FIDESYS
strength analysis system

Math modeling for geophysical and geomechanical applications using industrial CAE Fidesys

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CTO, PhD

Introduction

Fidesys LLC is an engineering software company with offices in Moscow, Russia and NJ, USA, founded in 2009 as a research group of **Lomonosov Moscow State University.**
Fidesys LLC develops the next-gen universal software suite for high-end structural analysis (CAE, computer-aided engineering) using a new generation of FEA methods.

CAE Fidesys is used in oil and gas, mechanical engineering and mining industries.

The company is a resident of the **Skolkovo Innovation Center** and a member of **NAFEMS**, the International Association for the Engineering Modelling, Analysis and Simulation Community.

CAE Fidesys is verified according to the NAFEMS standards.

Our Team

- **20 programmers–mathematicians** (master students, postgraduates and PhDs from the top Russian universities*)
- **11 consulting professors**, working in the **Russian Academy of Sciences**, **Columbia University**, **University of New Hampshire** and **Iowa State University**
- Management, sales and marketing specialists with extensive experience in various technical fields and international background

Board of directors incl. top-mangers of IT industry (former VPs of PTC CIS, Autodesk CIS)

Key expertise: precise math modeling for strength analysis and related engineering fields

*incl. Lomonosov Moscow State University, Bauman Moscow State Technical University, Moscow Institute of Physics and Technology, and other leading regional universities

Business directions

Fidesys

Development, support and commercialization of CAE Fidesys

Engineering services based on computational kernels of CAE Fidesys

Presentation plan

Industrial applications of CAE Fidesys:

1. Geomechanical simulation.

   Industrial software for Gazpromneft: borehole (deviated, horizontal, fishbone) stability analysis in prestressed media with plastic zones. Hydrogeomechanical coupling.

2. Seismic modeling.

   High order spectral element method for precise fullwaveform modeling. Induced anisotropy due to geomechanical stresses. Wave propagation in fractured media.

3. Numerical analysis of rock samples.

   Anisotropic effective elastic and thermal properties.

GEOMECHANICAL SIMULATION

Wellbore stability problem

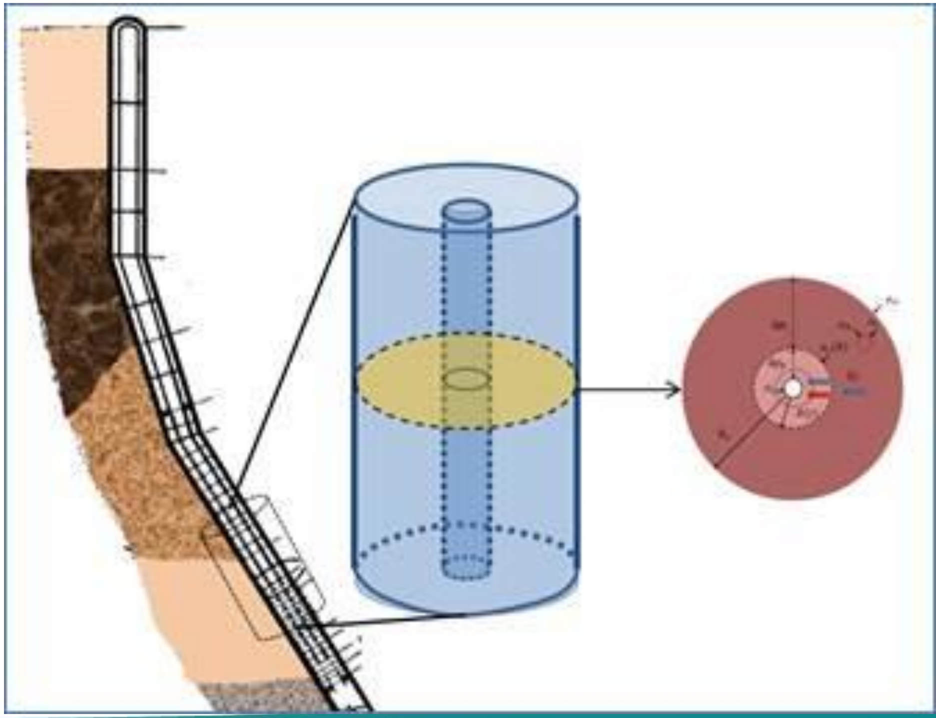
One of the key problems of geomechanics is the determination of technological parameters, for which the wellbore will maintain its stability.

The different rock's properties (modulus of elasticity, Poisson's ratio, density, friction and dilatancy angles, strength and yield strengths for tension and compression, adhesion, porosity, permeability, compressibility, etc) should be taken into account.

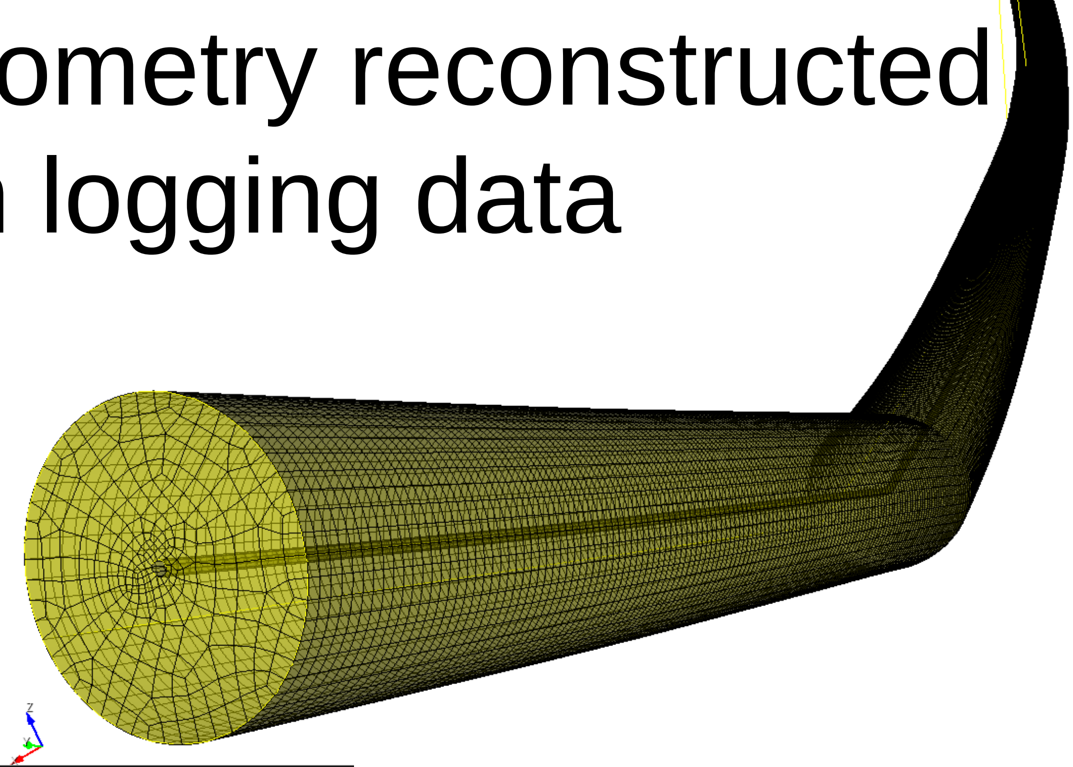
In addition, the rock is prestressed, which is determined by the components of the generally anisotropic nonuniform stress tensor.

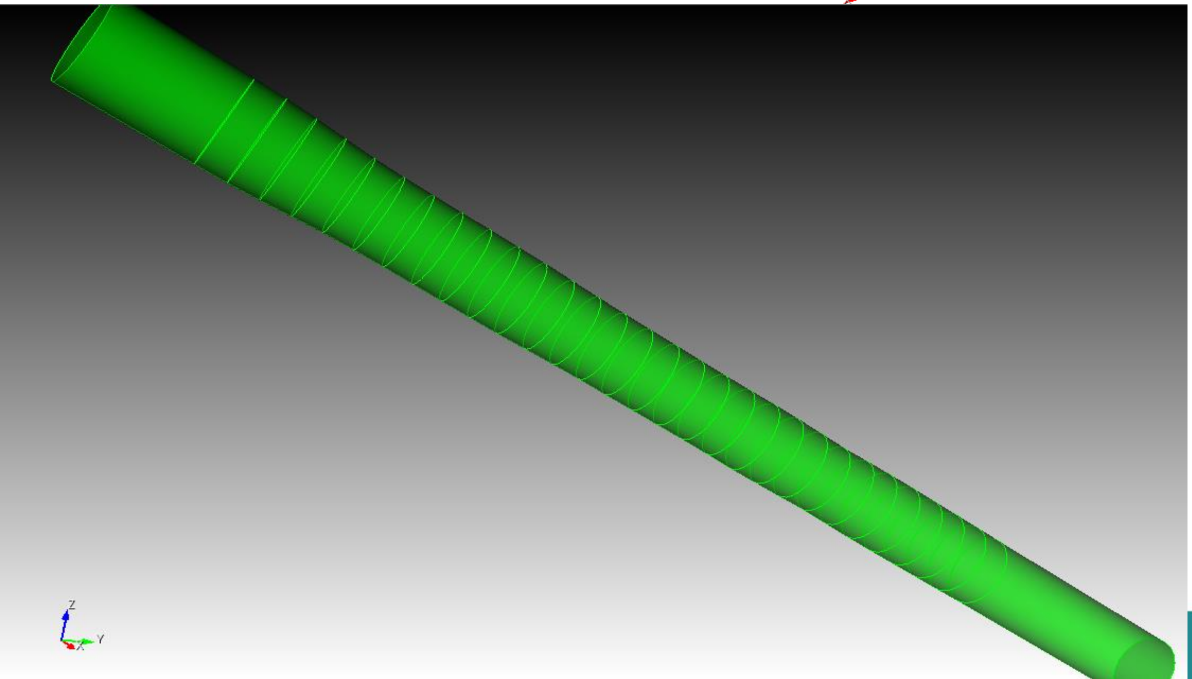
When drilling,in general, a bit and mud generates a pressure on the rock, thereby deforming it and redistributing the stresses (superposition of generally finite deformations), causing the reaction of the rock to the applied impact.

Bio-Terzagi Model of non-stationary poroelastoplasticity is developed.

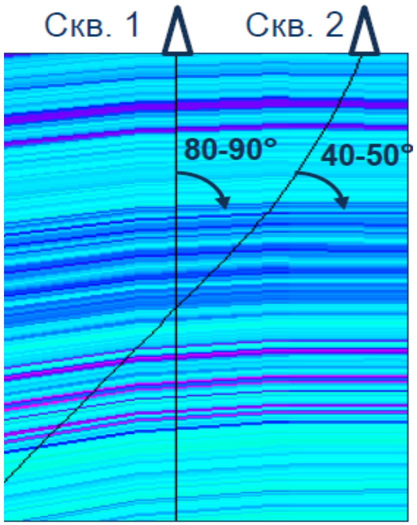


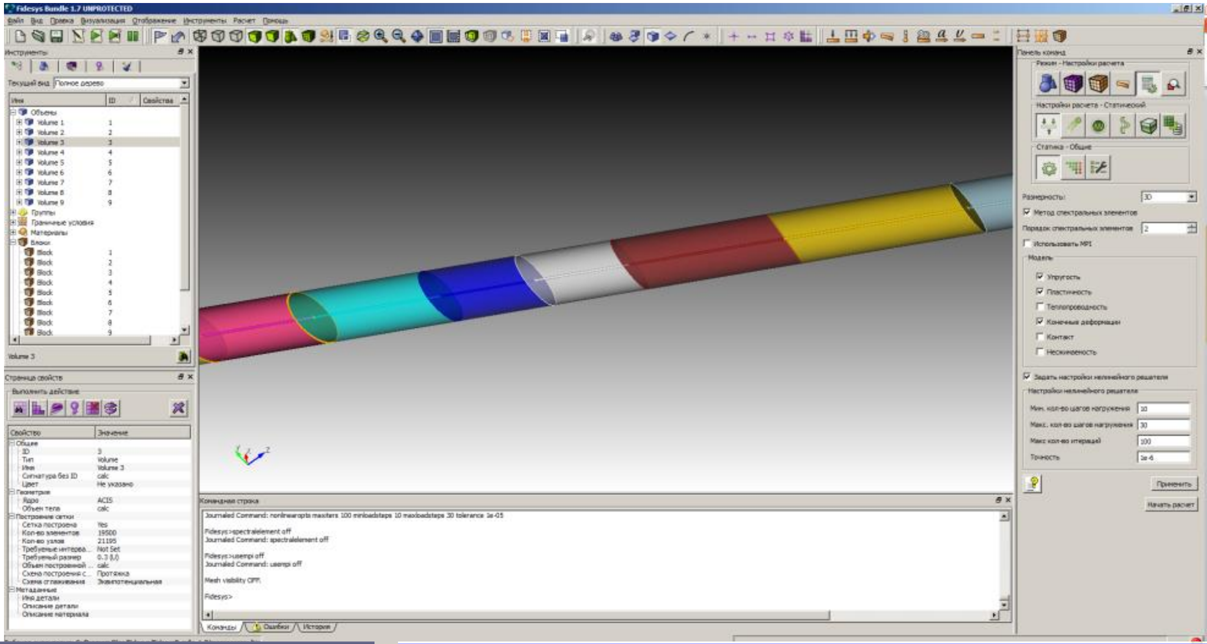
Wellbore geometry reconstructed from logging data

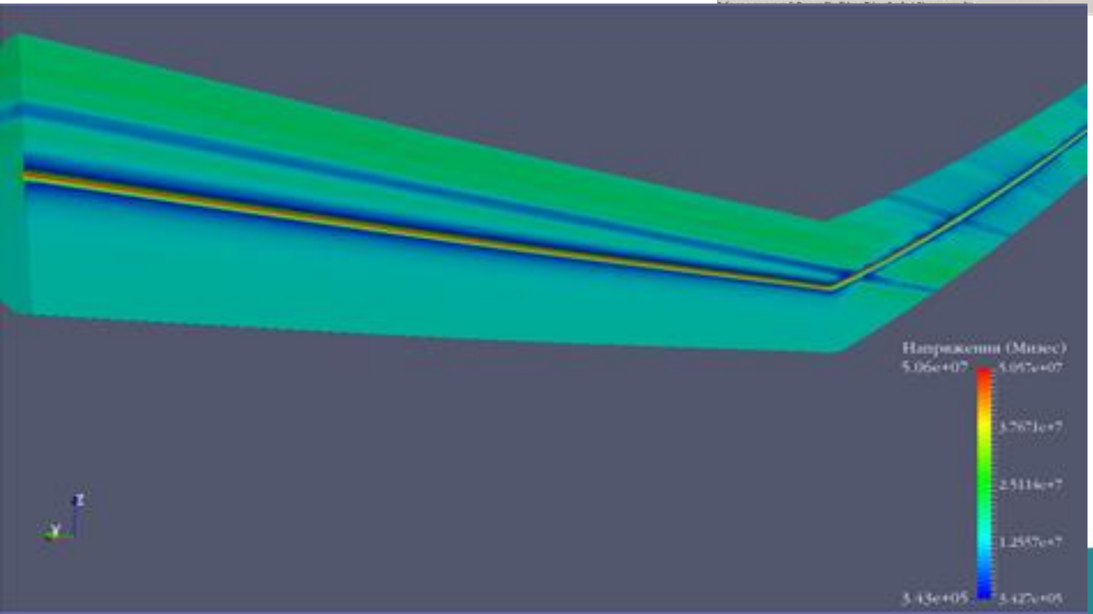


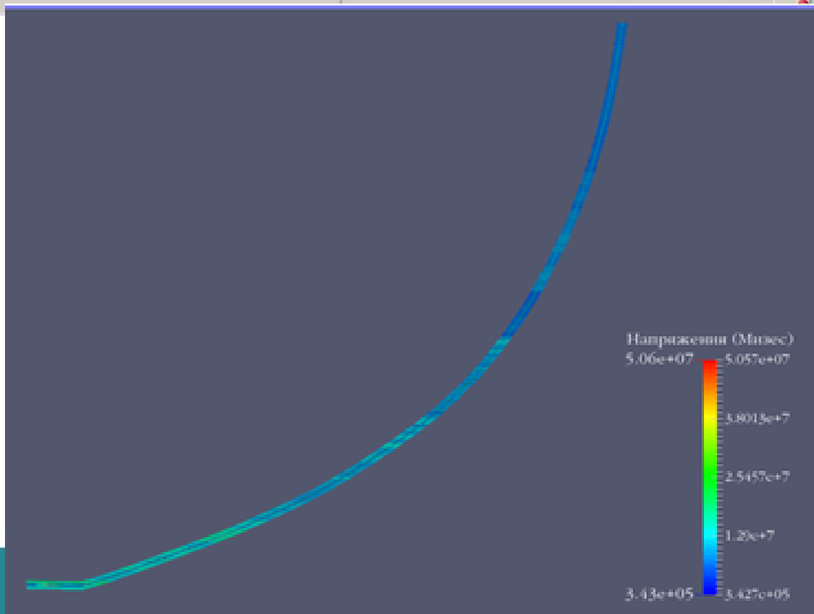


3D stability analysis for the wellbore in a layered media

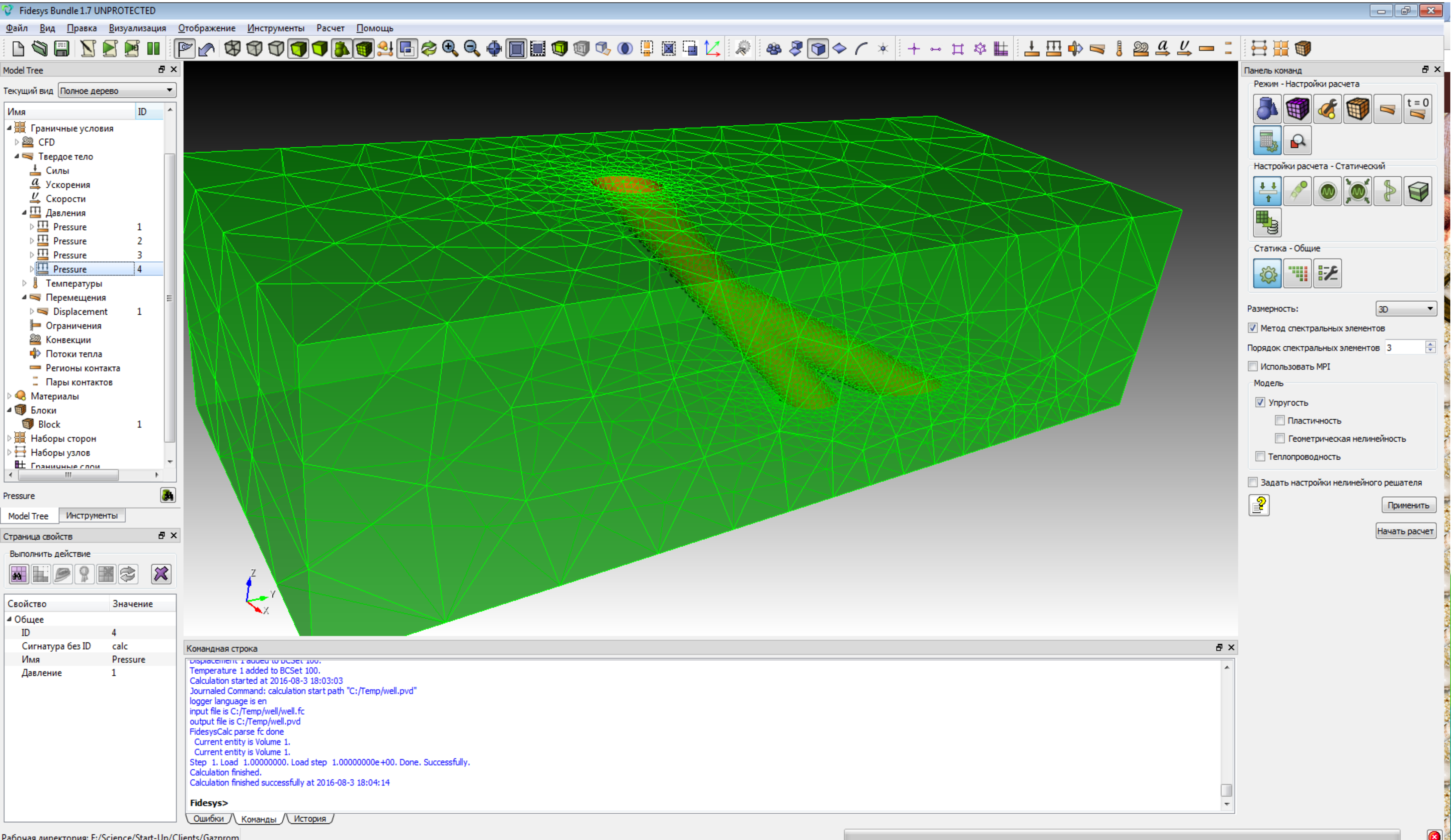




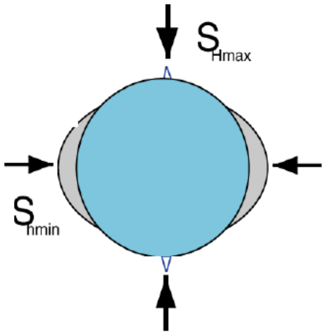


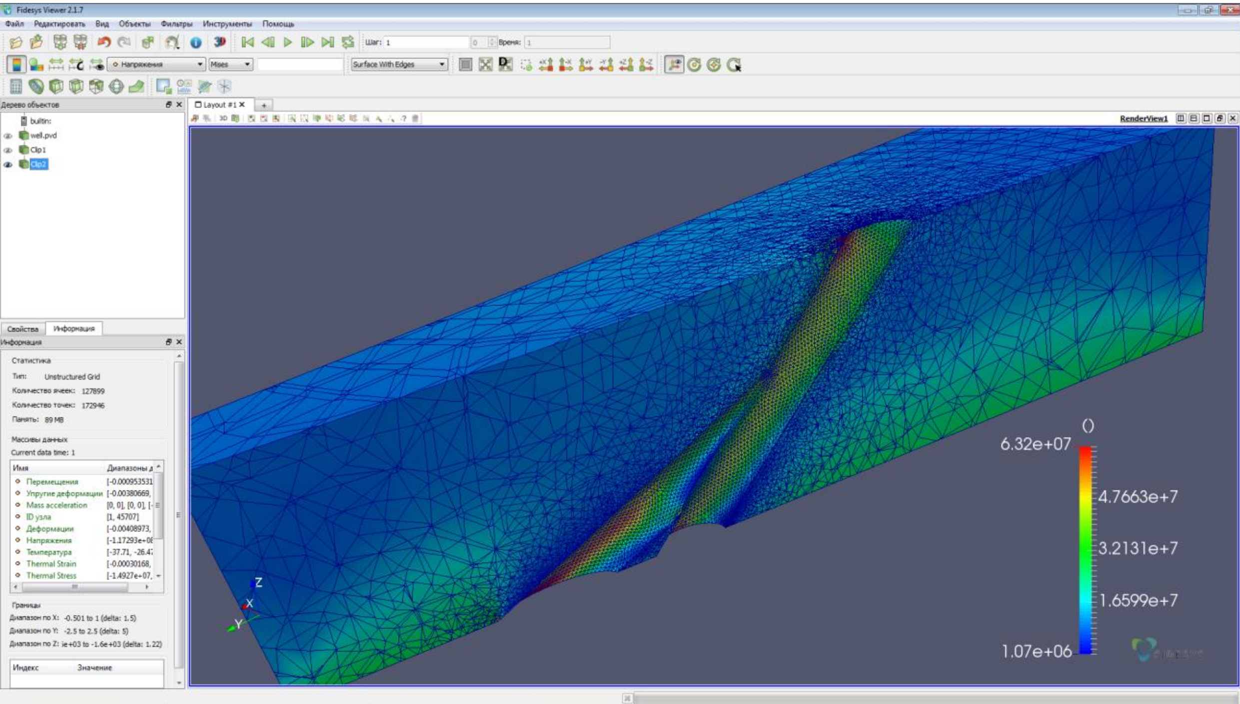


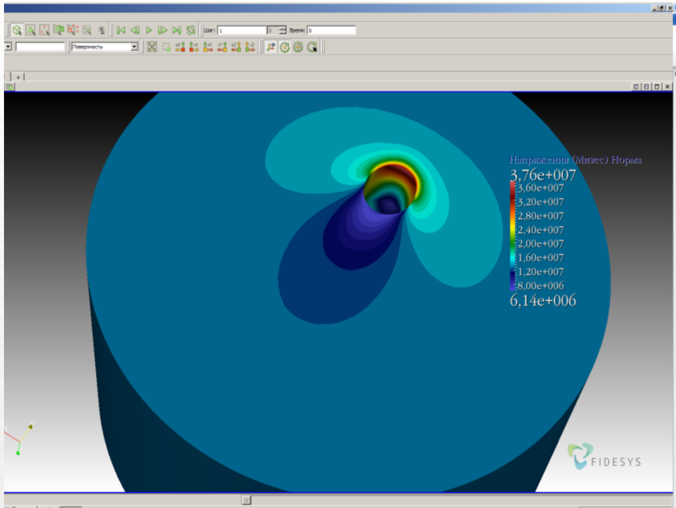
FEA model of the fishbone wellbore in CAE Fidesys



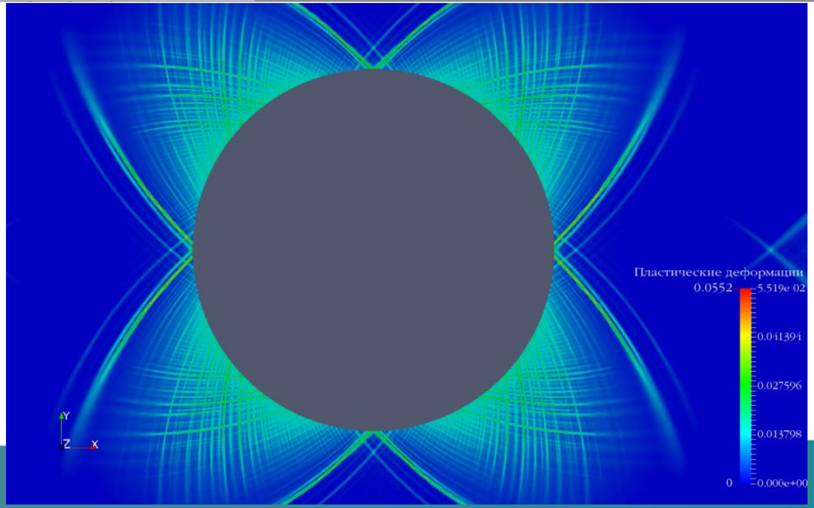
Localization of elastoplastic stresses

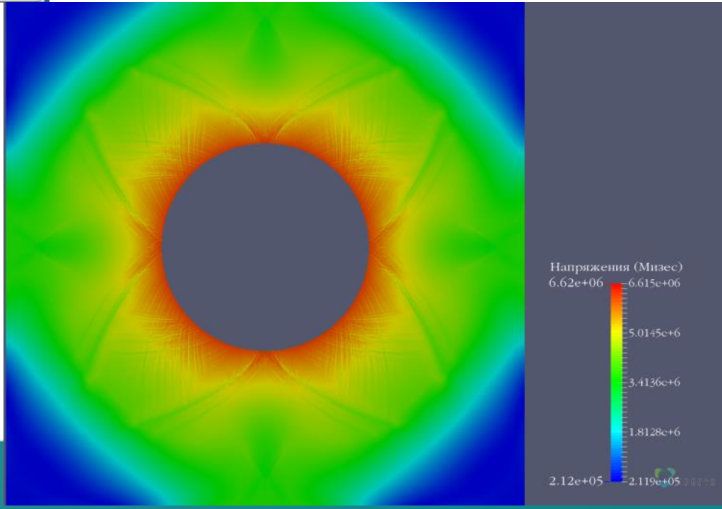






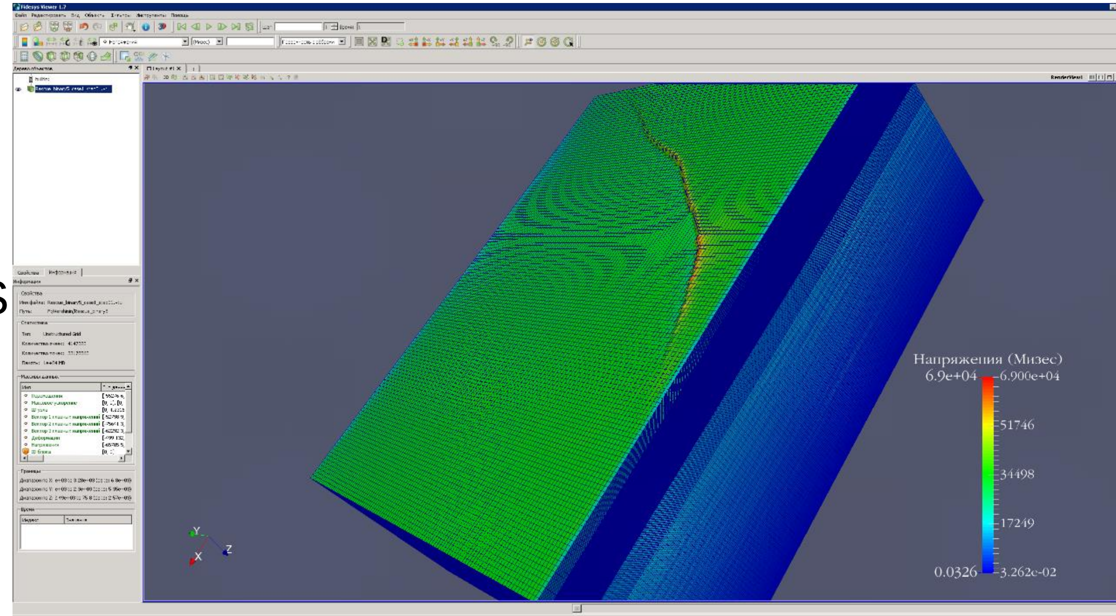
Luders plastic sliding lines nearby the wellbore

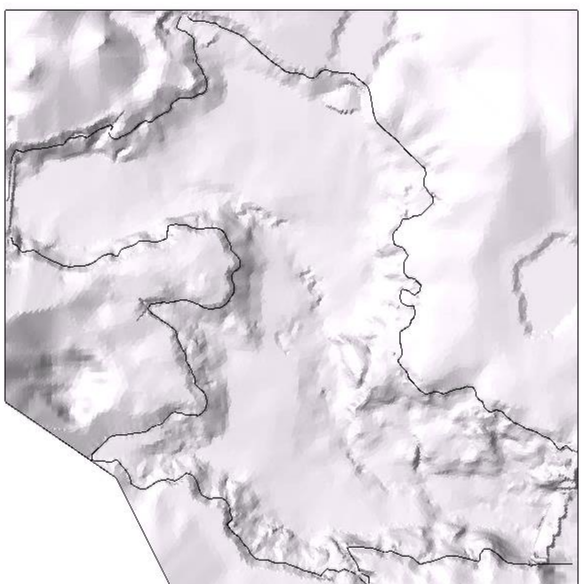


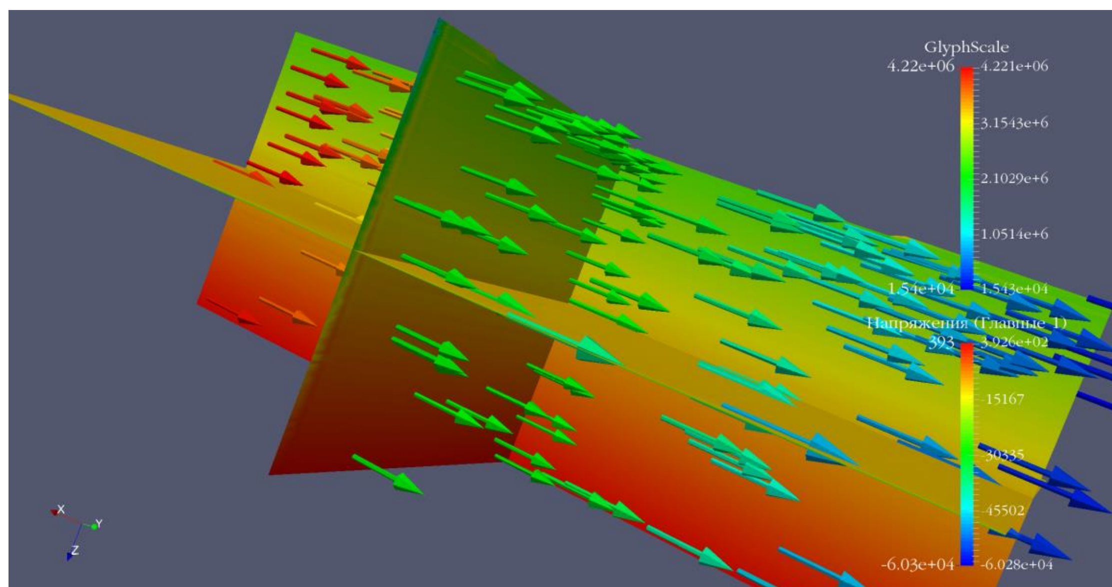


Integration with Roxar RMS

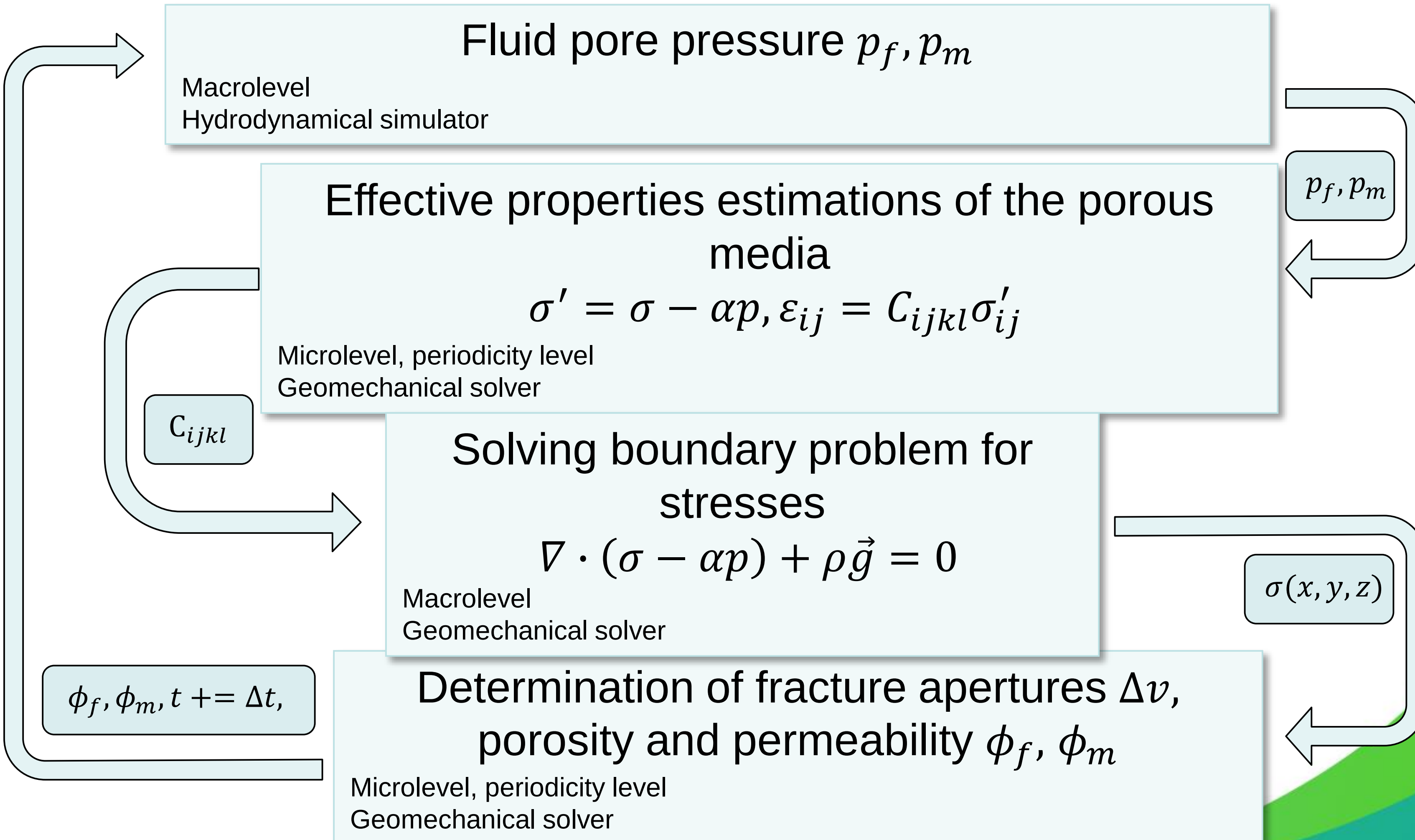
- Full 3D geomechanical stresses and strains distribution;
- Direct automatic transfer of the geological model from Roxar RMS into CAE Fidesys;
- Predictive modeling for optimization and virtual prototyping.





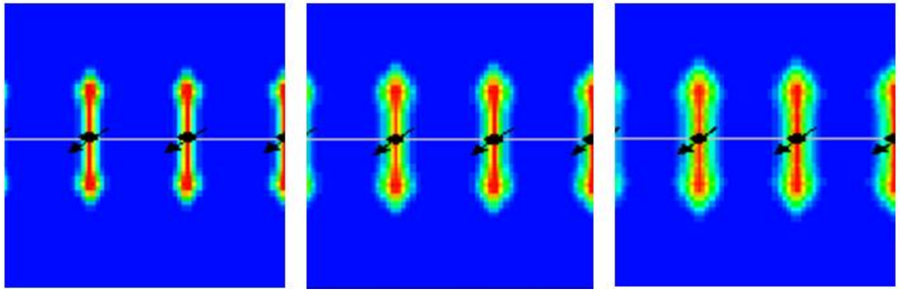


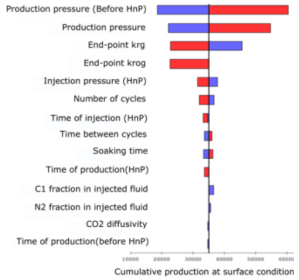
External two-way coupling for solving hydrogeomechanical problem (double porosity with induced anisotropy)

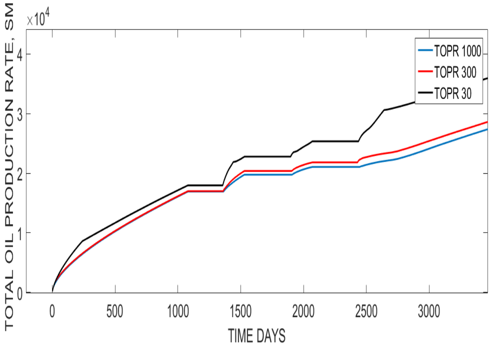


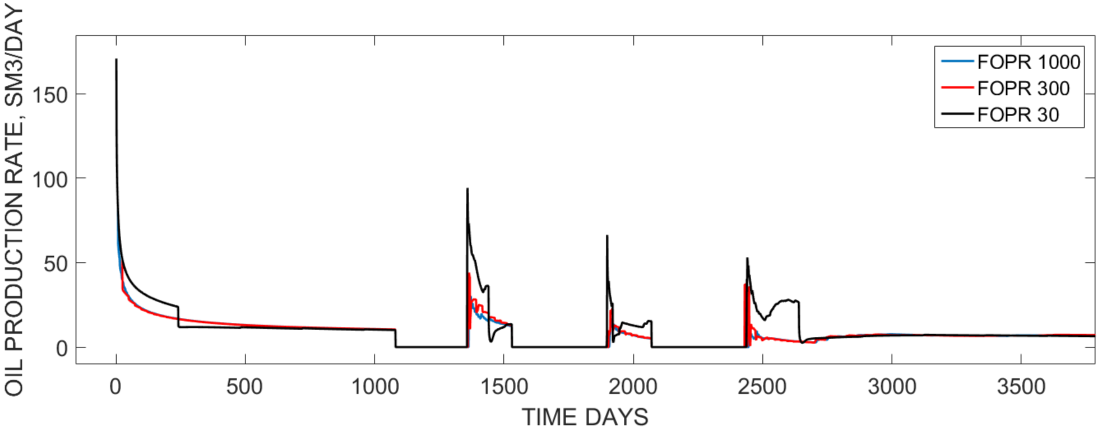
Evaluation of geomechanical effects due to cyclic injection of carbon dioxide into the reservoir

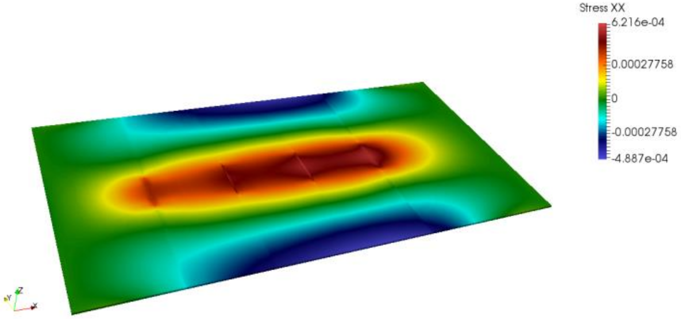
- **Optimization of reservoir injection scenario**











The geomechanical processes in the rock significantly affects the distribution of permeability and filtration properties of the reservoir. For a small number of steps for coupling the hydrodynamic and geomechanical models (30 steps for 20 years of calculation), the results of the calculations show a more positive forecast of the efficiency of the CO2 injection technology. However, with a further increase in the number of interfaces (300 steps) between two models, the results demonstrate a decrease in efficiency, both in terms of accumulated and daily production.

SEISMIC MODELING

Mechanical model of induced anisotropy

I. **What is *induced anisotropy*?**

Consideration of pre-loaded solids:

1. Anisotropy in mechanical properties of geolayers induced by stresses and strains due to gravity/temperature/formation history/accumulated strains etc
2. Stress concentrations near holes/inclusions/fractures (possibly propagating).

II. What is *nonlinearity*?

1 Nonlinear dependency between stresses and strains (nonlinear constitutive relations, physical nonlinearity)

2. Finite strains (nonlinear dependency between strain tensor and deformation gradient, geometrical nonlinearity)

Additionally

3. Constitutive relations for viscoelastic solids (i.e. material properties changing with time, Q-factors)

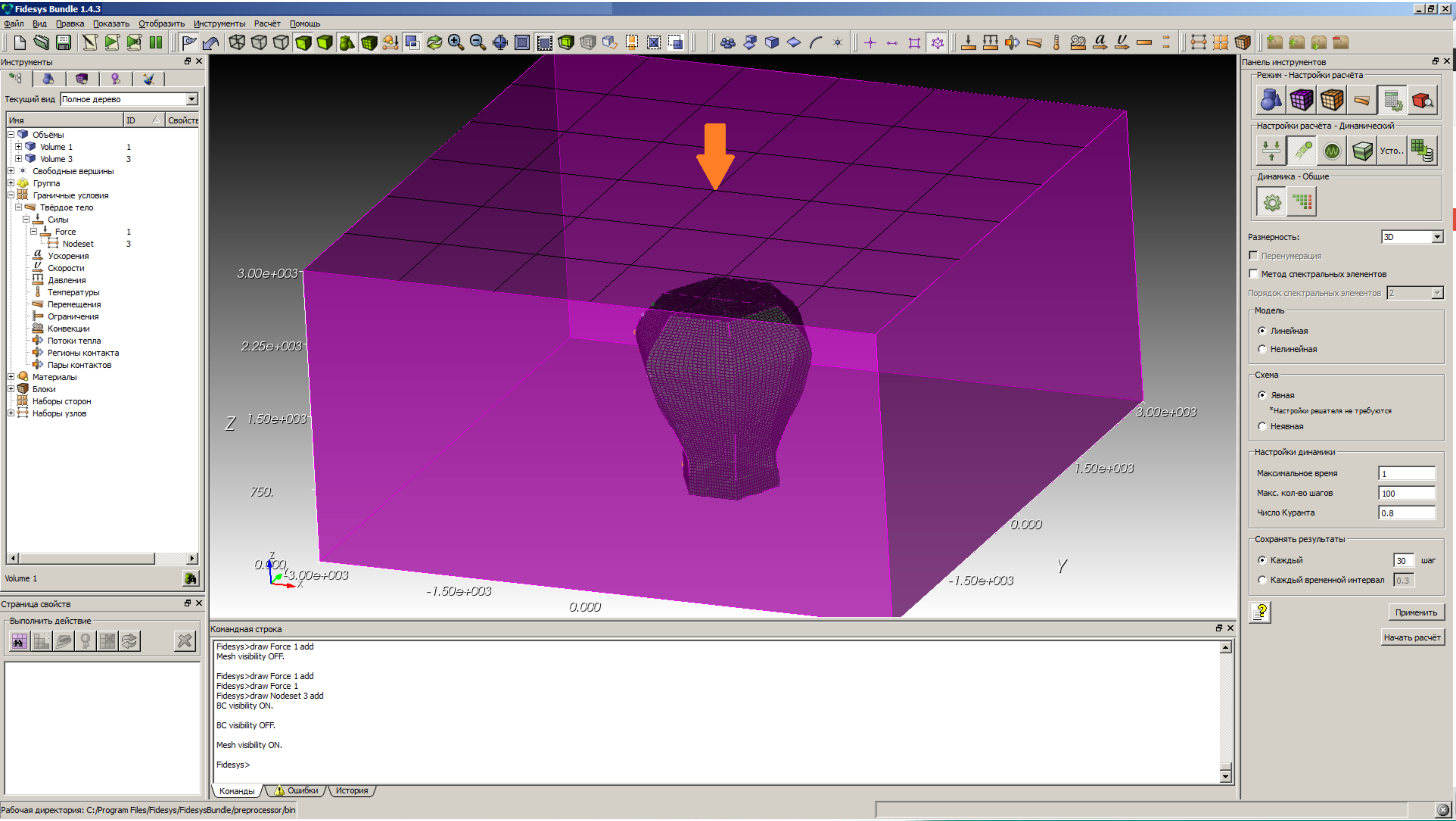
4. Fractured solids (for example fracture corridors => estimation of effective properties of fractured or porous materials)

III. **Theory of repeated superposition of large deformations** (a set of nonlinear vector partial differential equations for different solid's states)

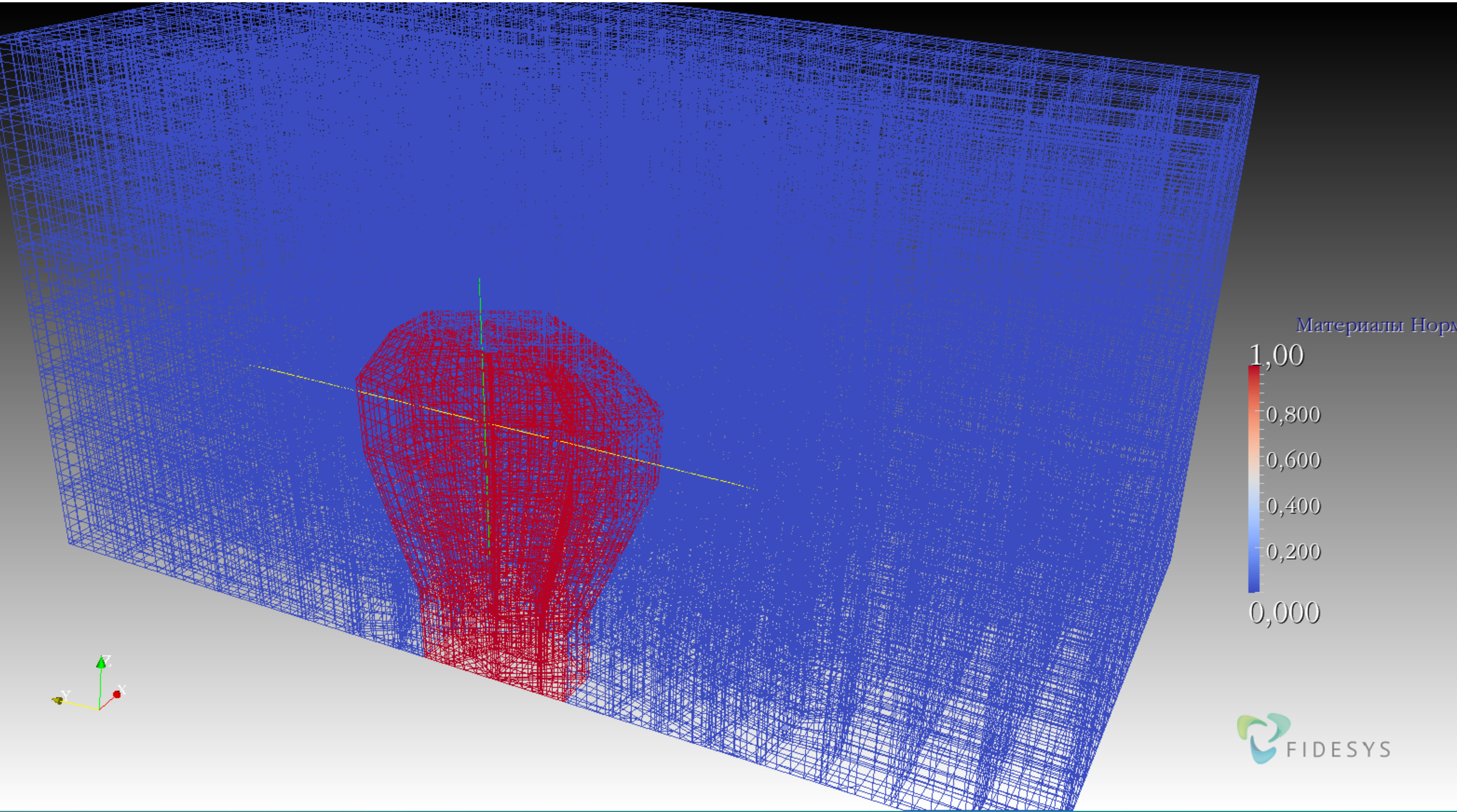
Typical case - *s*uperposition of small deformations on large ones («split» system of vector equations) – wave propagation in a pre-stressed solids.

Test geometry for the salt dome

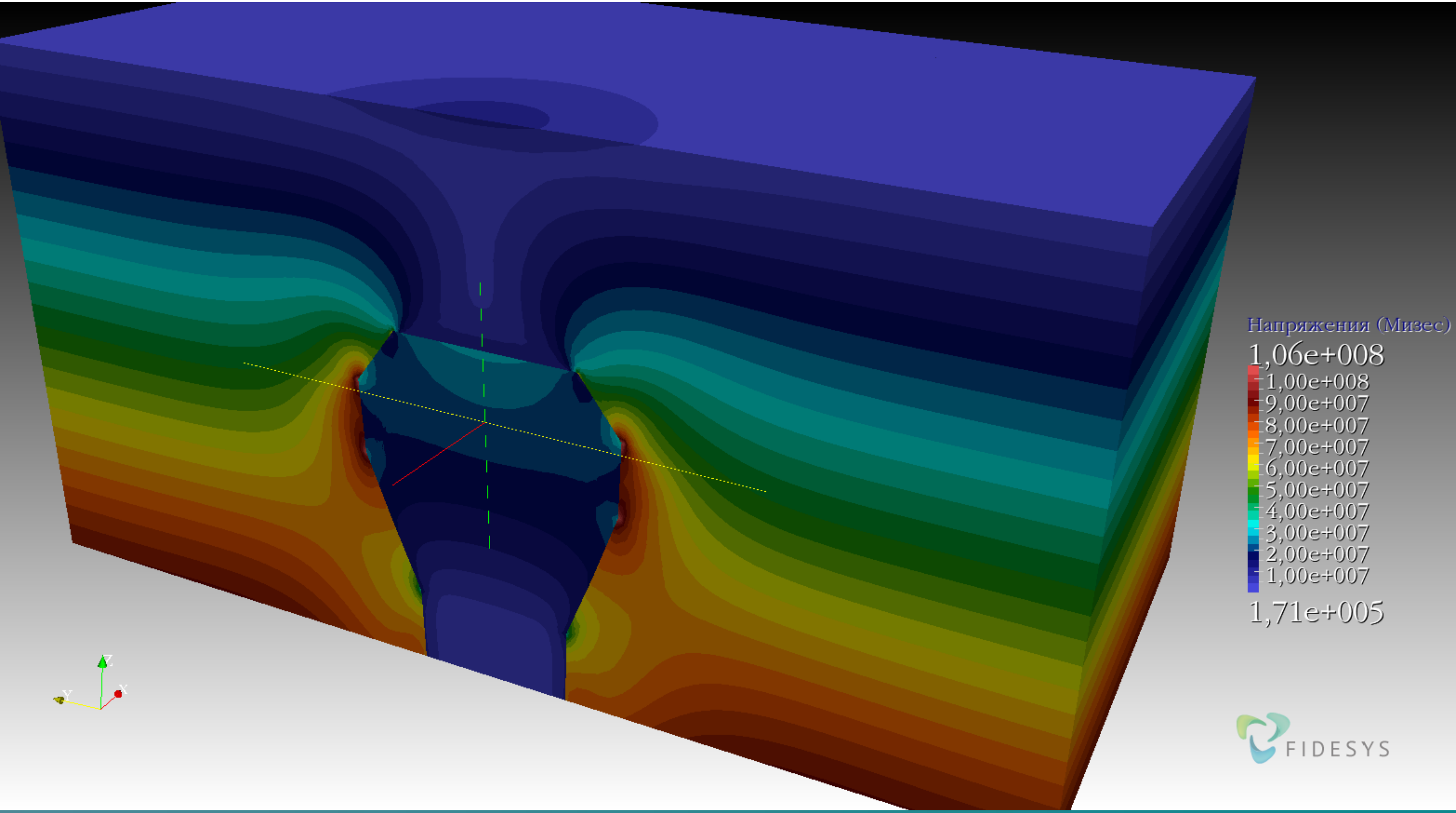
Model dimensions: 6000m x 6000m x 3000m



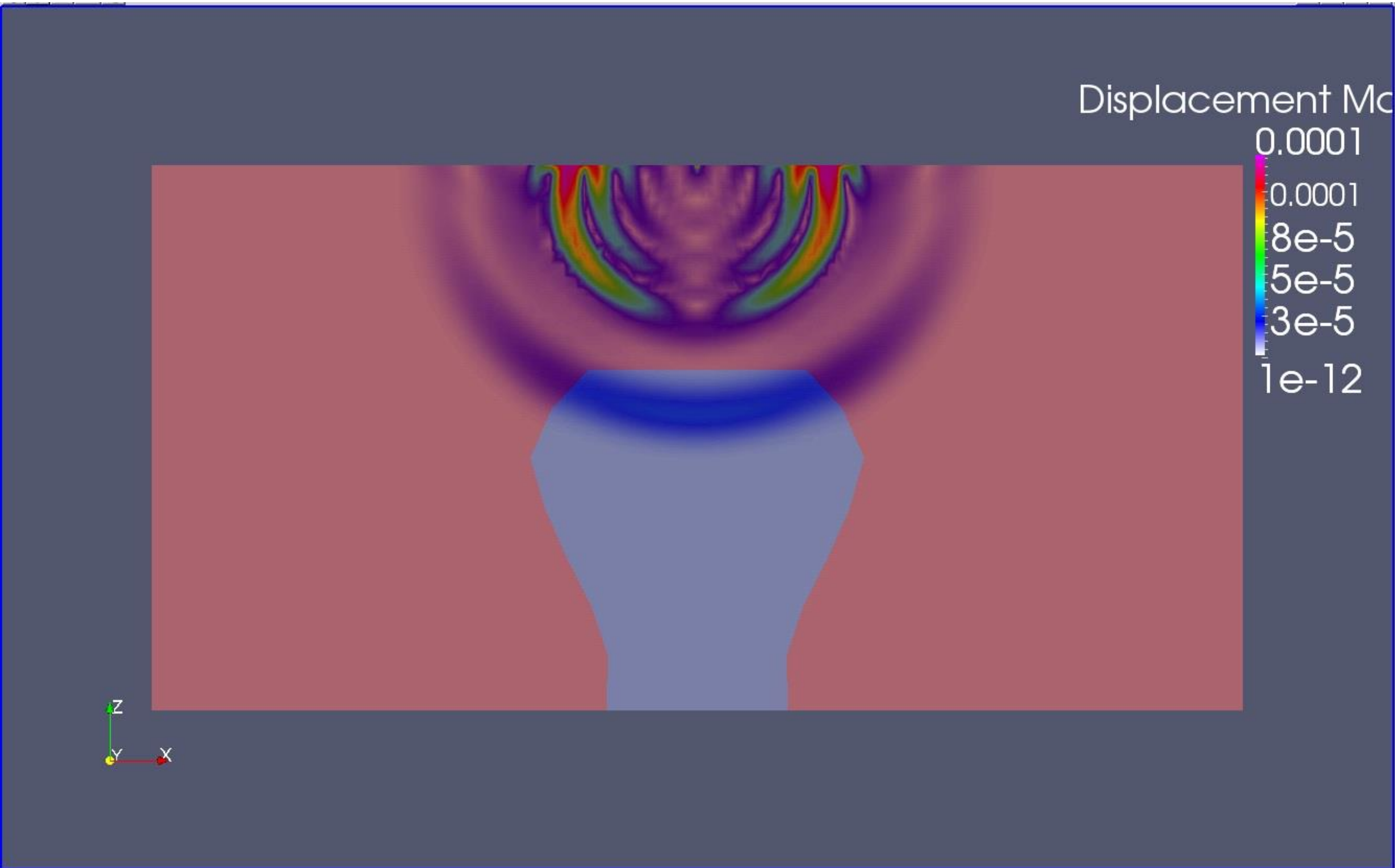
Spectral element mesh



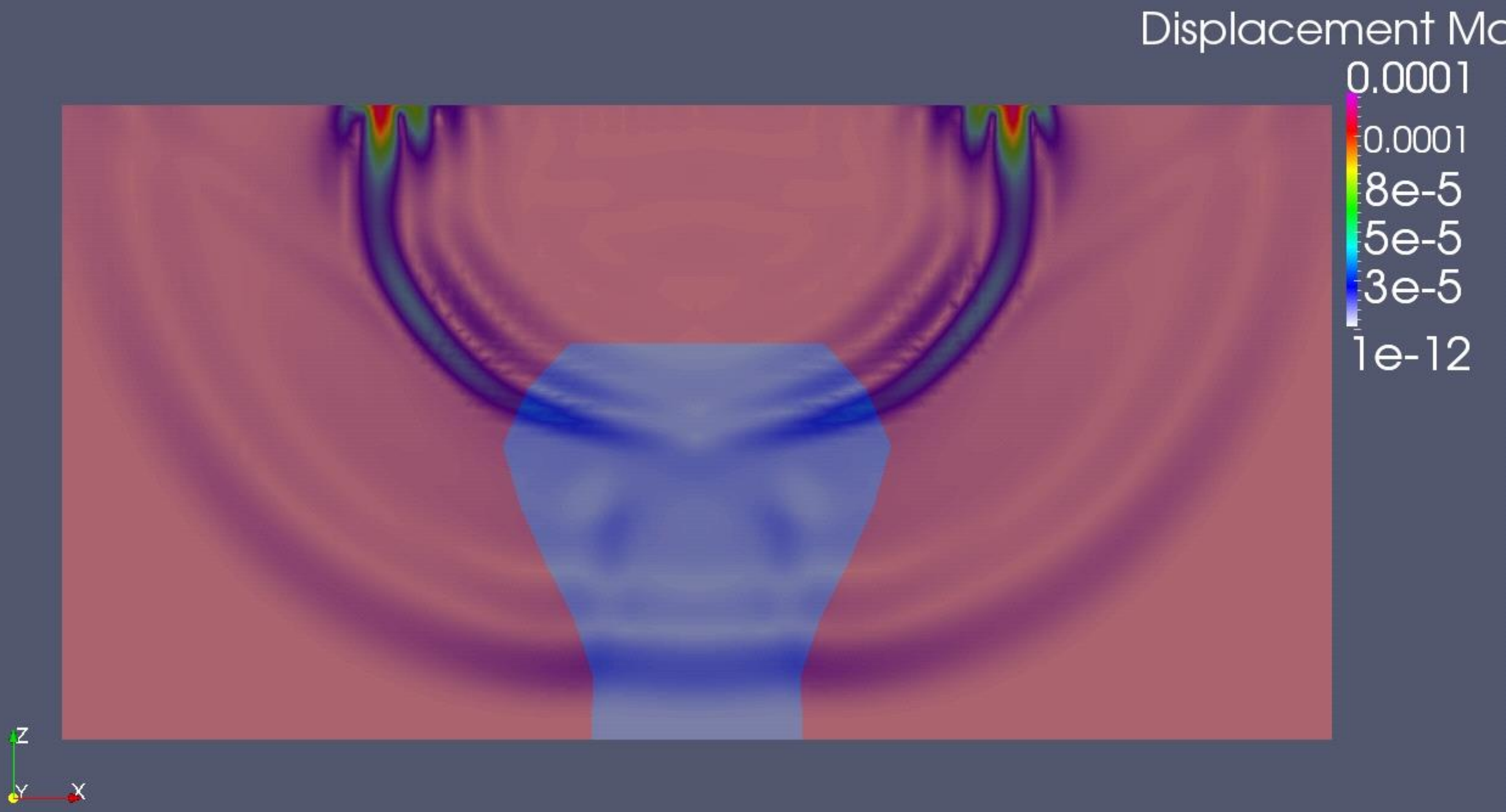
Initial geomechanical stresses



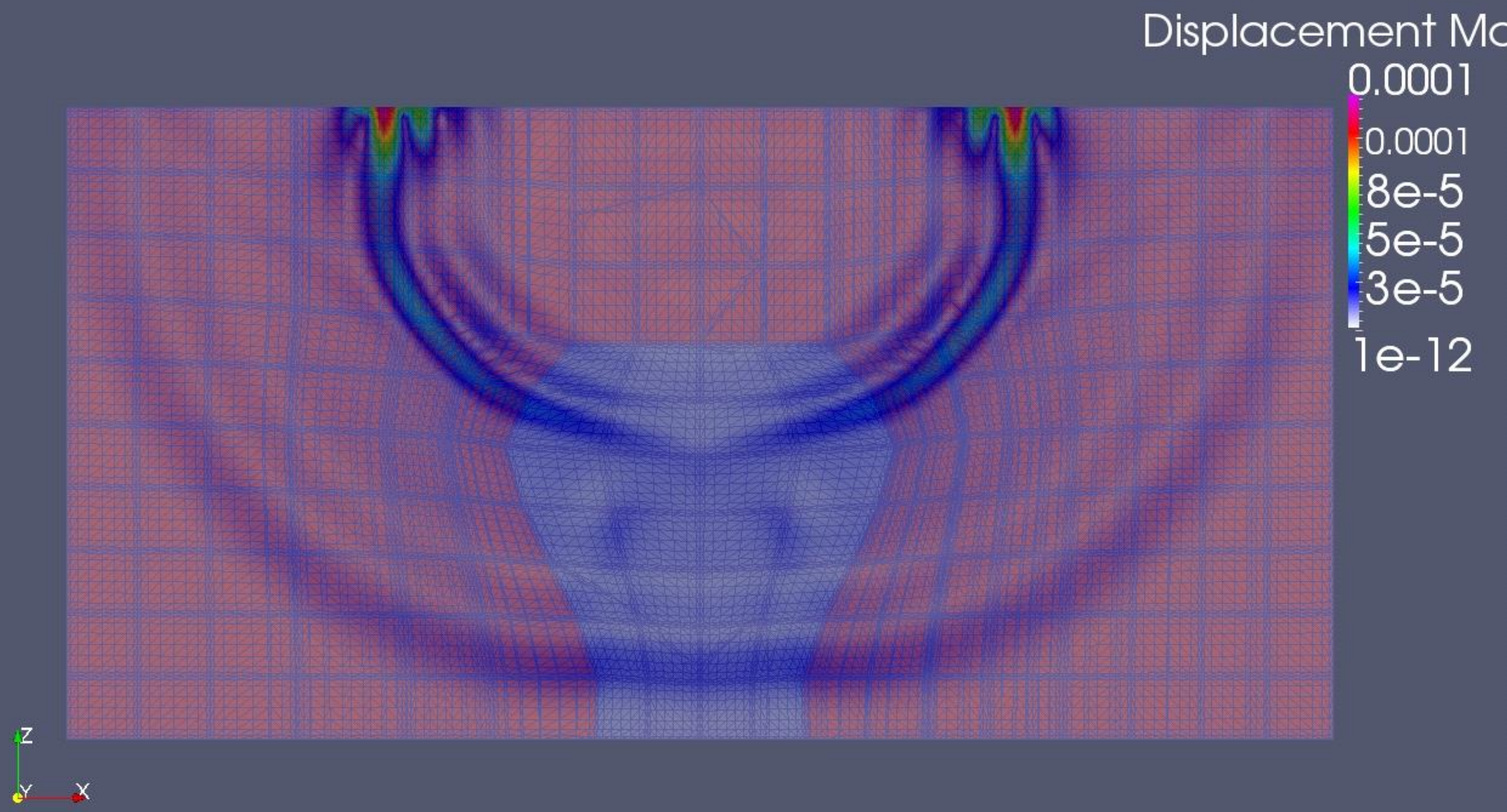
Wavefronts of displacement fields



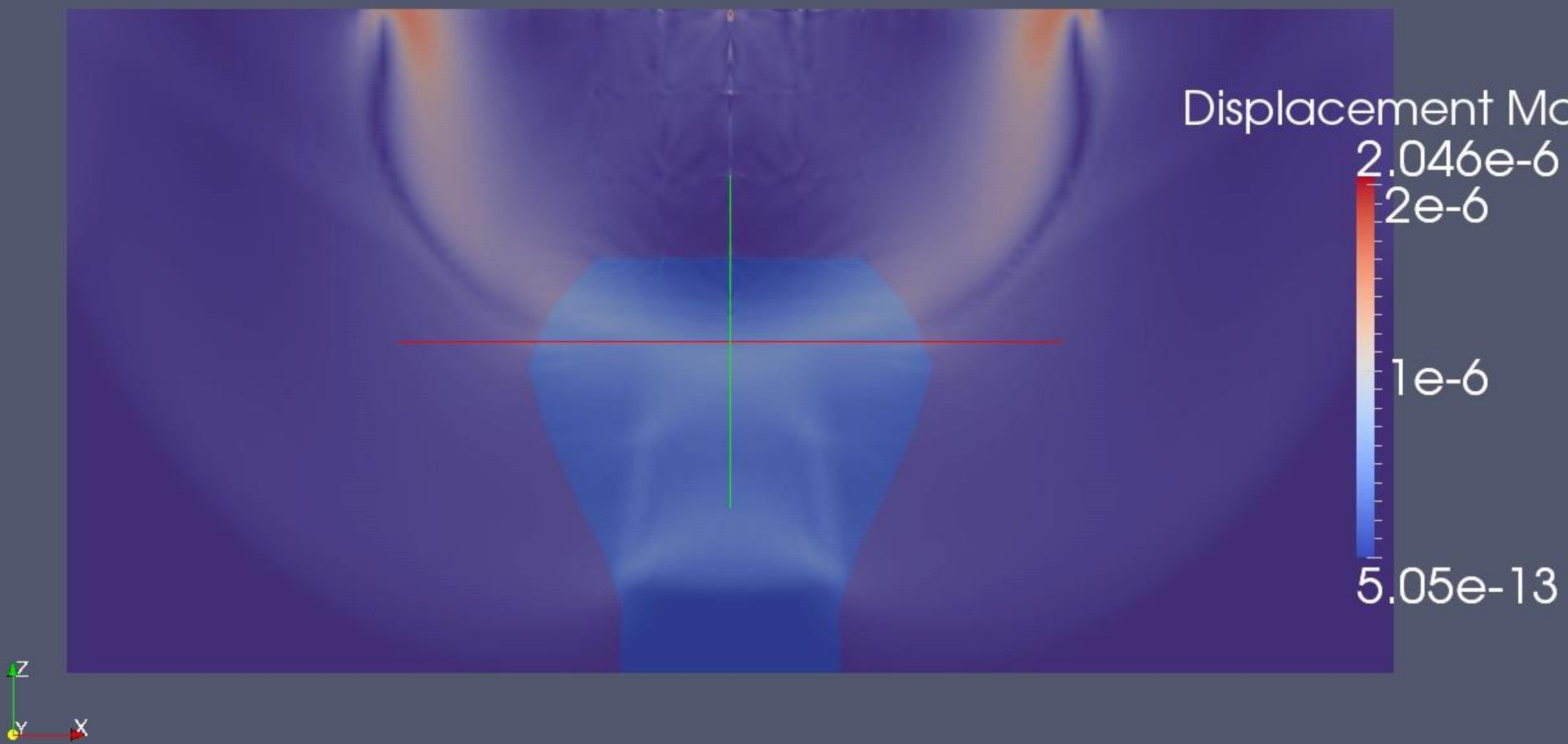
Wavefronts of displacement fields



Spectral element mesh

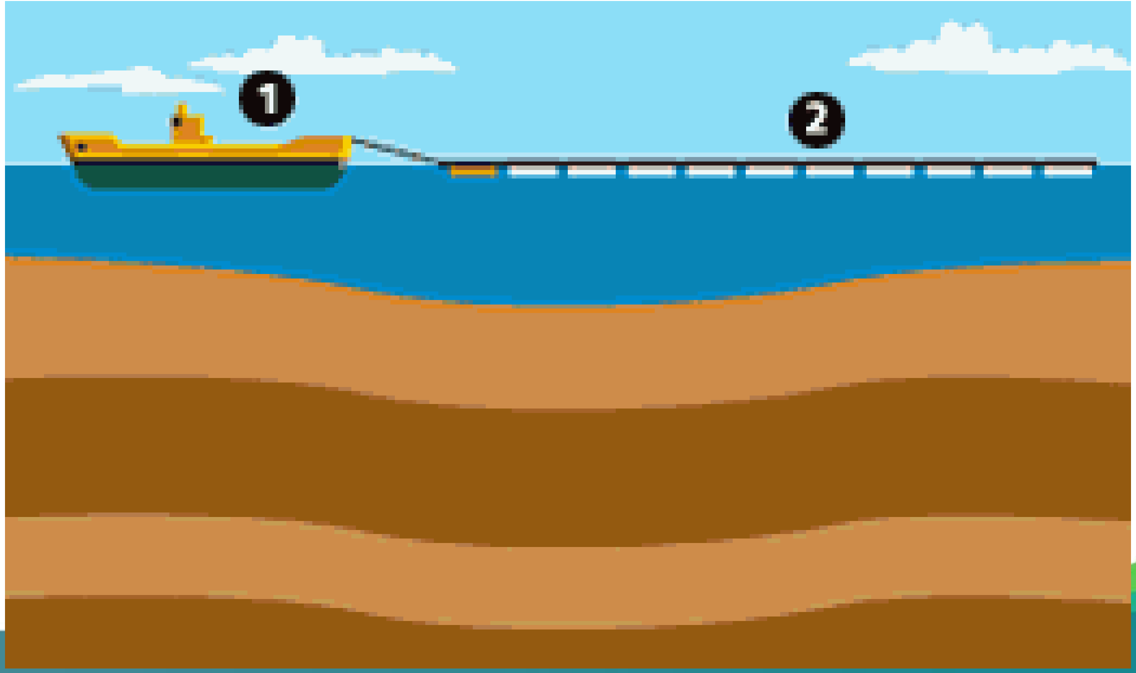


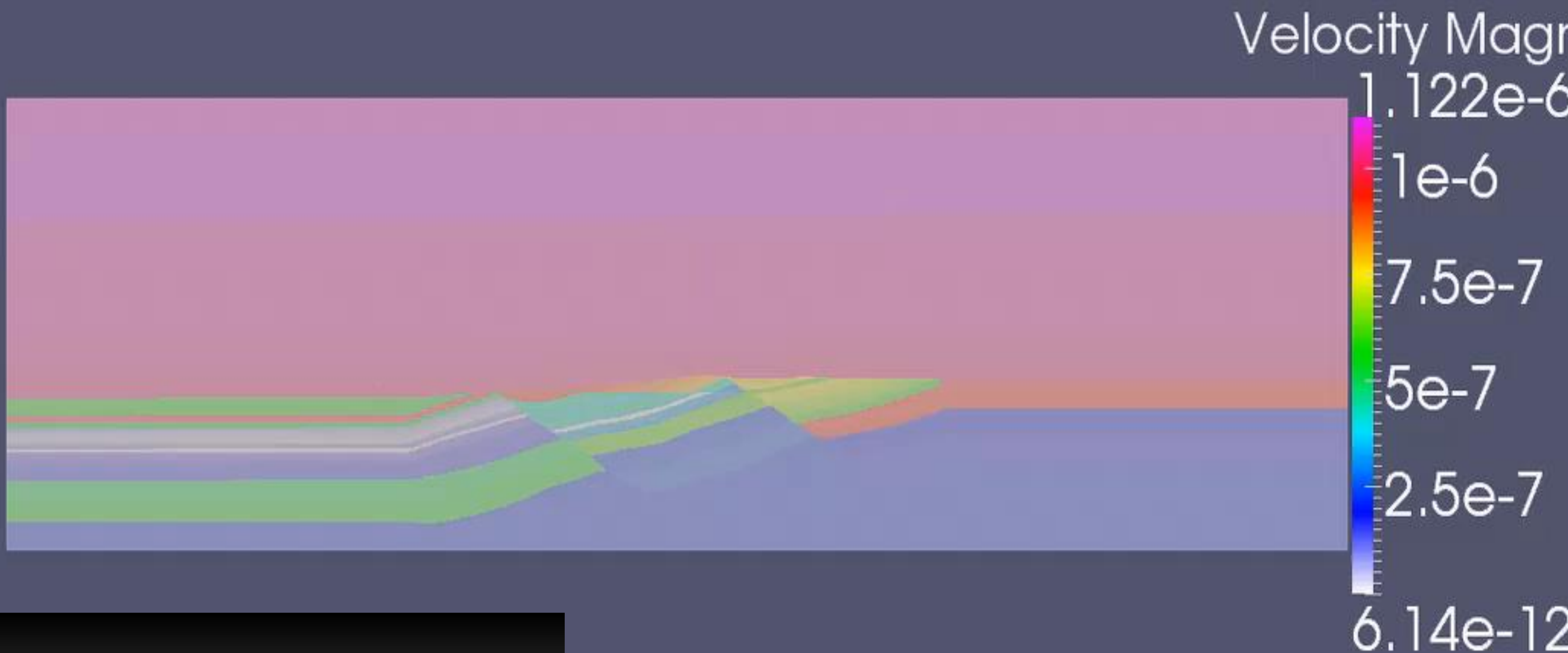
Numerical dispersion in case of FEA



Marine seismic

1. Existing software for modeling marine seismic doesn’t take into account complex geological structures at the sea bed and layers beneath it.
2. An accuracy of modern marine seismic surveys require a high-precision numerical modeling especially for the complicate 3D objects.
3. 3D full waveform seismic modeling dictates application of cutting-edge numerical algorithms and HPC technologies.

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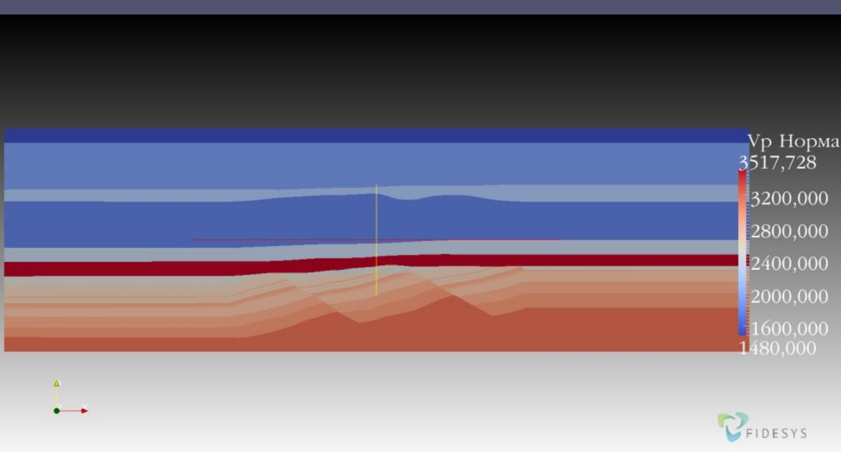
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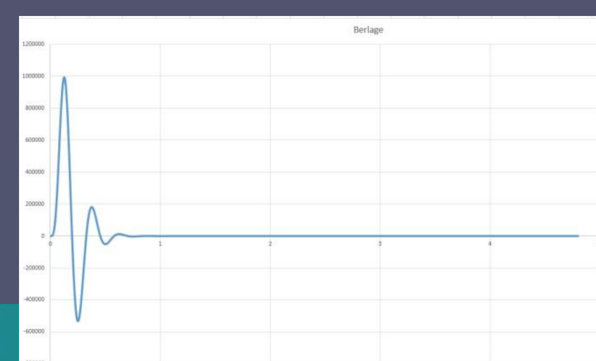
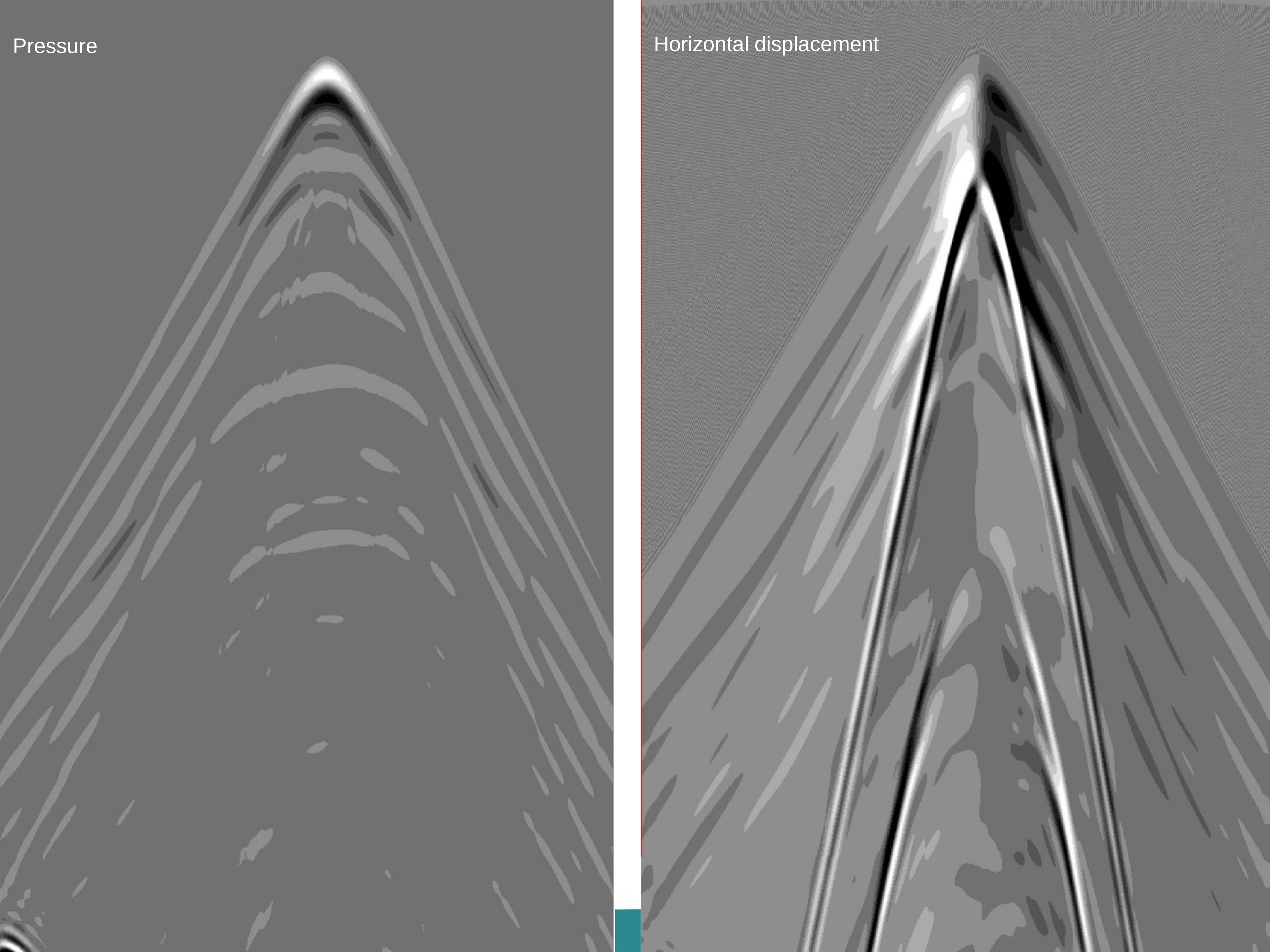
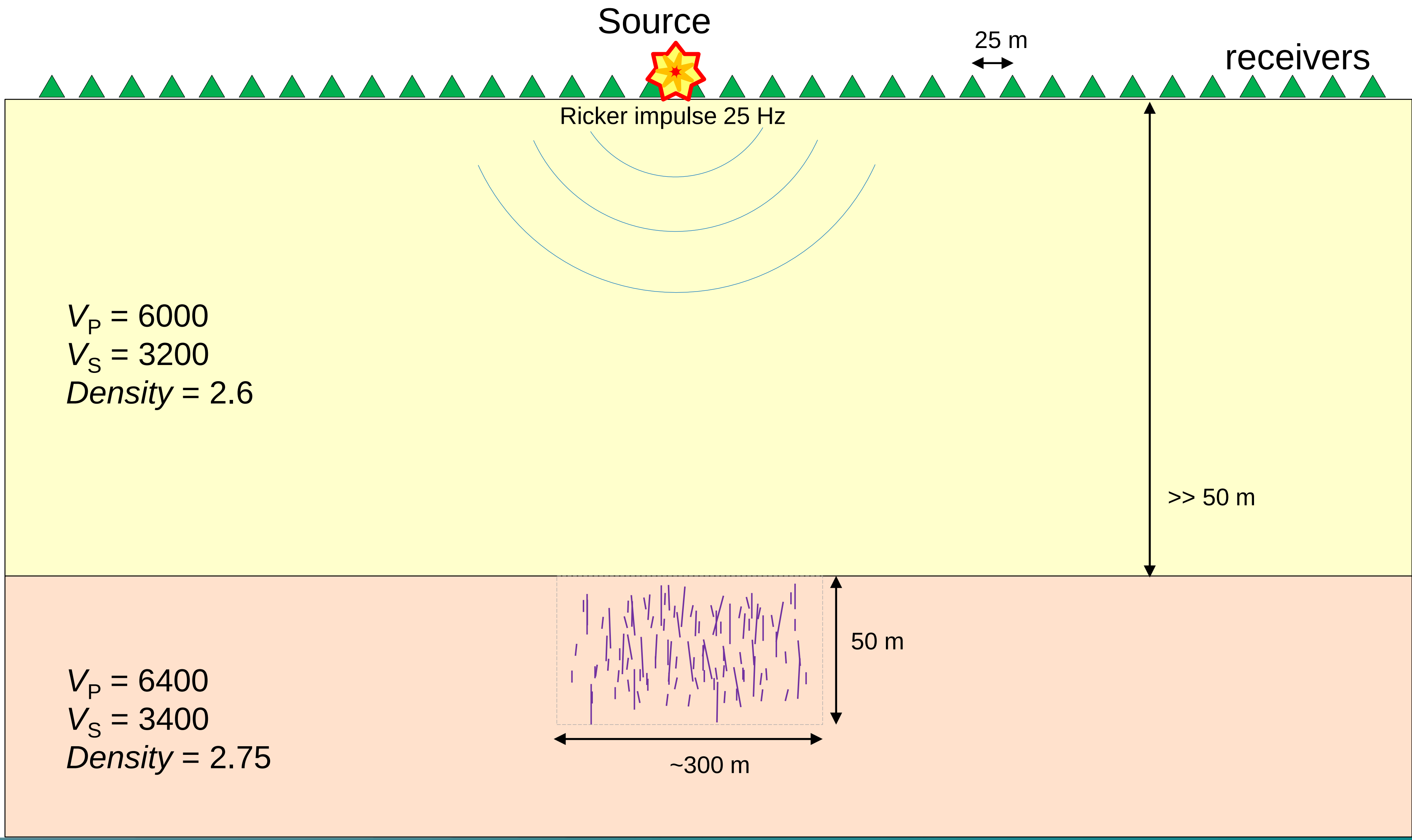

Berlage

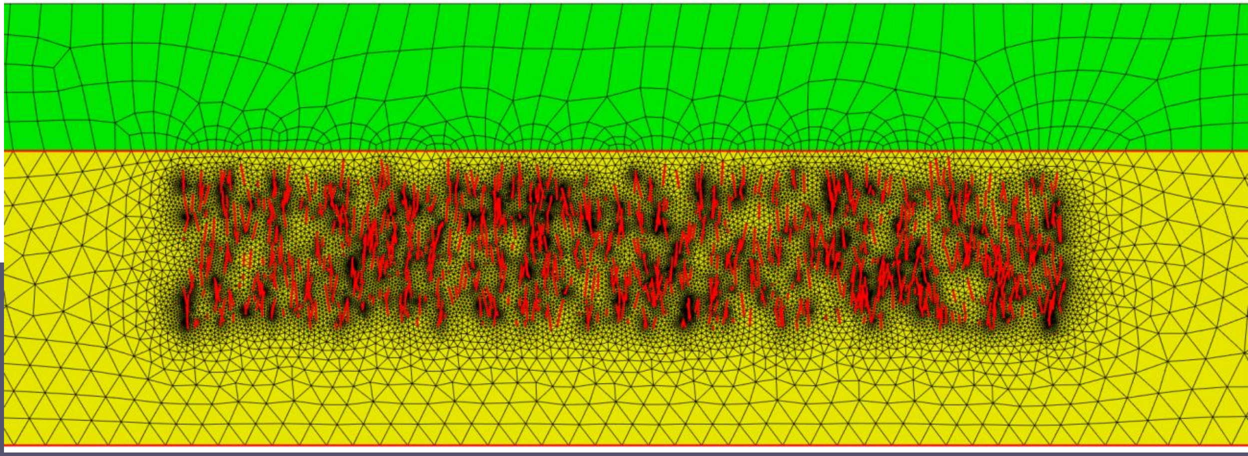

Pressure
Horizontal displacement

Seismic monitoring of fractured media



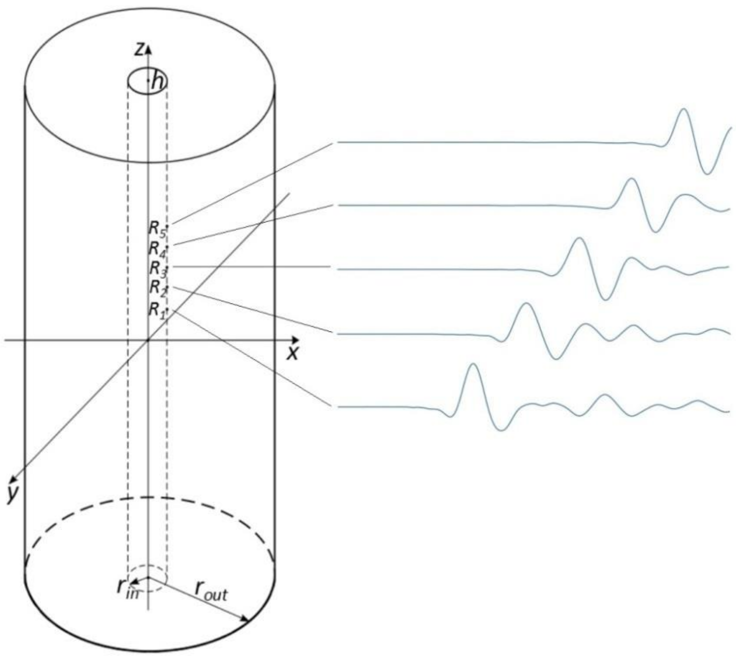
Numerical modeling

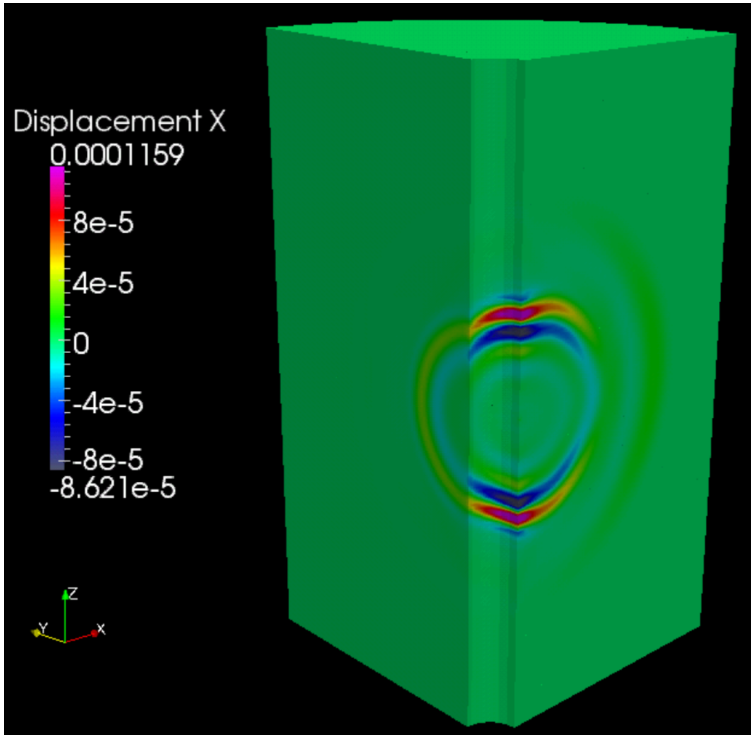
Two-layered fractured media
(fracture lengths 0.5-10 m, inclination angles +/- 15°),
Fractures are natural sources of secondary waves.



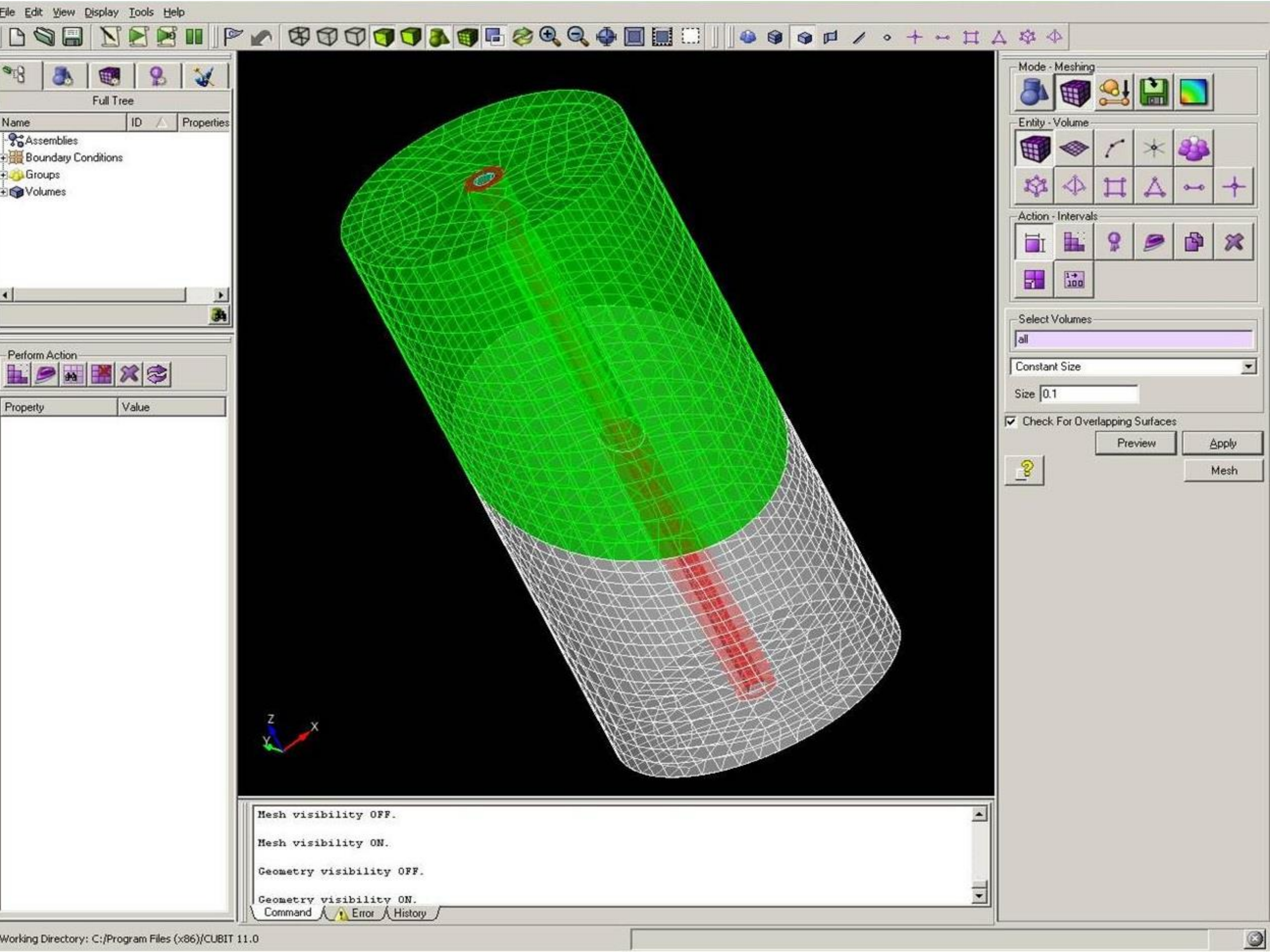
Acoustic logging simulation

3d spectral element method simulation of sonic logging in anisotropic viscoelastic media / Marwan Charara, Anatoly Vershinin, Evgeniya Deger et al. // SEG Expanded Abstracts. — Vol. 30. — 2011. — P. 432–437.





3D full waveform modeling of wave propagation near the wellbore zone drilled in the prestressed media with finite deformations



File Edit View Display Tools Help
Full Tree
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Properties
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Boundary Conditions
Groups
Volumes
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Entity - Volume
Action - Intervals
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Mesh visibility ON.
Geometry visibility OFF.
Geometry visibility ON.
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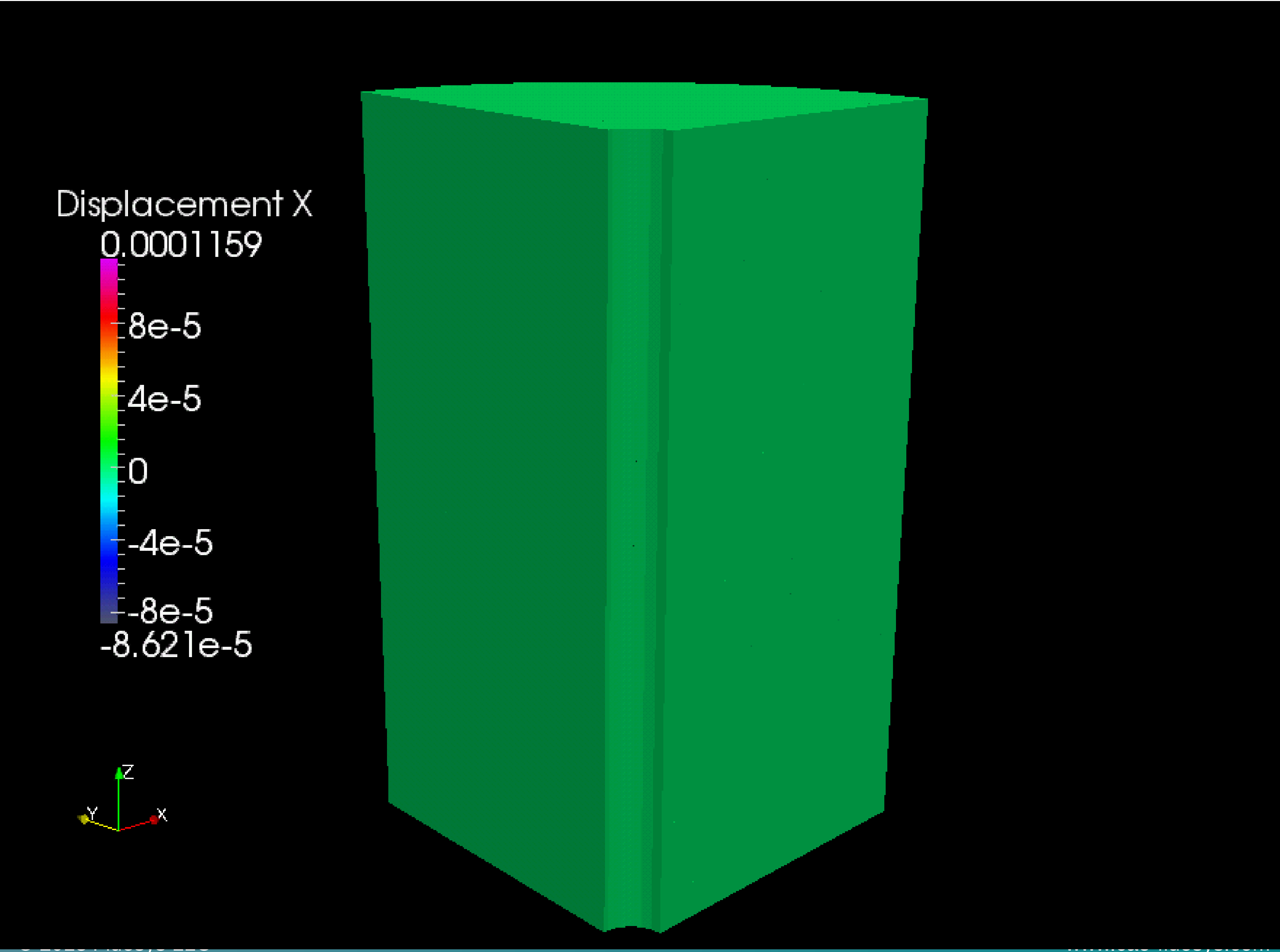
Displacement X
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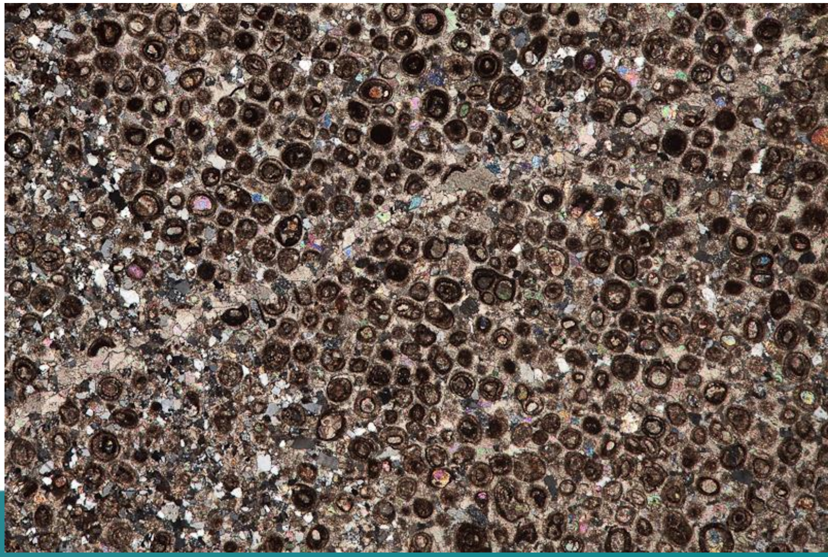
8e-5
4e-5
0
-4e-5
-8e-5
-8.621e-5
Z
Y
X

NUMERICAL ANALYSIS OF ROCK SAMPLES

What is core sample?

Rock sample (usually of cylindrical shape) extracted from a borehole using a special kind of a drilling technique



STATE OF THE ART

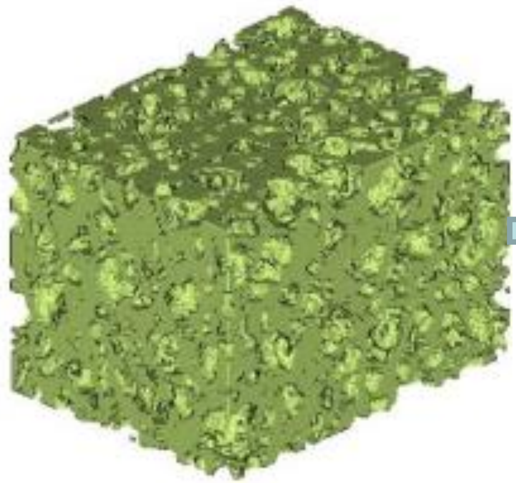
- Expensive and complicated real experiments on samples in the lab
- A large number of samples from the field requiring fast and accurate analysis
- Impossible to reproduce real physical conditions in the lab

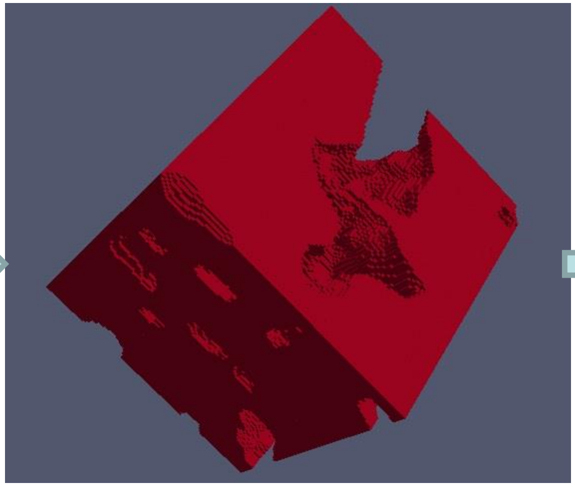
Possible solutions:

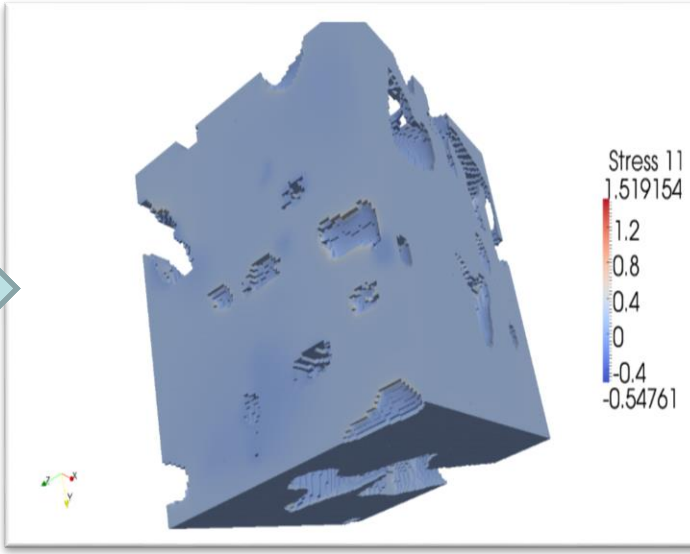
1) Computer tomography helps to extract a 3D internal pore structure of a core sample in a digital “voxel” representation
2) Reducing number of unknowns by means of vectorizing a voxel model (mesh-based geometry) and further unstructured meshing techniques
3) Performing a series of numerical experiments including complicate 3D stress-deformed states
4) Homogenization (estimation of effective properties)
5) Modeling of wave propagation through the sample with a nonzero pore pressure
6) Fracture mechanics in a loaded core sample taking into

account a change of a pore structure while loading

Effective properties estimation







We search effective properties in a way of the Hook's law:

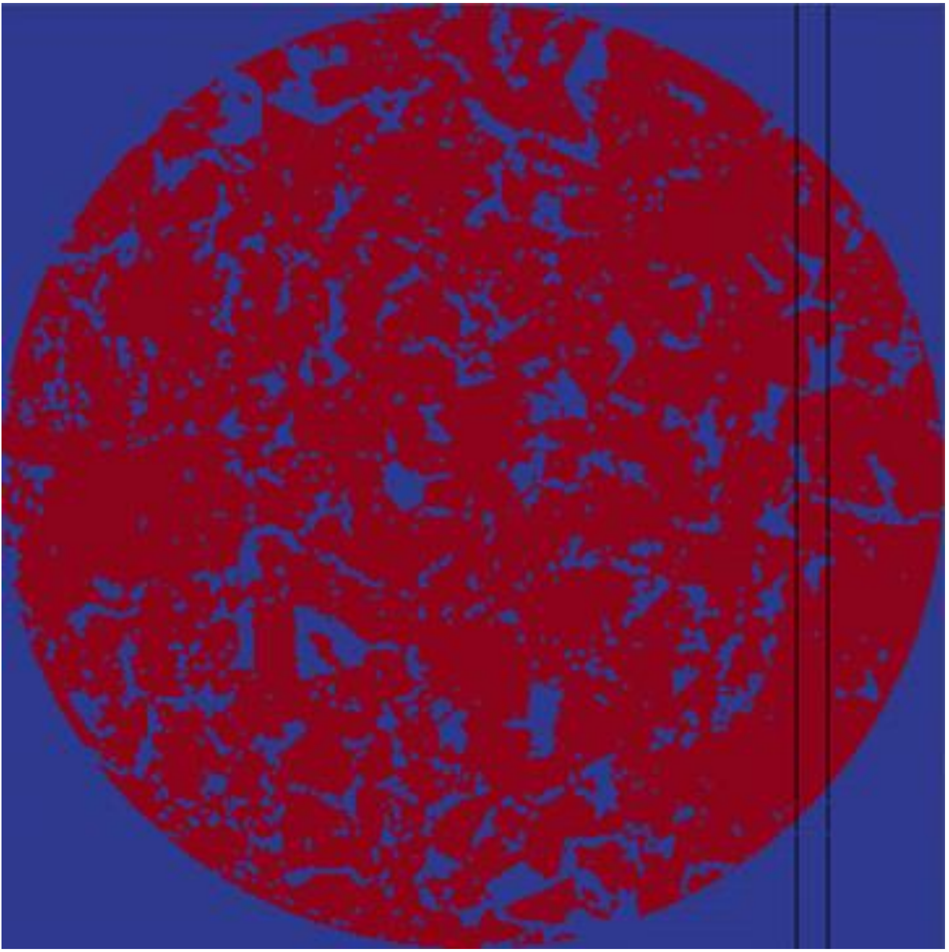
$$\sigma_{mn}^{e} = C_{mnij} E_{ij}^{e}$$

Numerical experiments (as opposed to real ones) allow changing material properties, constitutive relations, pore pressure. We model several types of experiments: 1-, 2-, 3-axial, hydrostatic etc.

Modeling results:

- Anisotropic mechanical properties of core samples;
- Stress and strain fields;
- Dependencies on skeleton properties, porosity, etc.

Computer tomography data



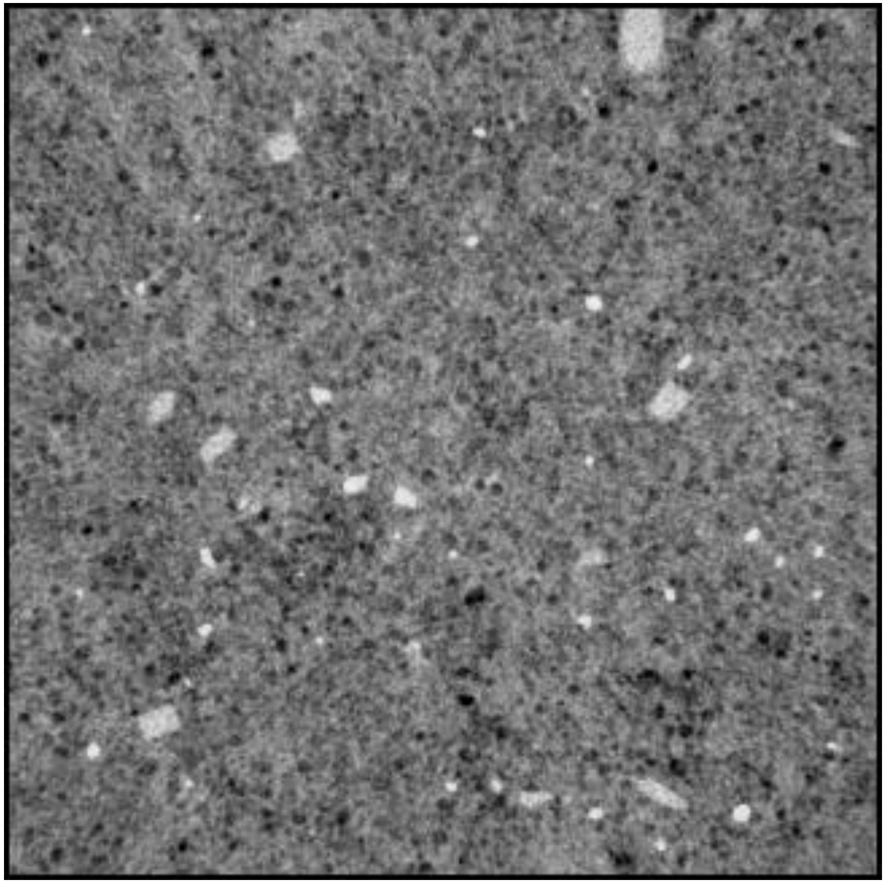
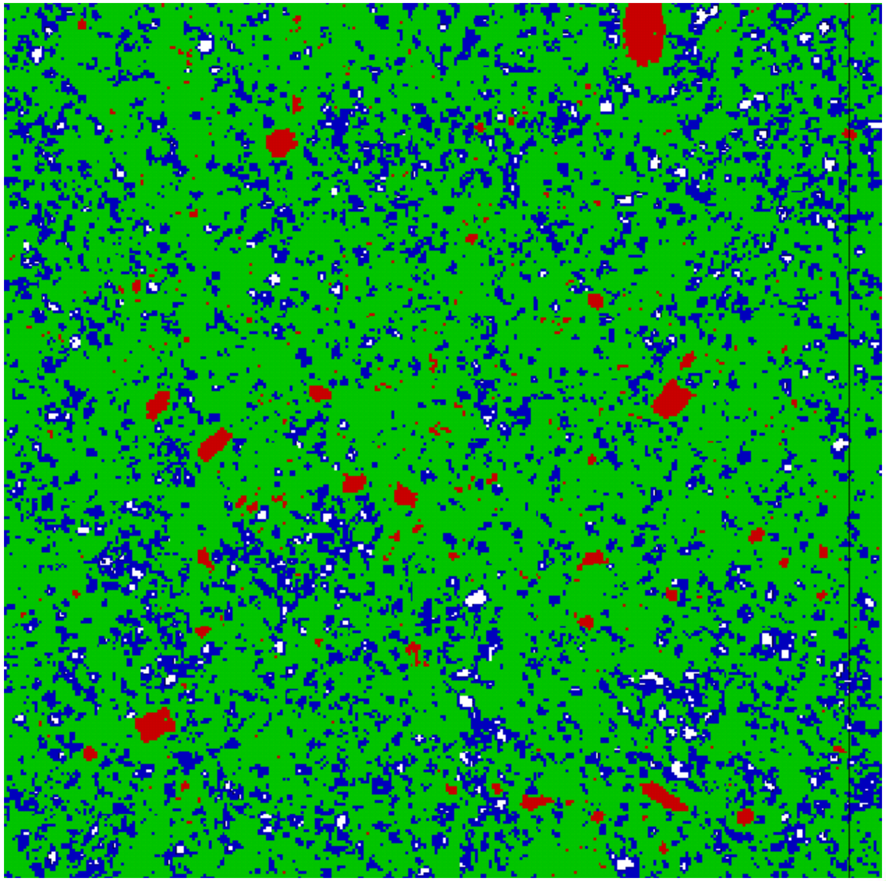
Total number of voxels: 1300x1300x1300
Voxel size – 10 micro meters

Each voxel is either void or a skeleton material with the following material properties: Young’s modulus 70 GPa, Poisson coefficient 0.15.

Voxel binary data takes about 2 Gb.

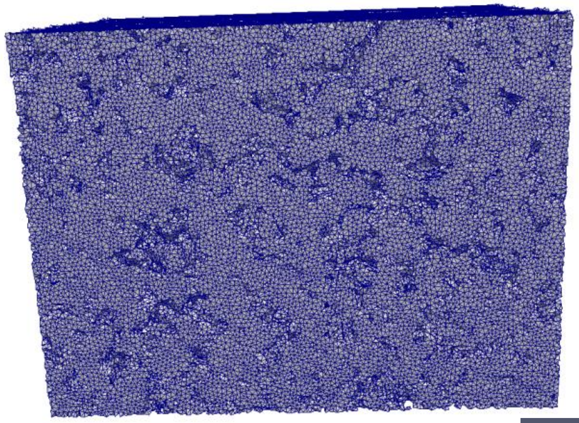
Core sample’s tomography was performed by IntroVision Lab.

CT-scan data for shales

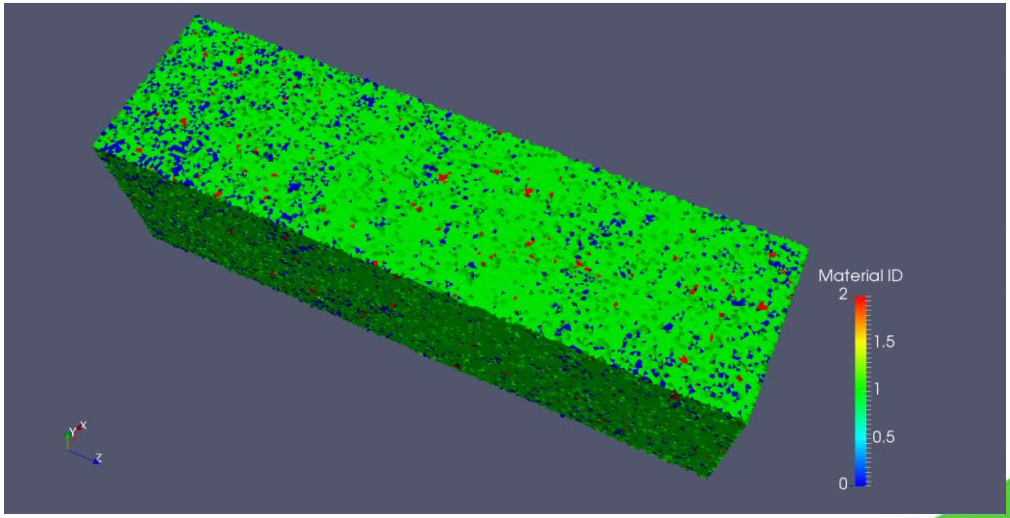
 

CT-scan images and their interpretation was provided by geological department of Lomonosov Moscow State University

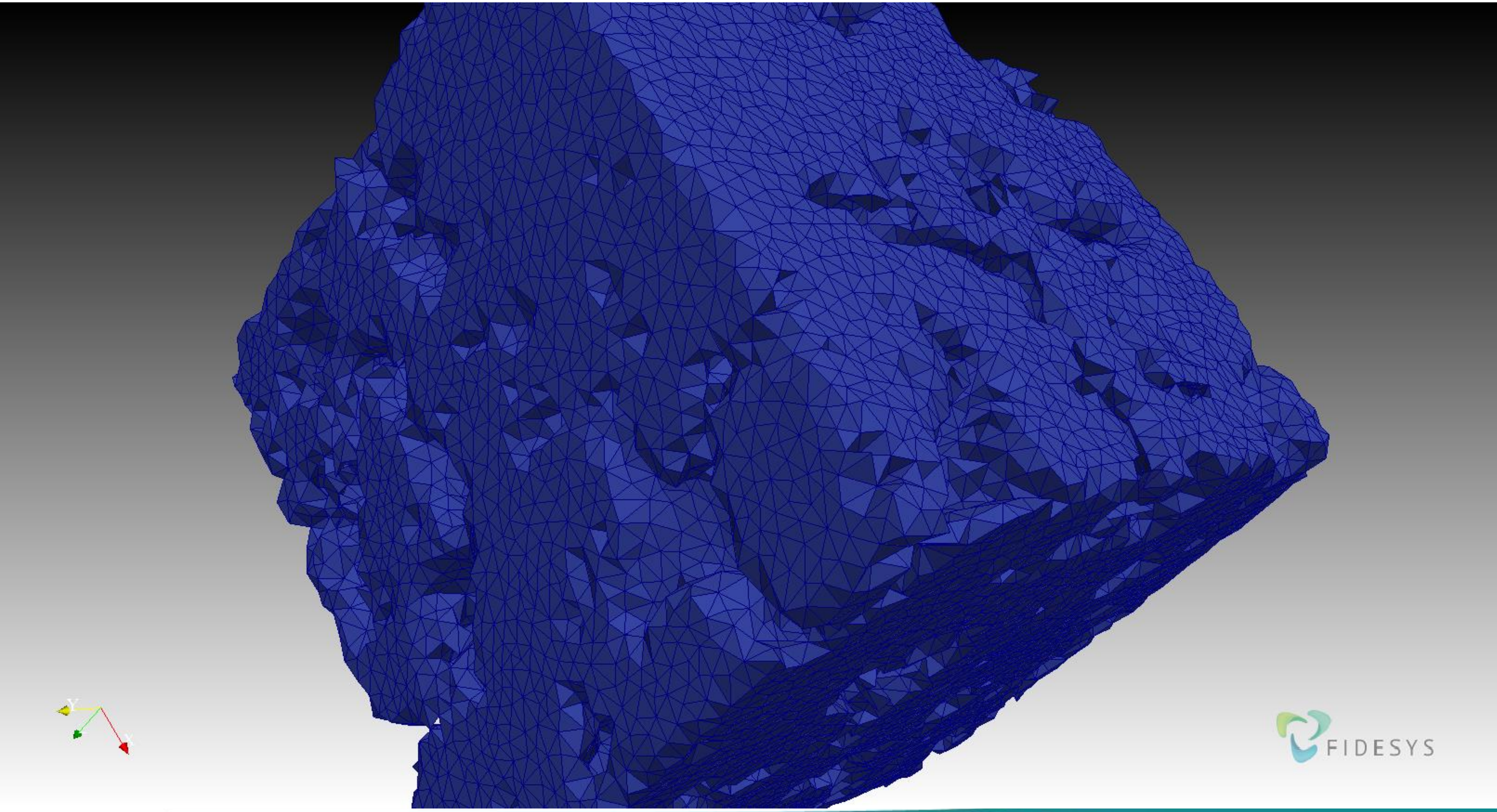
FEA mesh generation



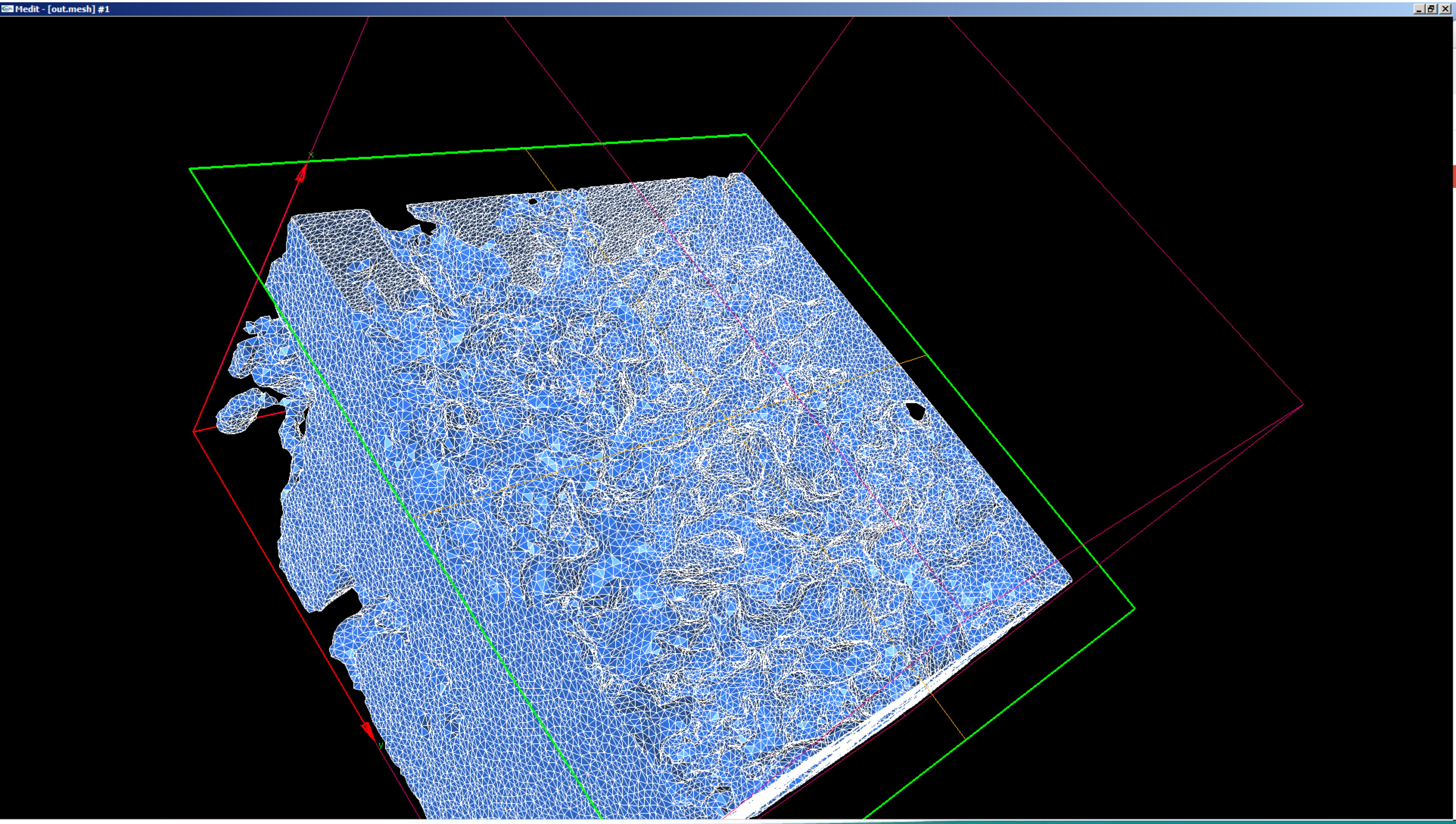
The mesh is generated based on the imaging data for the size of the rock sample fragment of 900x900x1200 voxels. The obtained mesh size is 2 million tetrahedrals.



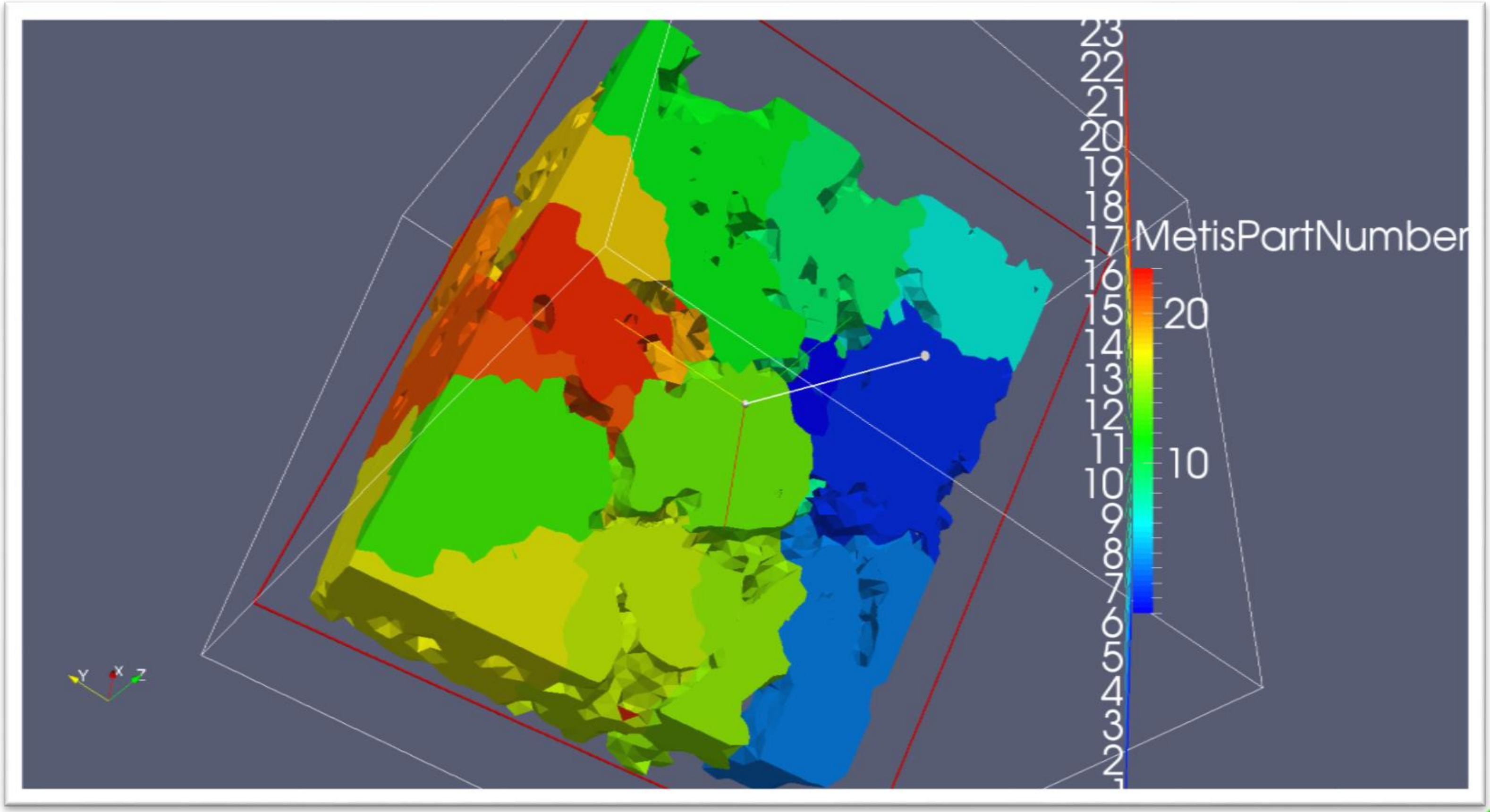
Unstructured mesh representing pore structure



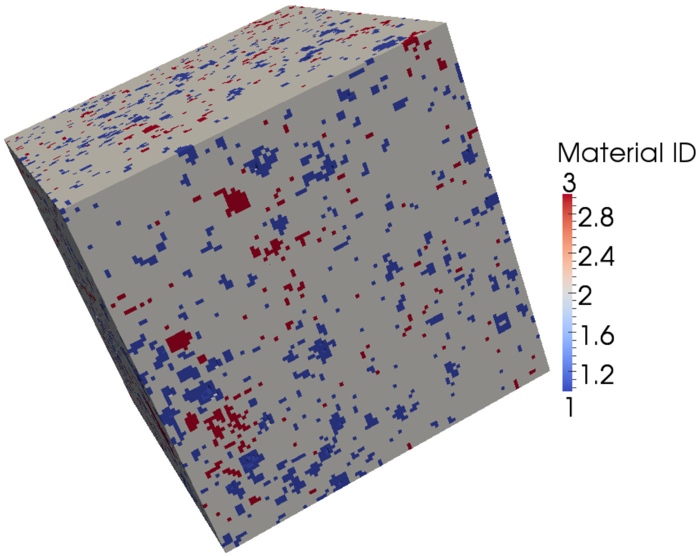
Internal structure of a core sample



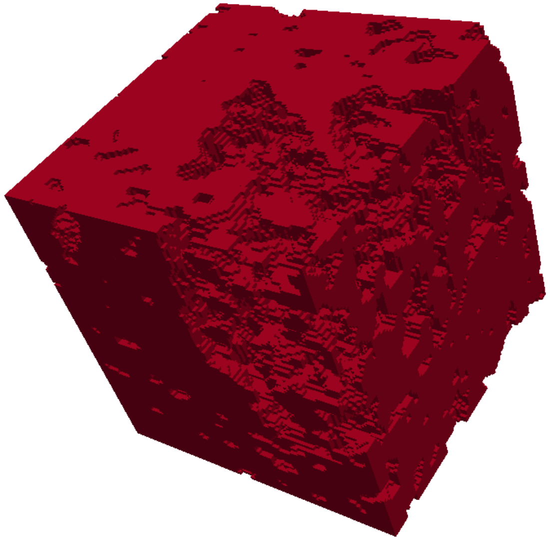
Domain decomposition for HPC



Two scales



Full sample (meso):
Voxel size - 264.58 mkm
Core Dimensions 80 mm
Pyrite: E = 291.2 GPa, v = 0.16
Calcite: E = 80.4 GPa, v = 0.32
Pores
Grey zone



Part of grey zone extracted from the full sample (micro):
Voxel size - 0.8 mkm
Core Dimensions ~ 2 mm
Calcite: E = 80.4 GPa, v = 0.32

Results for full-size shale sample

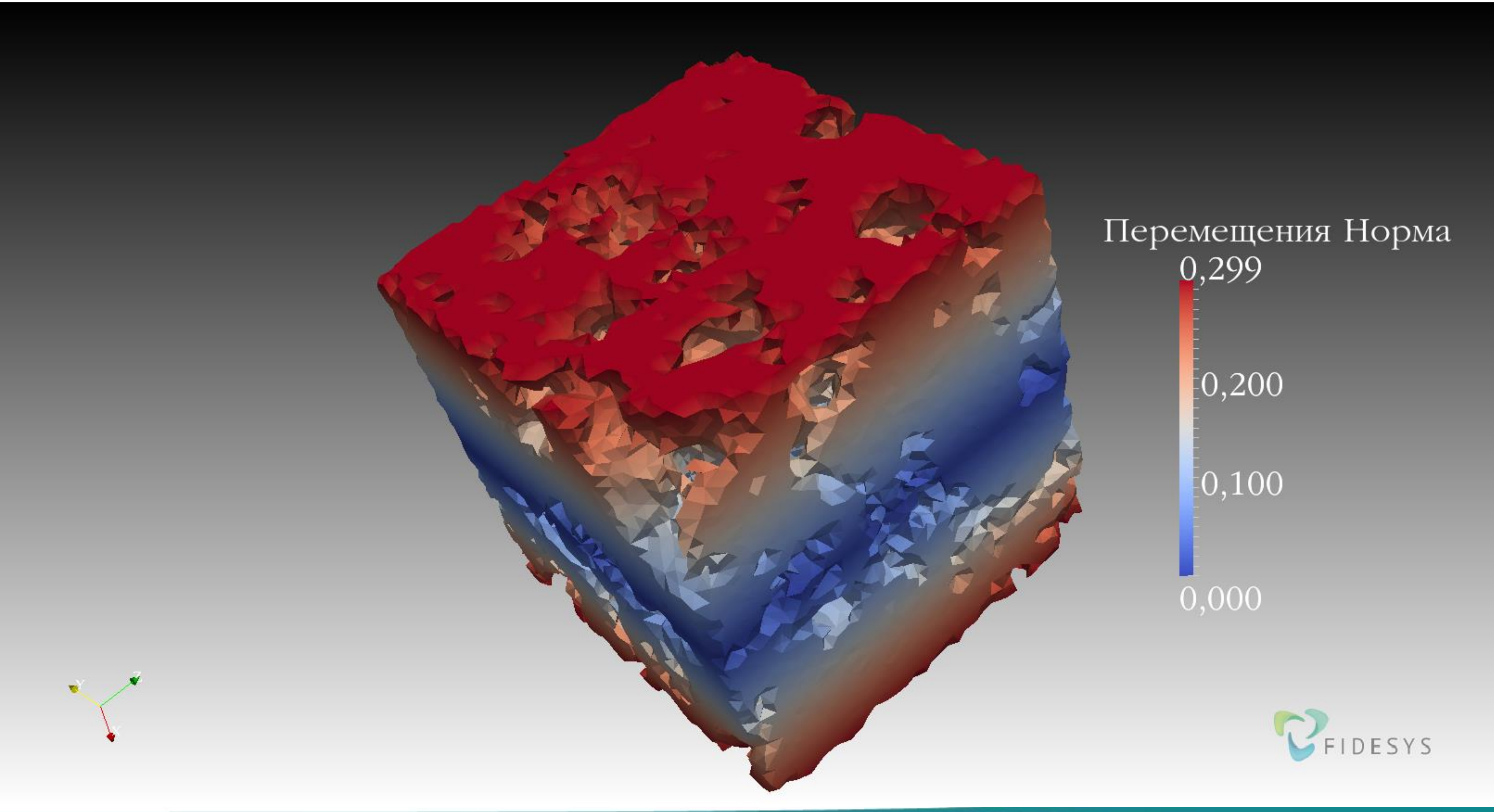
Myasnikov A. V., Vershinin A. V., Sboychakov A. M. A generalization of geomechanical model for naturally fractured reservoirs // *SPE Russian Petroleum Technology Conference and Exhibition*. — 2016.

- Numerical convergence is provided

Коэф-т разгрубления	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.1	**Вокс. модель**
Кол-во узлов	895654	131220	40680	16698	9307	5798	3376	2352	1717	1151	**1020100**
Кол-во элементов	5286753	752411	227476	91137	49700	29253	16782	11521	8337	5413	**984274**
Погрешность	0.31%	0.41%	1.01%	1.61%	1.16%	0.49%	0.49%	1.29%	1.30%	0.77%	

- Calculation was conducted on the tetrahedral mesh of 7 millions of tetrahedrons, built on the basis of voxel model of 320x320x1171 voxels
- Volumetric fraction of materials: pores - 0.85%; soft rock - 12.93%; calcite - 83.87%; pyrite - 2.35%
- Effective core sample properties: 78.13 GPa Young's modulus, Poisson's ratio of 0.32

3D simulation at the pore level



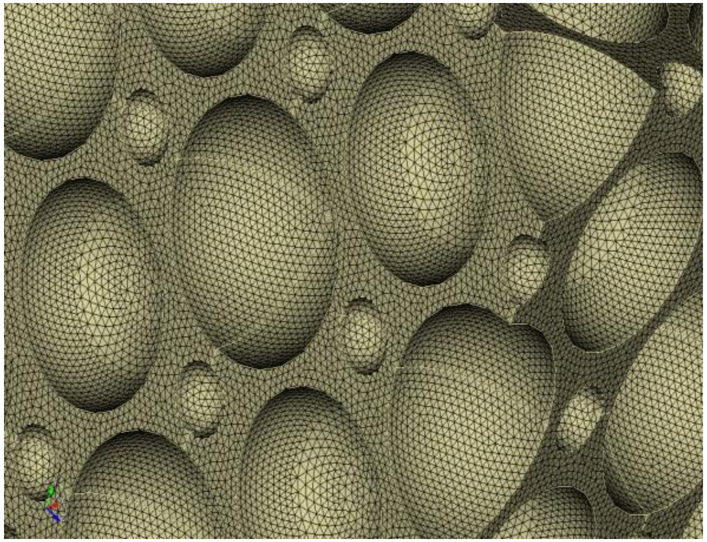
Averaging of periodic cells

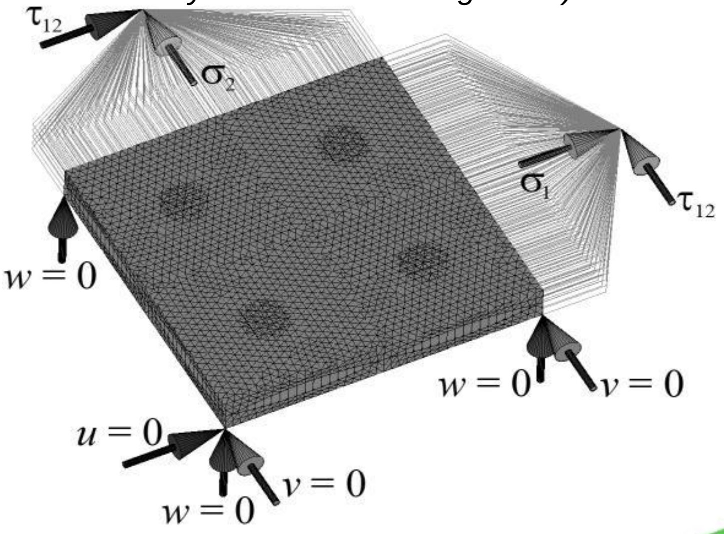
The method of asymptotic averaging is well applied for effective properties estimation of periodic structures.

This method gives exact (in mathematical sense) effective properties while solving **«problems at a periodicity cell»**.

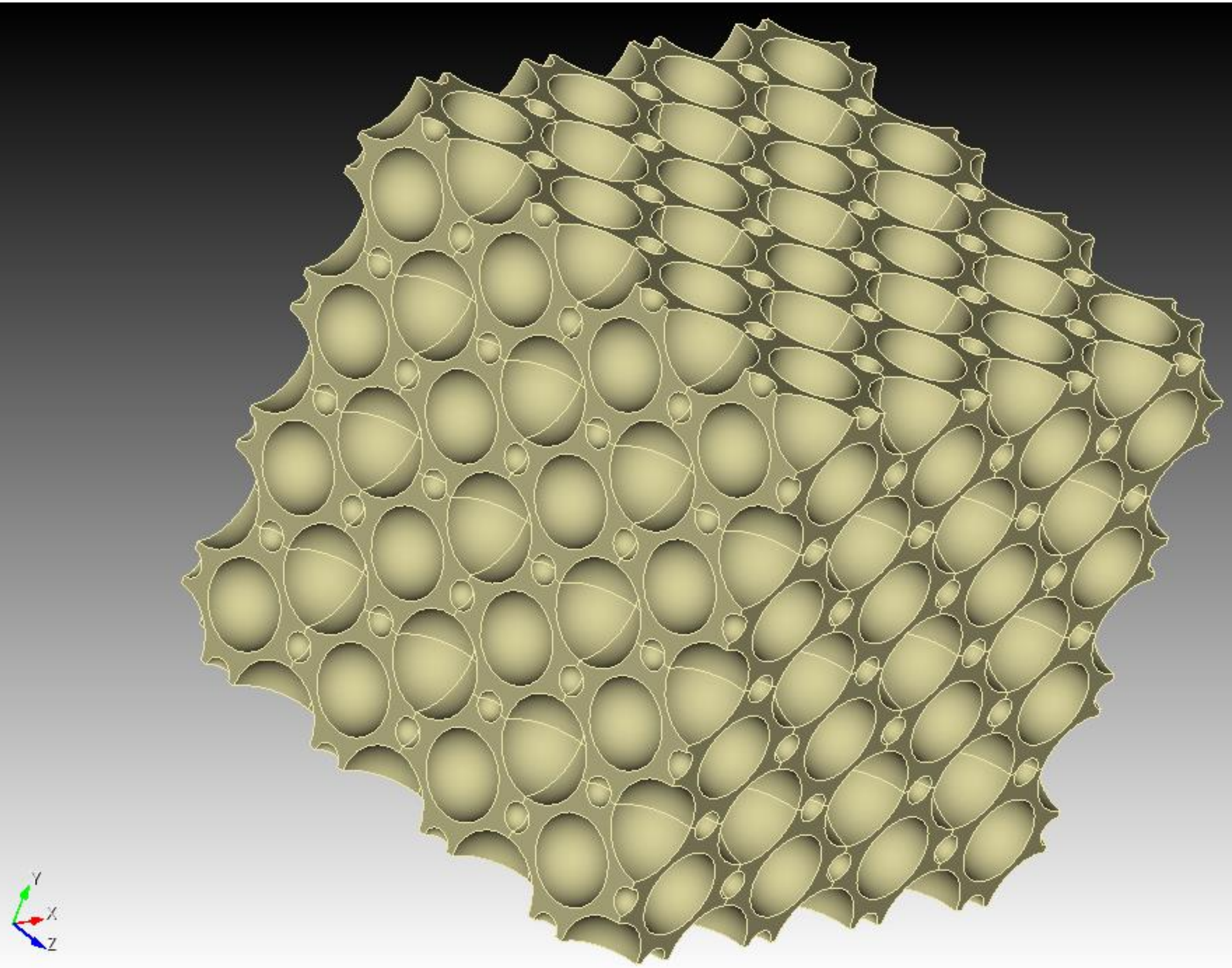
Levin V.A., Zingerman K.M. Effective Constitutive Equations for Porous Elastic Materialsat Finite Strains and Superimposed Finite Strains // Trans. ASME. (The American Society of Mechanical Engineers). Journal of Applied Mechanics. 2003. V. 70, No. 6.

Levin V.A., Lokhin V.V., Zingerman K.M. Effective Elastic Properties of Porous Materials With Randomly Disposed Pores. Finite Deformation // Trans. ASME. (The American Society of Mechanical Engineers). Journal of Applied Mechanics. 2000. Vol. 67. №4. P. 667-670.

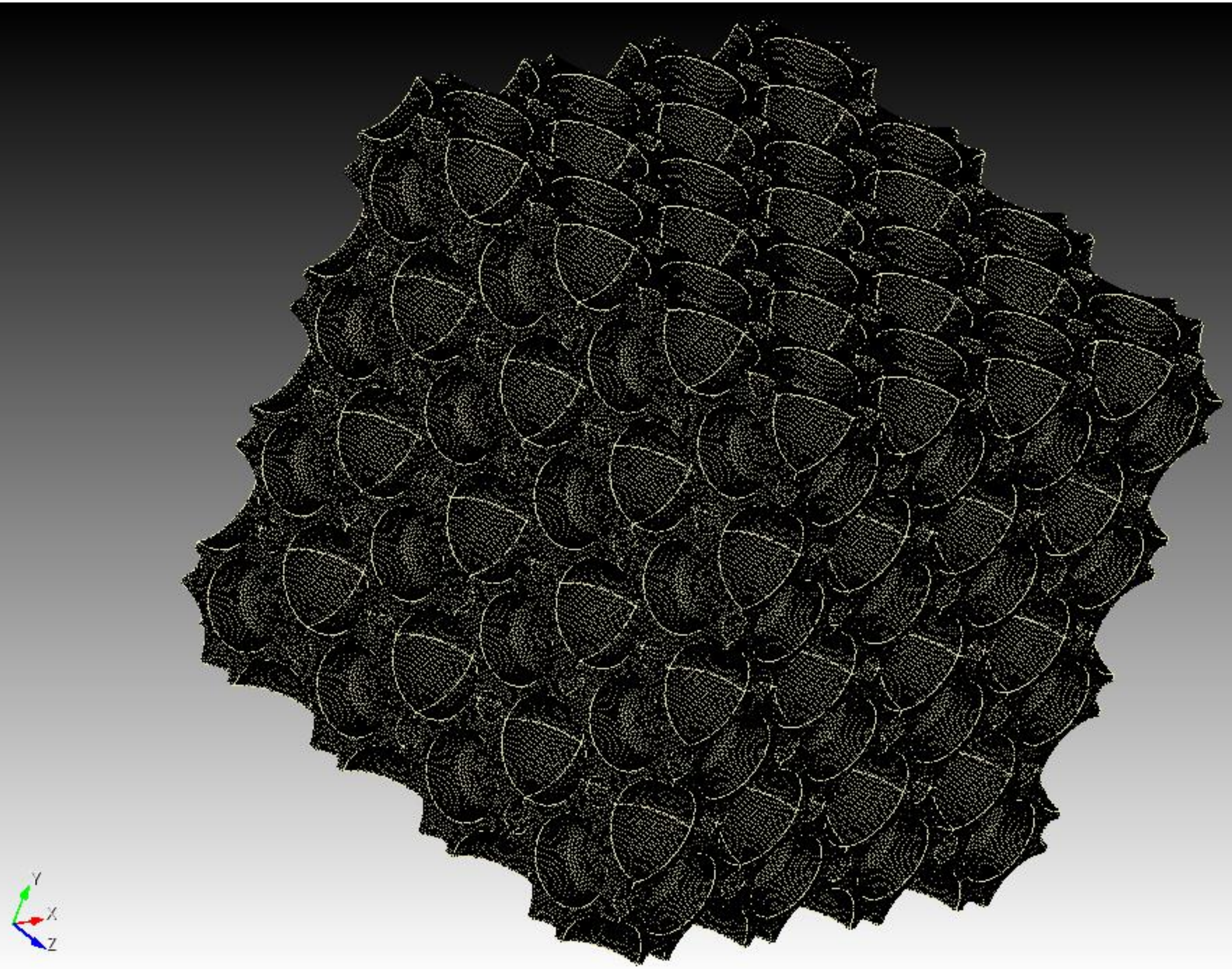




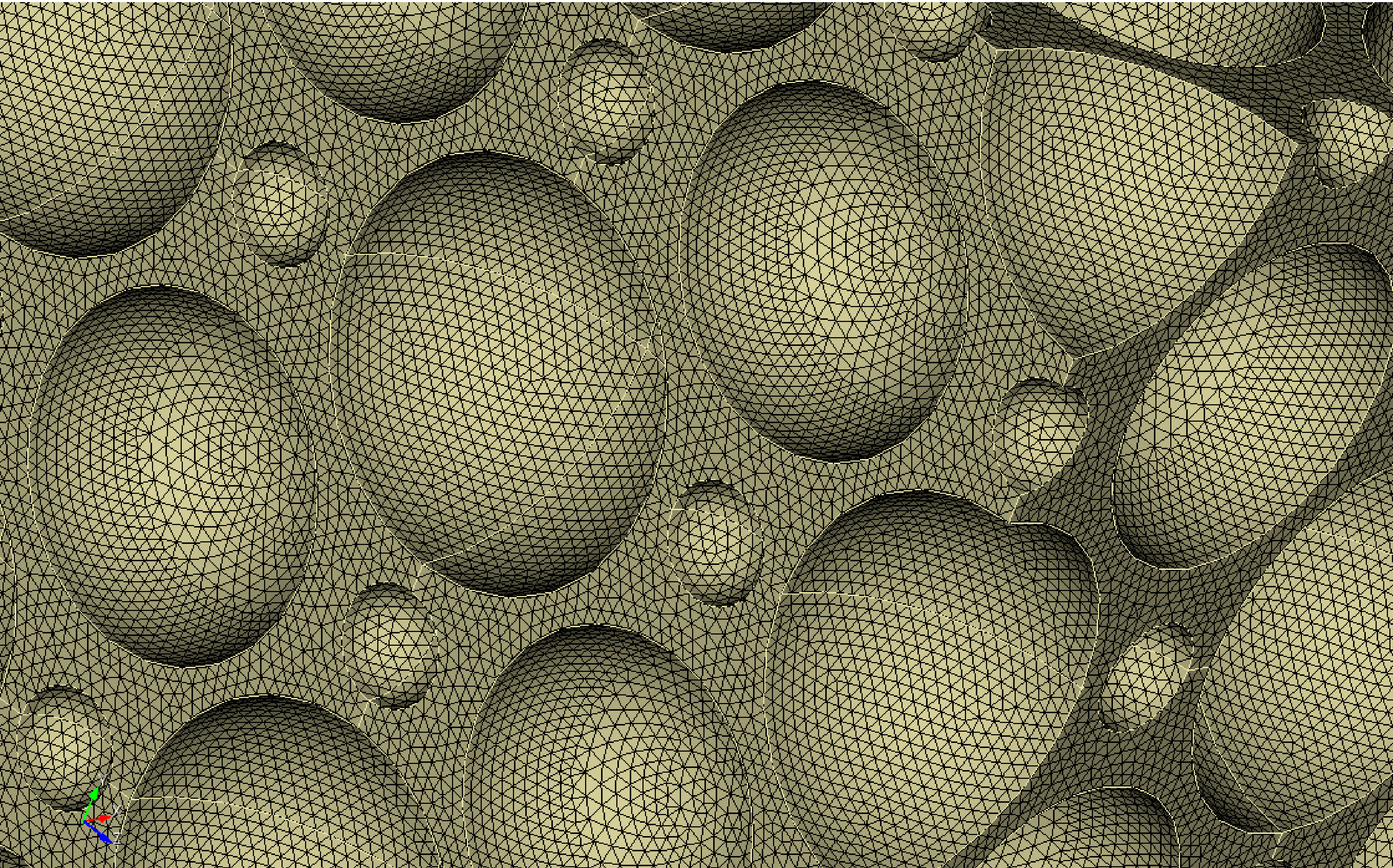
Model



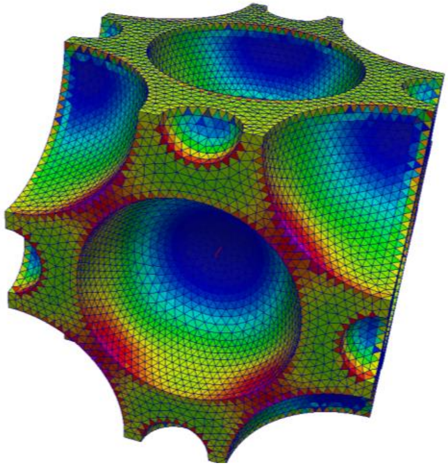
Finite element mesh

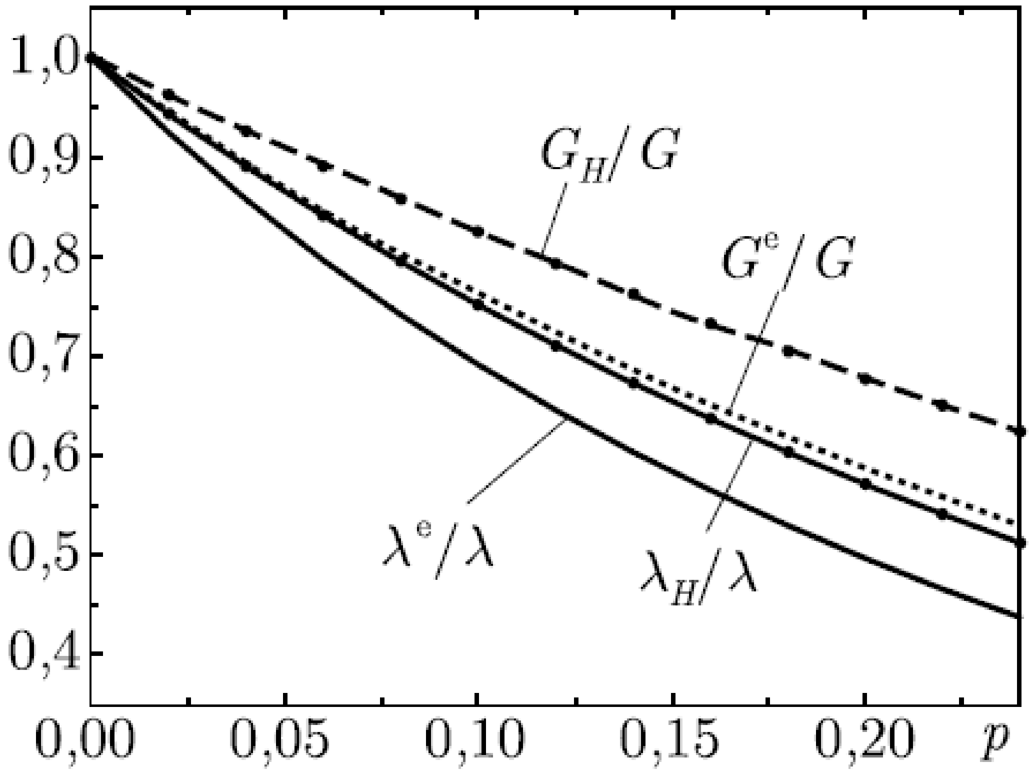


Finite element mesh



Results

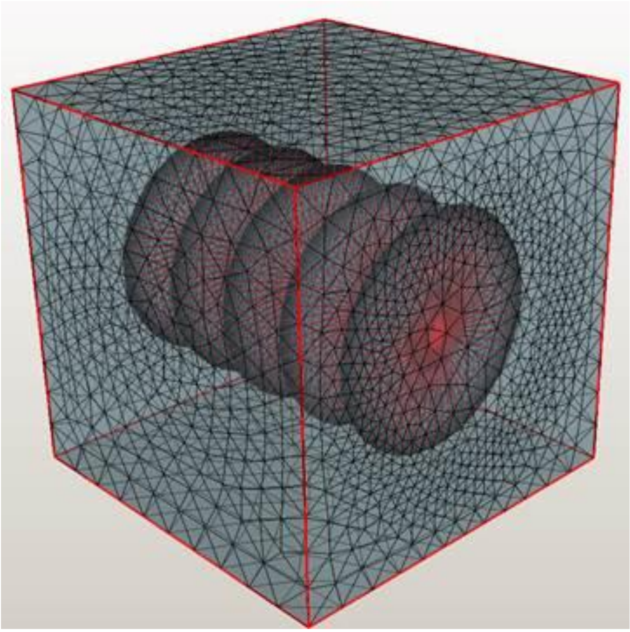




Effective properties (Lame parameters) dependency on porosity for linear(e) and nonlinear(H) cases

Effective properties of fractured media

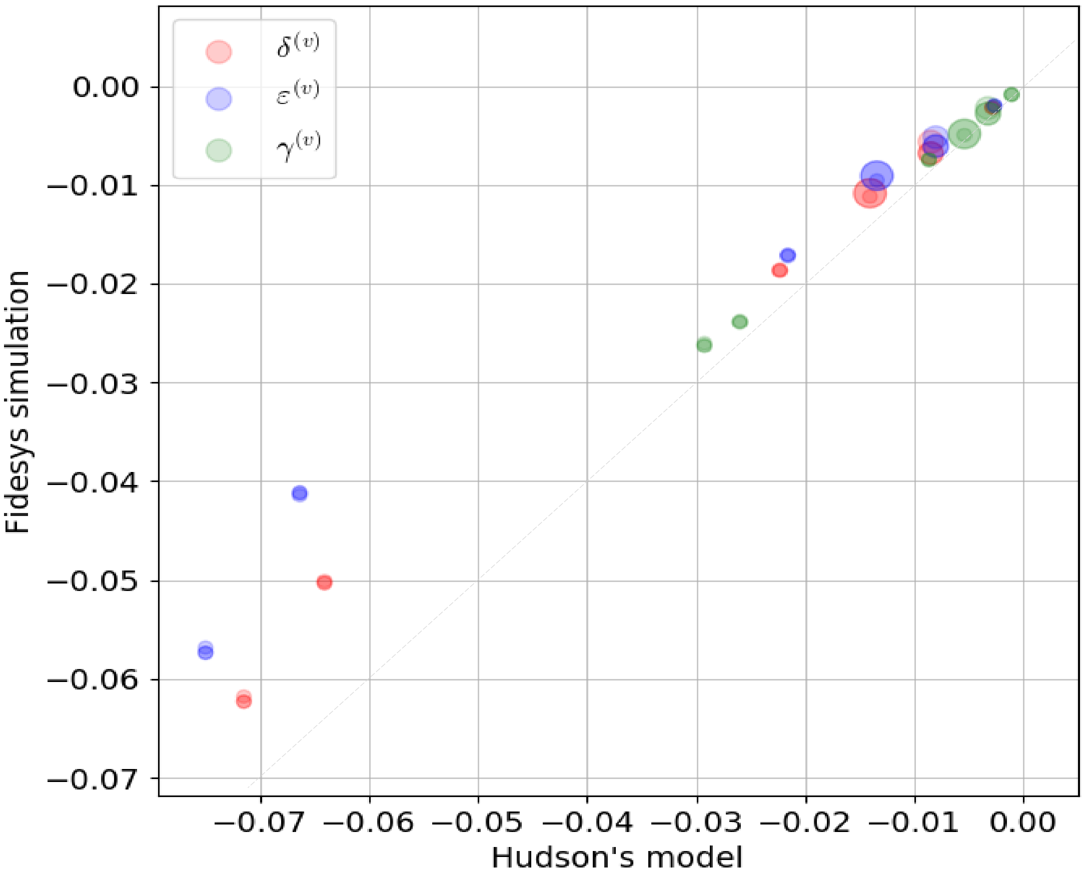
- Fractures are modeled as plane ellipsoidal inclusions filled with fluid or gas
- Elastic moduli depends of several fracture parameters:
  - Aspect ratio
  - Number of fractures (~ fracture porosity)
  - Type of media inside fractures (fluid/gas)
- In case of rotational ellipsoids (ellipsoid's axes $r_1 = r_2 >> r_3$) and isotropic matrix the resulted effective fractured media is transversely isotropic



Test model for effective periodicity cell of ellipsoidal fractured media

Numerical results

Effective moduli $\mathbf{C}_{ij}$ are used to compute dimensionless anisotropy parameters of Ruger-Tsvankin $\varepsilon^{(v)}$, $\delta^{(v)}$, $\gamma^{(v)}$ which in turn are compared with analytical values predicted by Hudson model (Hudson, 1980)

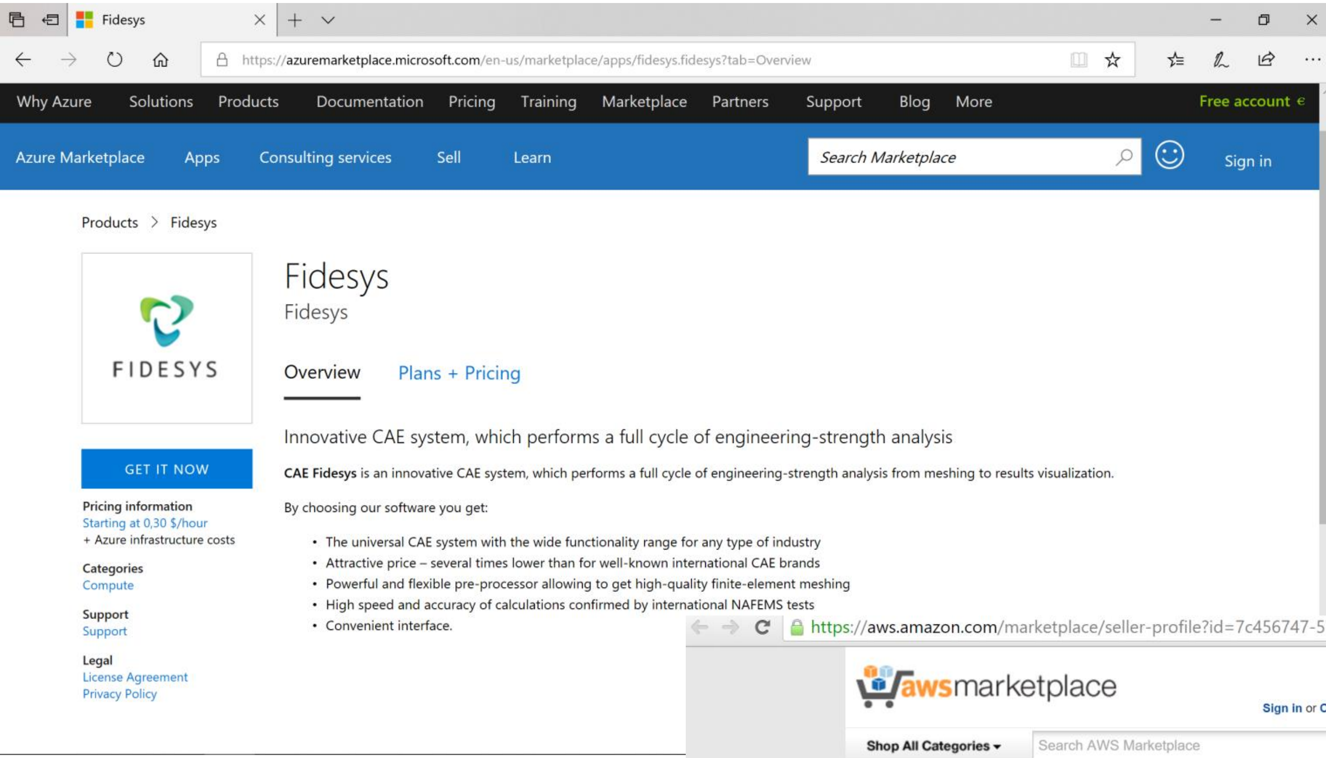


CAE Fidesys allows one to build periodic cells of arbitrary geometries and relative orientations of fractures and inclusions (Hudson model considers only the case of uniformly distributed fractures of the same shape and size)

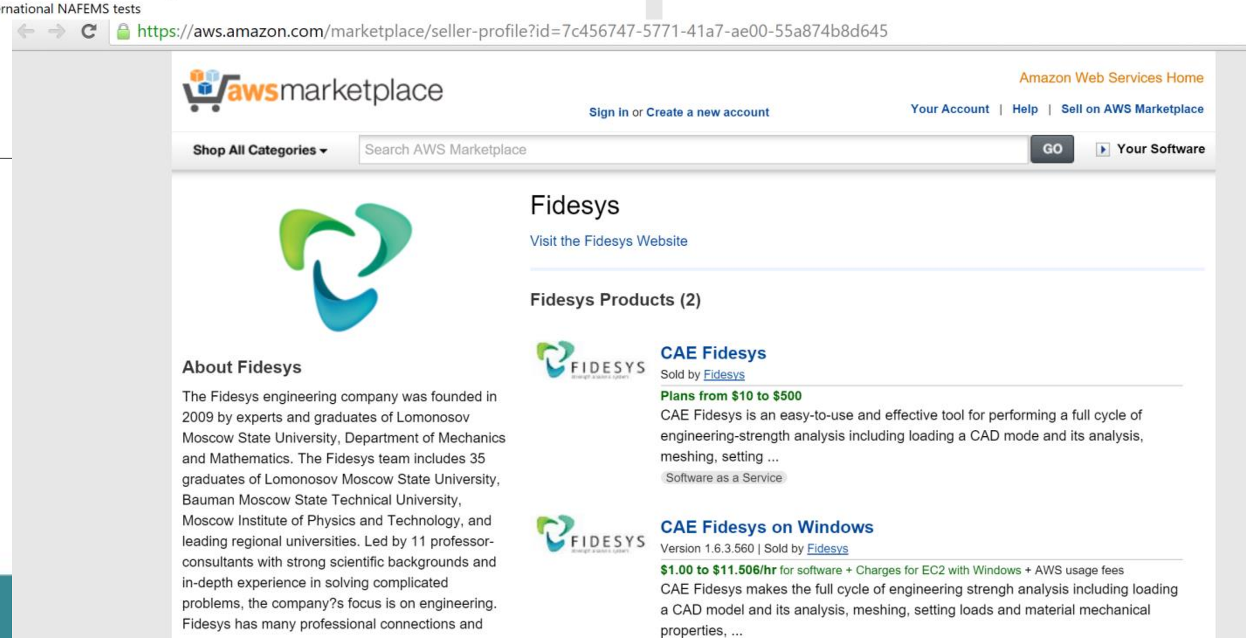
Custom software development

- On the basis of CAE Fidesys's software modules, a custom corporate or industry-specific software for geophysical analysis is developed (e.g. Fidesys Geomechanics for NTC Gazpromneft).
- The customized package will be more functional and easy-to-use than the general purpose CAE. It is focused on specific problems of the client.
- Development cycle of a custom software takes about 6-18 months depending on the customer's specifications with the involvement of leading industry consultants.
- As a result, the customer obtains a dedicated corporate product.
- **The package can be used as a simulation software which is capable for fine tuning and extensively applied during R&D stage.**

Fidesys in Azure/Amazon marketplace



Preprocessing, simulation, analysis, rendering etc. are done in the cloud. 24/7 access in the browser.



Pay-as-you go and subscription based licensing models flexible for different problem sizes.

Corporate CAE-platform

- Private cloud solution for the client's internal usage
- Available from any device connected to internal Ethernet/VPN
- Cost reduction: cost of ownership, support, security

Thank you!

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