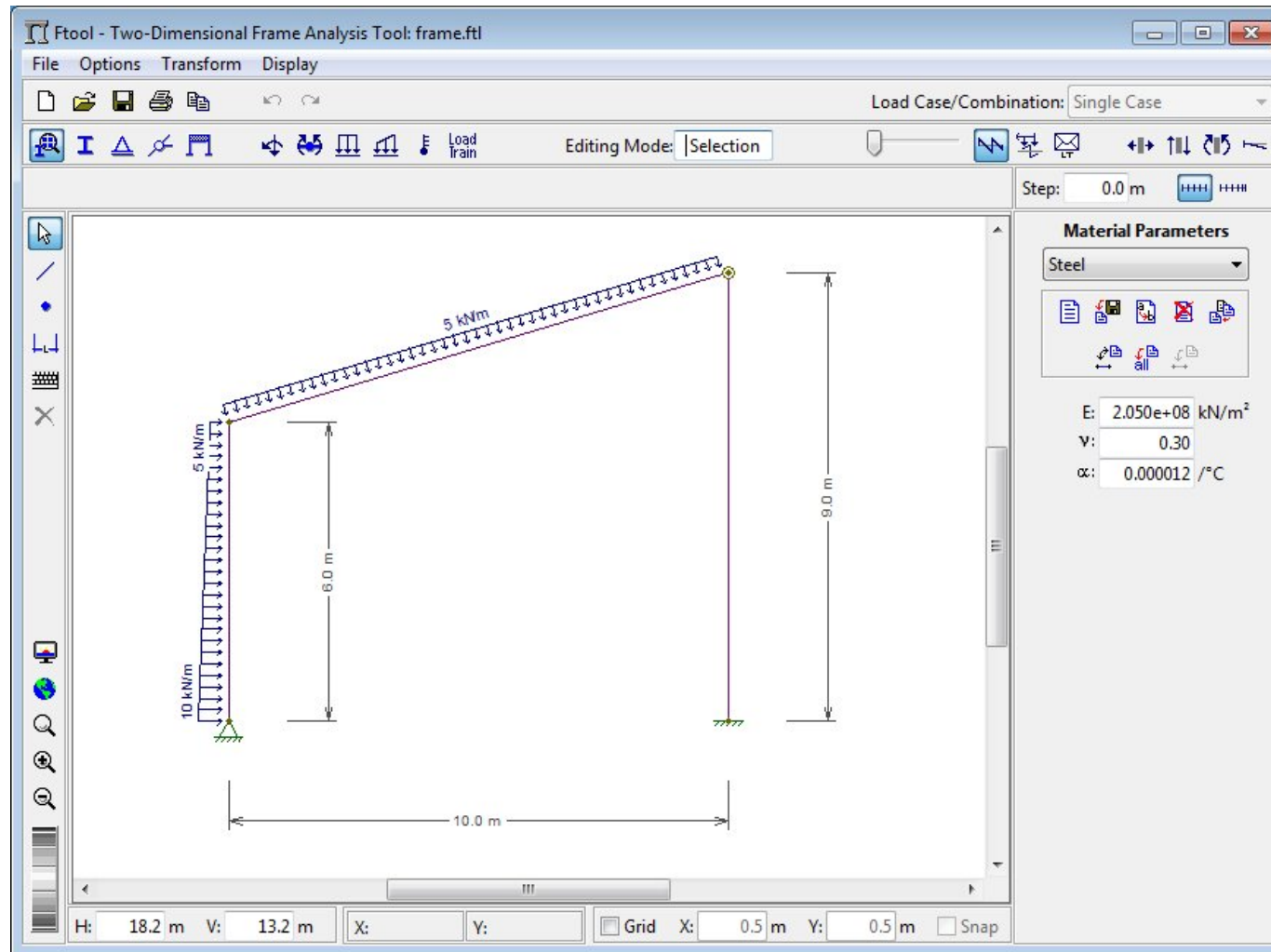
Generation of solid mesh by 3D mapping



Educational software for Engineering

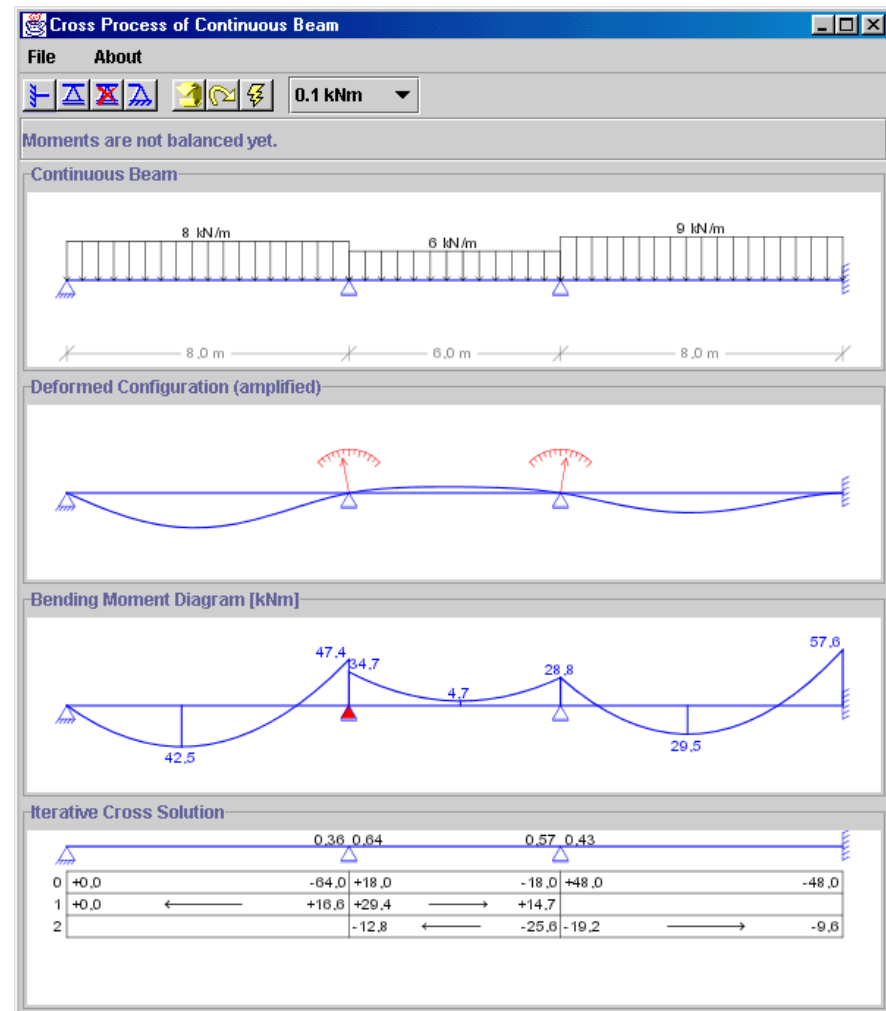
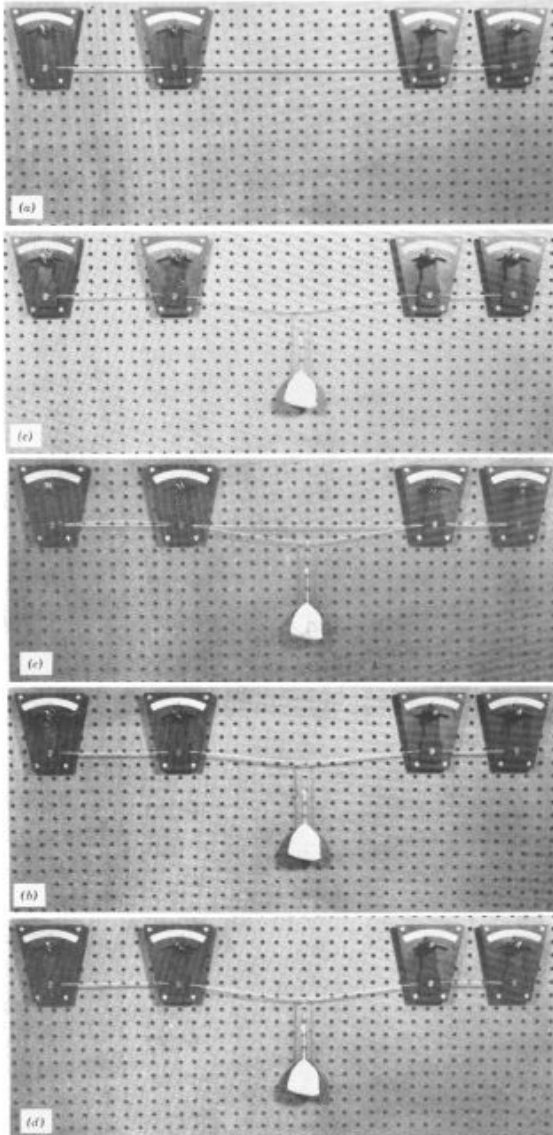
FEMOOP: FEM analysis based on Object Oriented Programming

Ftool: <http://www.tecgraf.puc-rio.br/ftool>



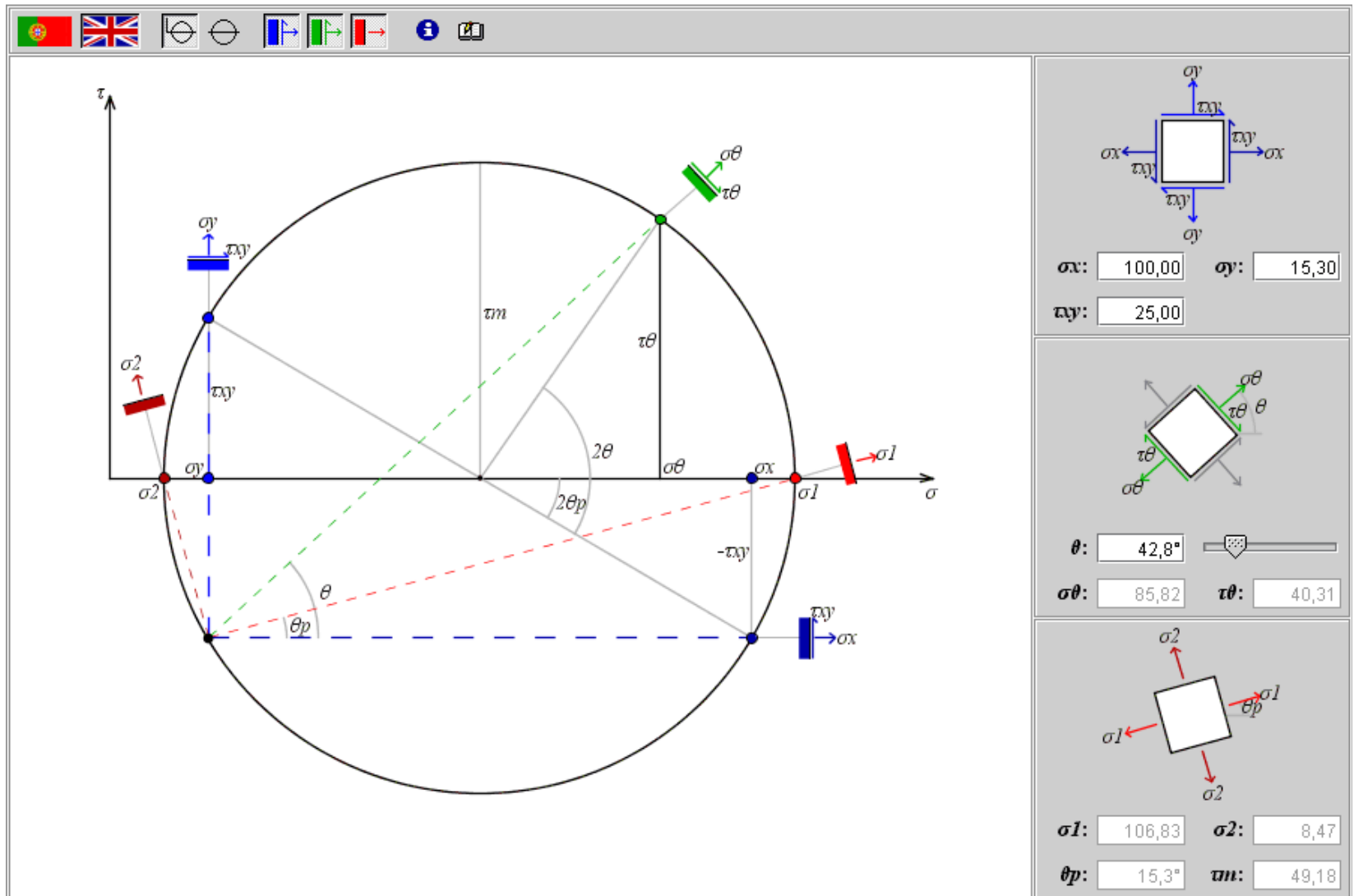
e-Cross: moment distribution method (in Java)

e-Cross: www.tecgraf.puc-rio.br/etools/cross



e-Mohr: Mohr's Circle tool (in Java)

e-Mohr: <http://www.tecgraf.puc-rio.br/etools/cross>



Conclusion

- The influence from Cornell is evident
- Tecgraf group in many aspects was shaped up by the Cornell group
 - Computer graphics
 - Mesh generation
 - Finite element simulation
 - Educational software
 - ...
- We are very grateful
In particular to Tony Ingraffea and his team
(Wash, Bruce, ...)