

Численное моделирование развития гидроразрыва в неупругих дилатирующих средах и зависимости пористости пропанта от нагрузки

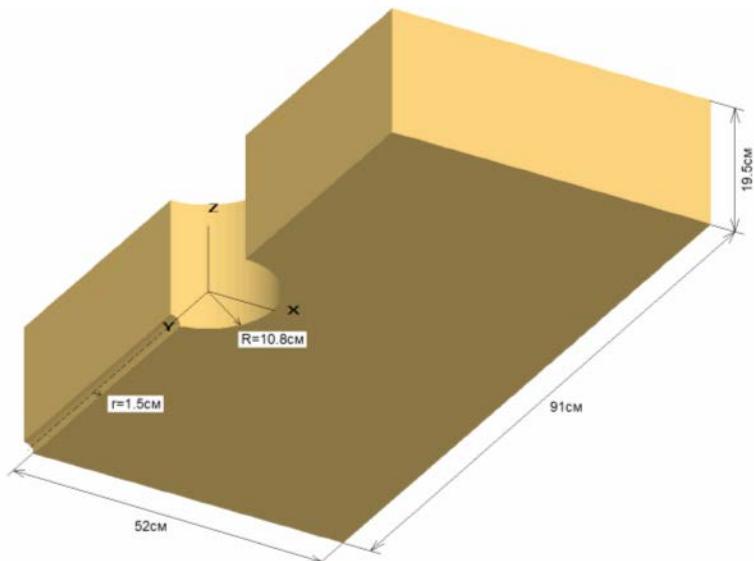
И.А.Гарагаш

ИФЗ РАН

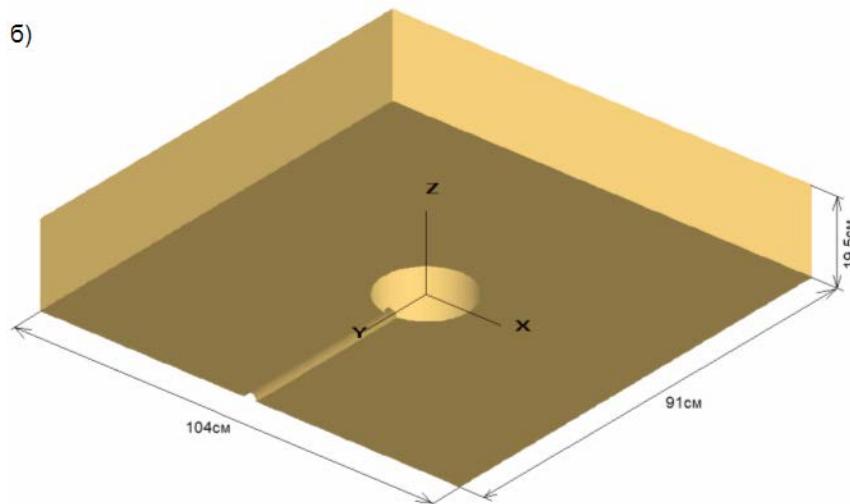
АНАЛИЗ ВОЗМОЖНОСТИ ПРОВЕДЕНИЯ ЛОКАЛЬНО НАПРАВЛЕННОГО ГИДРОРАЗРЫВА ЧЕРЕЗ РАДИАЛЬНЫЕ БОКОВЫЕ СТВОЛЫ МАЛОГО РАДИУСА В ТЕРИГЕННОМ И КАРБОНАТНОМ КОЛЛЕКТОРЕ

Вычисления выполняются для четырех вариантов начального напряженного состояния

a)



б)



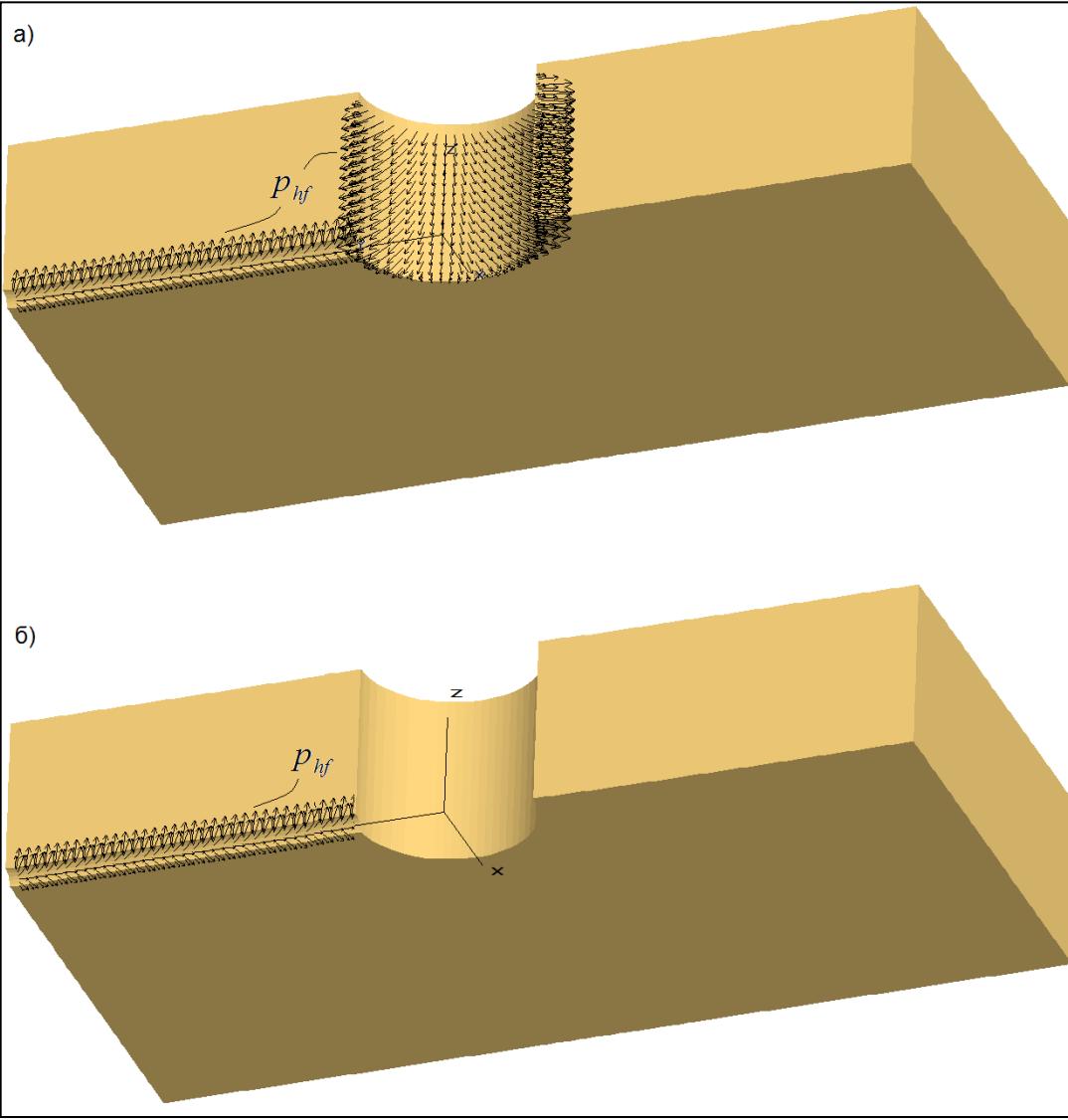
- Напряжения вызваны весом налегающей толщи: $\sigma_{zz}^0 = -5.35 \cdot 10^7 \text{ Па}$ и $\sigma_{xx}^0 = \sigma_{yy}^0 = -2.29 \cdot 10^7 \text{ Па}$ (по Диннику).
- Напряжения вызваны весом налегающей толщи $\sigma_{zz}^0 = -5.35 \cdot 10^7 \text{ Па}$ и равным горизонтальным тектоническим усилием, направленным по оси x : $\sigma_{xx}^0 = \sigma_{zz}^0 = -5.35 \cdot 10^7 \text{ Па}$, причем $\sigma_{yy}^0 = -2.29 \cdot 10^7 \text{ Па}$.
- Напряжения вызваны весом налегающей толщи $\sigma_{zz}^0 = -5.35 \cdot 10^7 \text{ Па}$ и горизонтальным тектоническим усилием, осуществляющим поворот вокруг оси z на 45° против часовой стрелки: $\sigma_{zz}^0 = \sigma_{xx}^0 = -5.35 \cdot 10^7 \text{ Па}$, причем $\sigma_{yy}^0 = -2.29 \cdot 10^7 \text{ Па}$. В этом случае начальные напряжения в системе координат xyz имеют следующие значения: $\sigma_{xx}^0 = \sigma_{yy}^0 = -3.82 \cdot 10^7 \text{ Па}$, $\sigma_{xy}^0 = -1.53 \cdot 10^7 \text{ Па}$, $\sigma_{xz}^0 = -5.35 \cdot 10^7 \text{ Па}$.

- Напряжения вызваны весом налегающей толщи $\sigma_{zz}^0 = -5.35 \cdot 10^7 \text{ Па}$ и горизонтальным тектоническим усилием, направленным по оси y : $\sigma_{yy}^0 = \sigma_{zz}^0 = -5.35 \cdot 10^7 \text{ Па}$, причем $\sigma_{xx}^0 = -2.29 \cdot 10^7 \text{ Па}$.

На всех границах объема, за исключением горизонтальной поверхности $z = 19.5 \text{ см}$, заданы условия жесткой стенки со скольжением.

На поверхности $z = 19.5 \text{ см}$ действует вес налегающей толщи $\sigma_{zz}^0 = -5.35 \cdot 10^7 \text{ Па}$.

Скважина заполнена флюидом, и давление в ней гидростатическое – на глубине пласта в 2 км $p = 1.96 \cdot 10^7 \text{ Па}$. Такое же давление в порах коллектора. Дилатансией в расчетах пренебрегаем.



Давление гидроразрыва создано в основной и боковой скважинах (а) и только в боковой скважине (б).

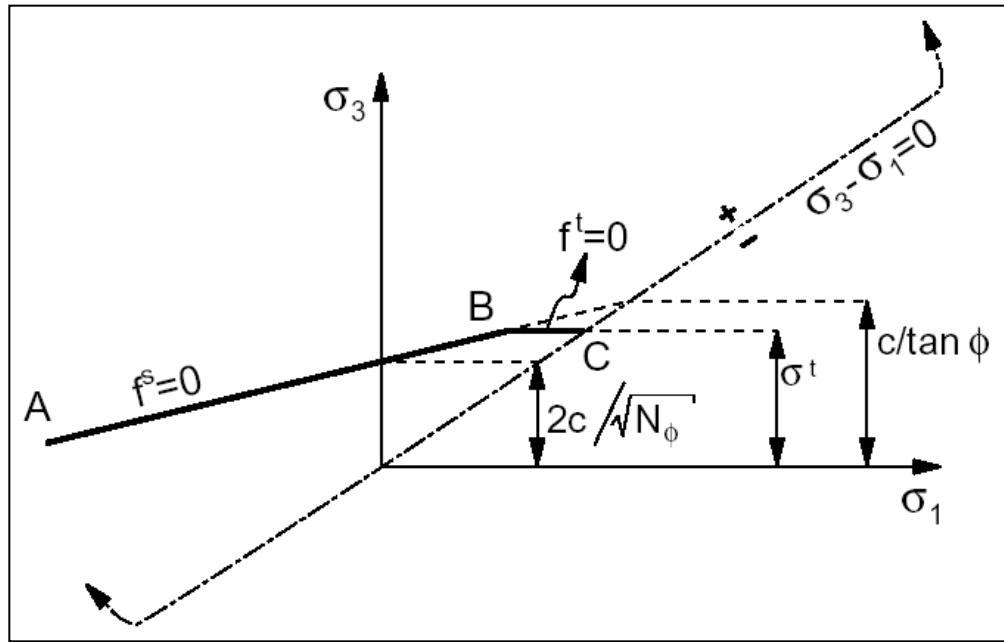
Модель пластического течения с предельным условием Кулона-Мора

$$f^s = 0, \quad f^s = (\sigma_1 + p) - (\sigma_3 + p)N_\phi + 2c\sqrt{N_\phi}$$

$$f_t = 0, \quad f_t = (\sigma_3 + p) - \sigma^t$$

$$N_\phi = \frac{1 + \sin \phi}{1 - \sin \phi}$$

$$N_\psi = \frac{1 + \sin \psi}{1 - \sin \psi}$$



Приращения пластических деформаций

$$d\varepsilon_{ij}^p = \lambda \frac{\partial g}{\partial (\sigma_{ij} + \delta_{ij} p)}$$

Потенциальная функция

$$g^s = (\sigma_1 + p) - (\sigma_3 + p)N_\psi$$

$$g^t = (\sigma_3 + p)$$

Приращения упругих деформаций

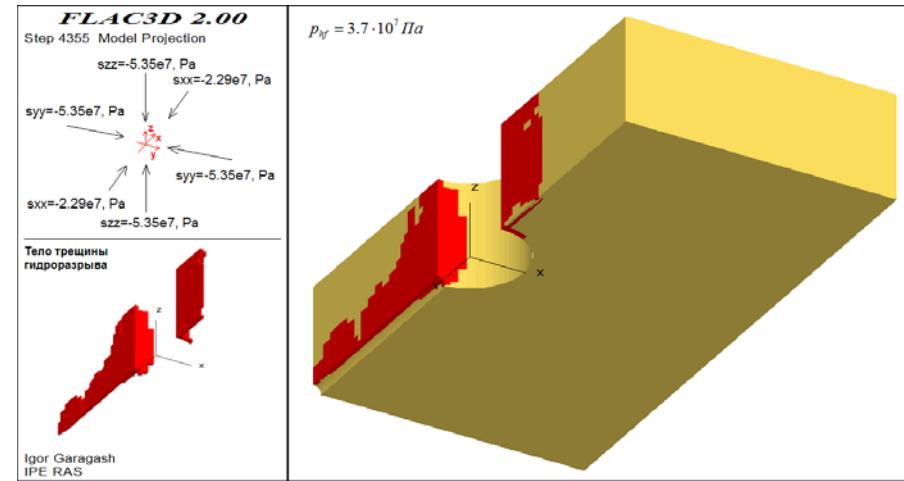
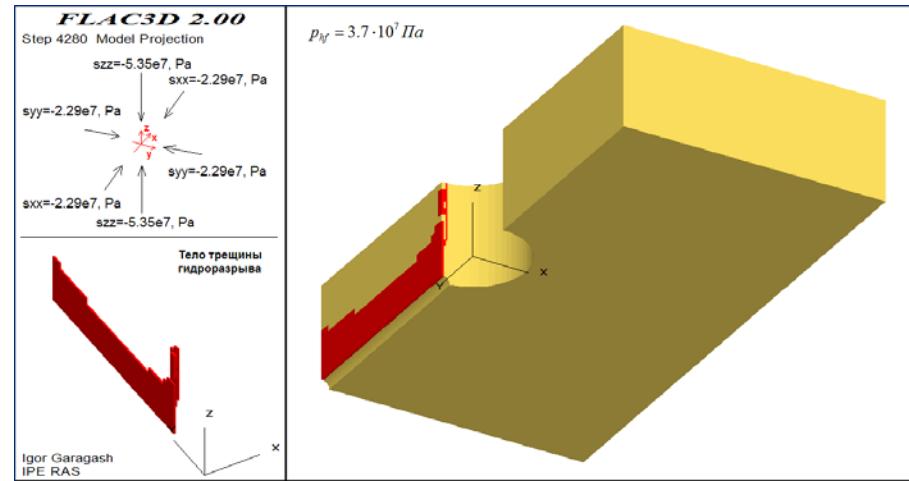
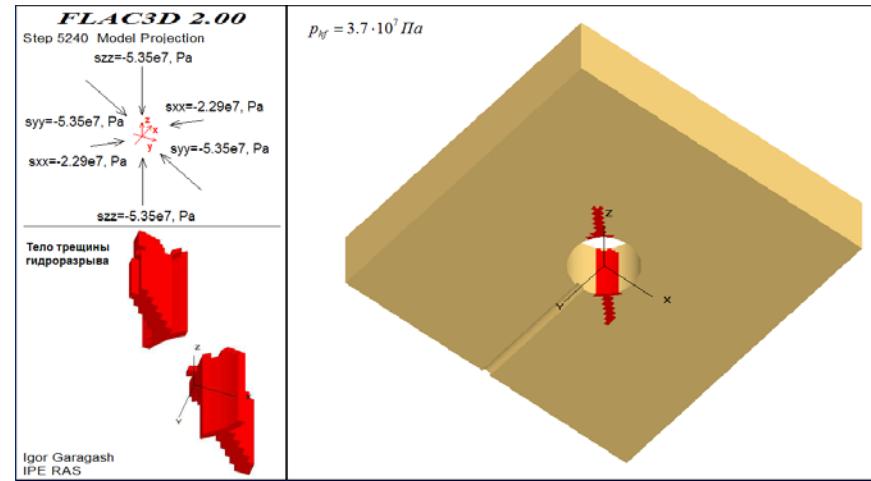
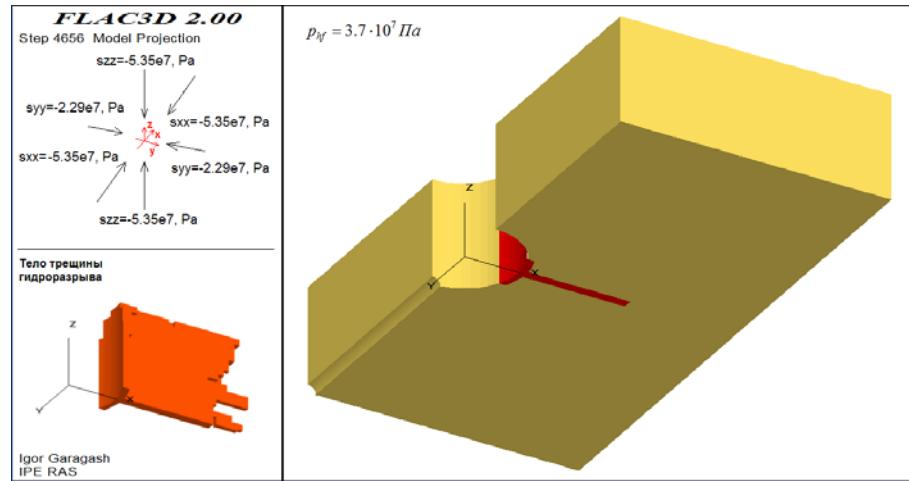


$$d\varepsilon_{ij}^e = \frac{1}{2G} [d(\sigma_{ij} + p\delta_{ij}) - \frac{\nu}{1+\nu} d(\sigma + p)\delta_{ij}]$$

ϕ - угол трения

ψ - угол дилатансии

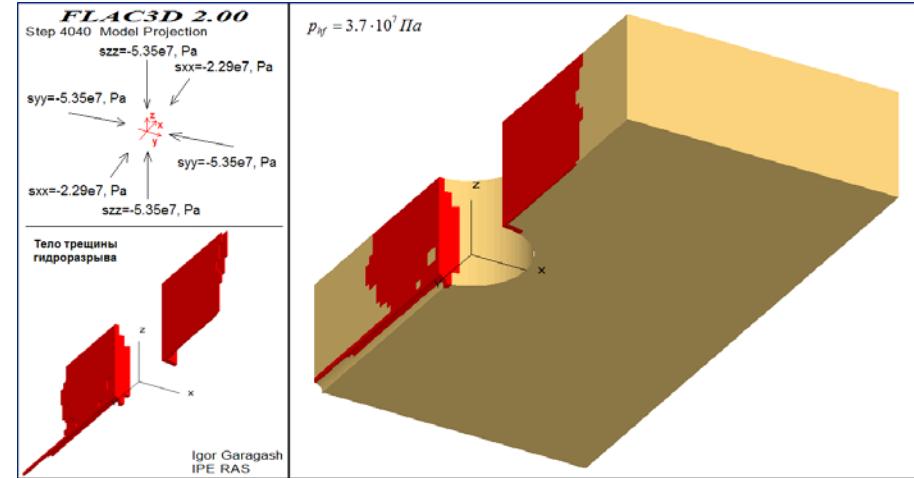
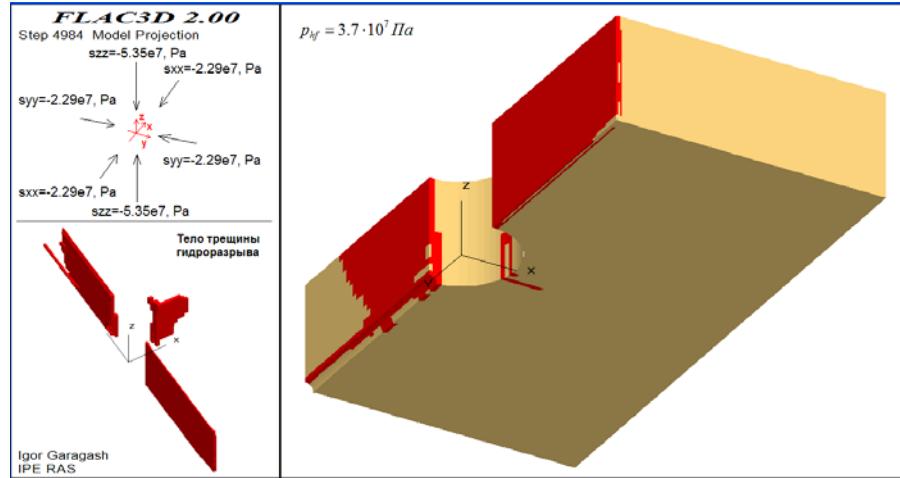
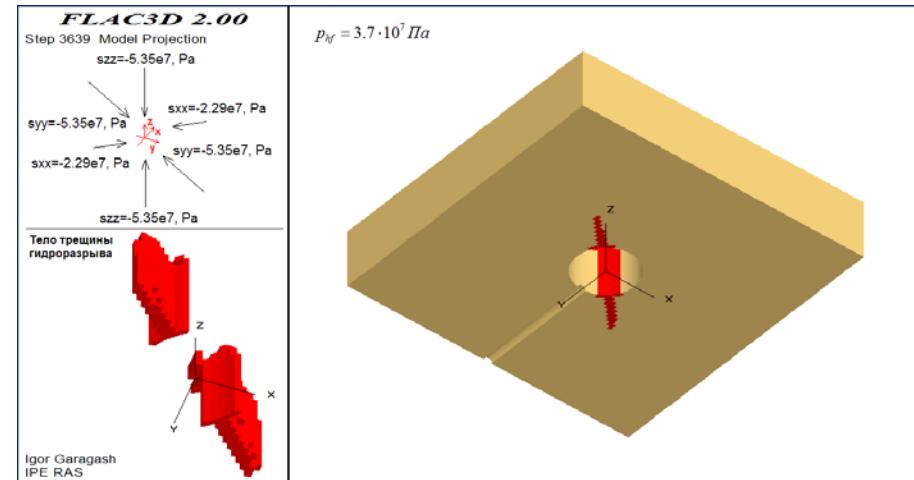
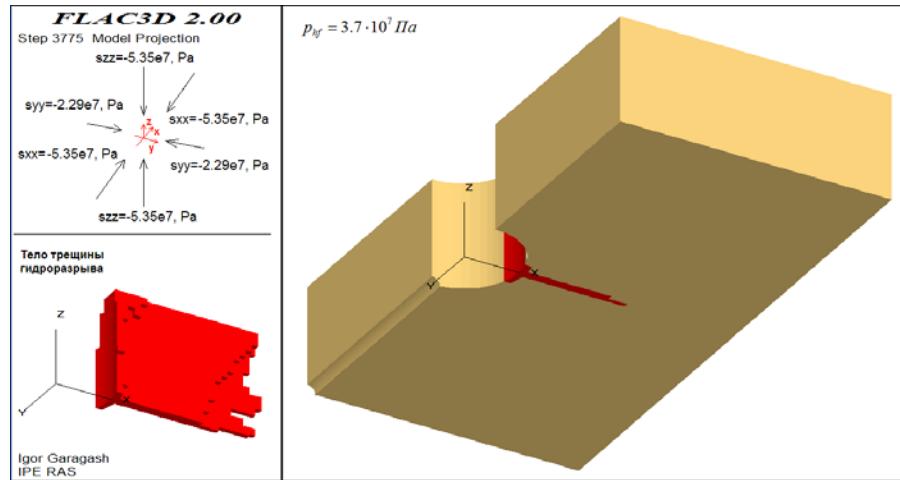
Терригенный коллектор



Распространение трещины гидроразрыва в терригенном коллекторе
Давление гидроразрыва создано в основной и боковой скважинах

$$p_{hf} = 3.7 \cdot 10^7 \text{ Pa}$$

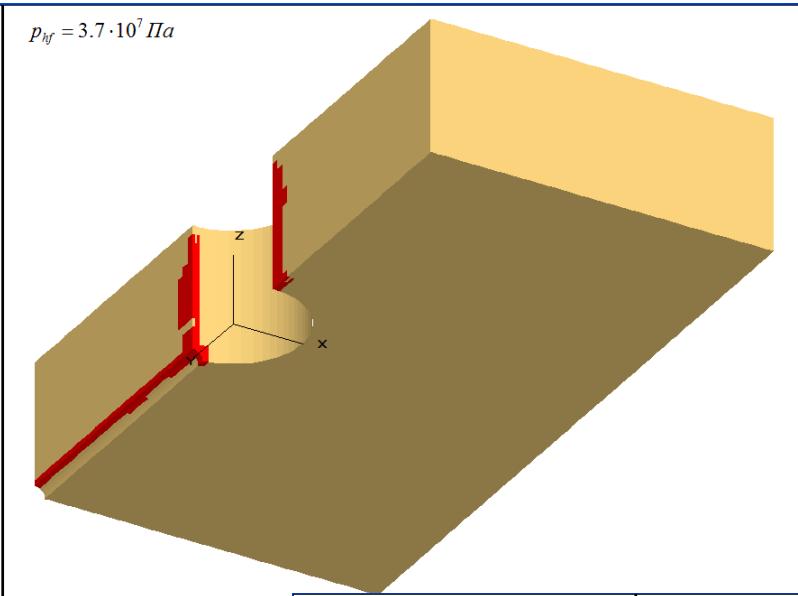
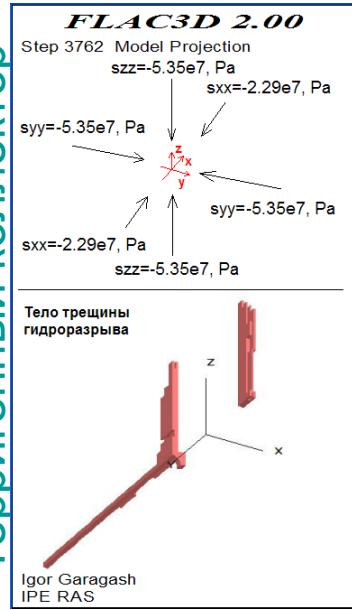
Карбонатный коллектор



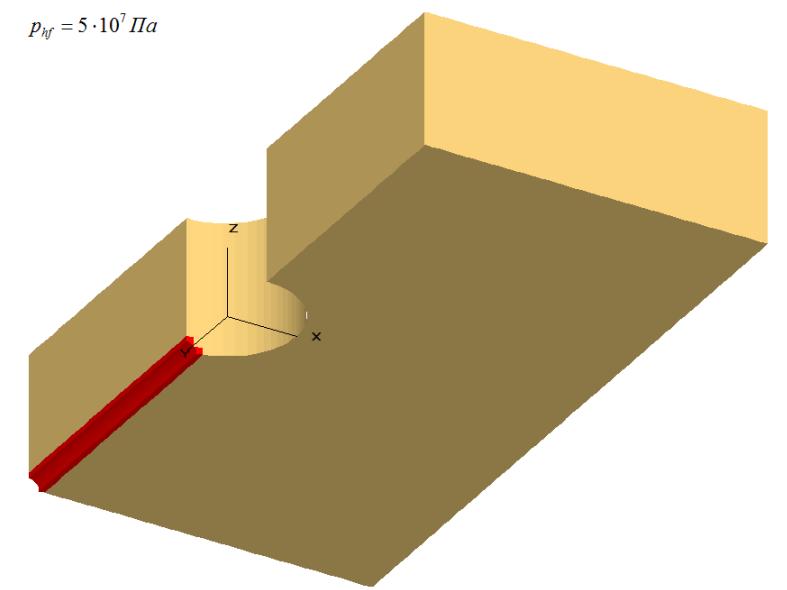
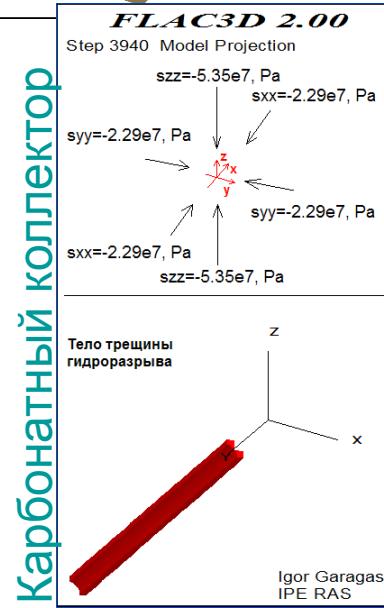
Распространение трещины гидроразрыва в карбонатном коллекторе
Давление гидроразрыва создано в основной и боковой скважинах

$$p_{hf} = 3.7 \cdot 10^7 \text{ Pa}$$

Терригенный коллектор



Карбонатный коллектор



Приложение давления только в боковой скважине

$$p_{hf} = 3.7 \cdot 10^7 \text{ Pa}$$

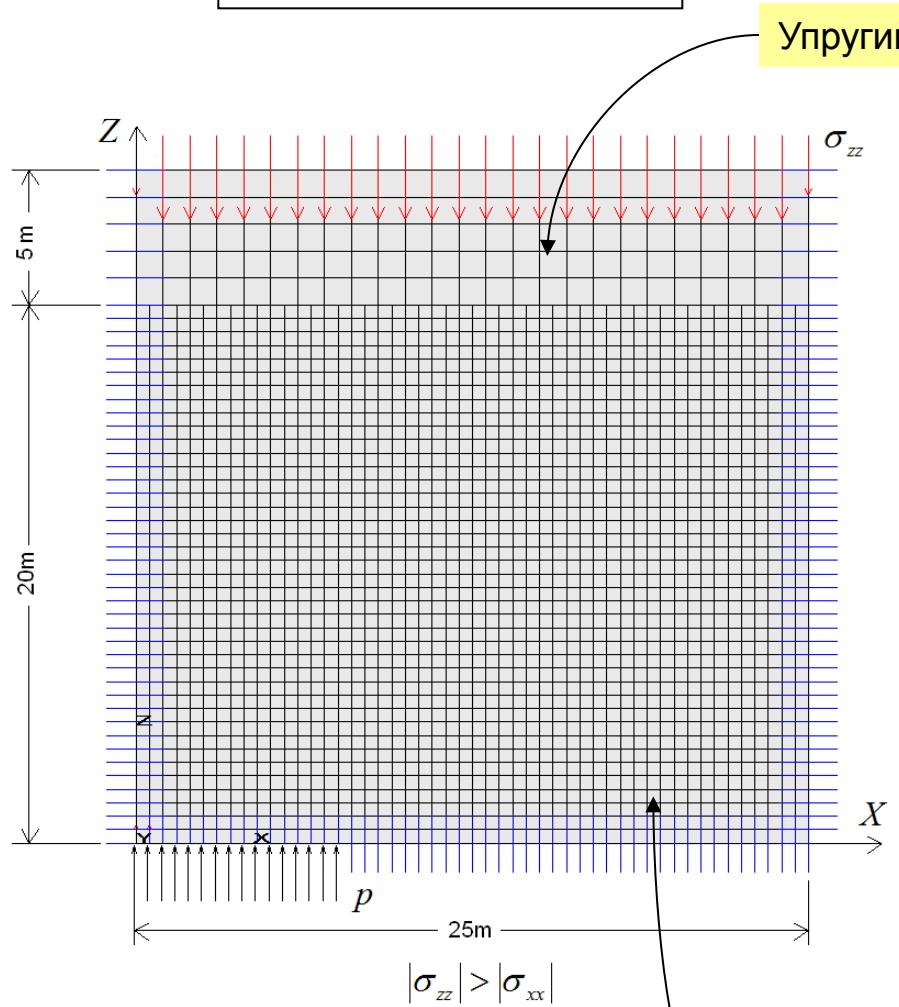
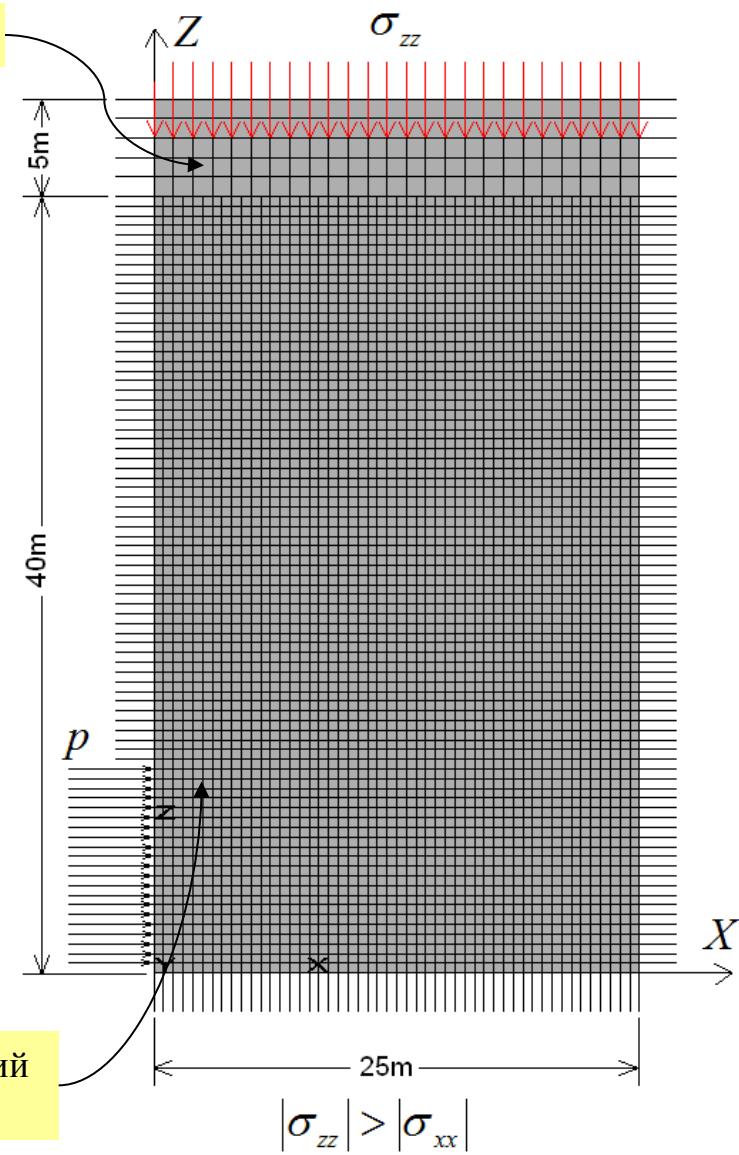
Численное моделирование гидравлического разрыва в горных породах с дилатансией

Изучено влияние локализации деформации на процесс гидроразрыва.

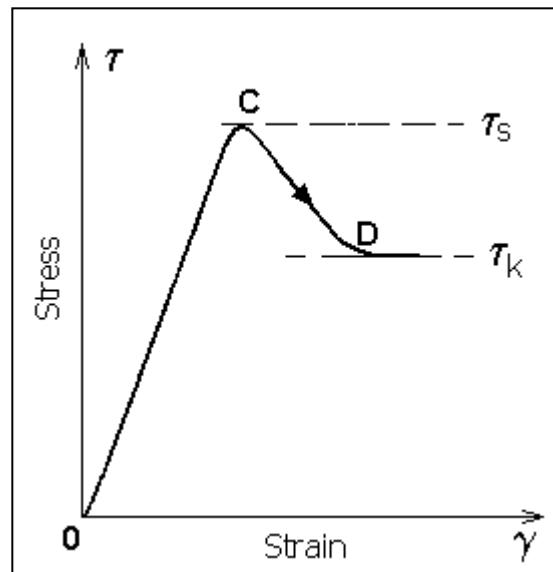
Рассматривается слой пористого осадочного материала с начальными напряжениями, обусловленными собственным весом пород.

В рамках плоской деформации моделируется процесс распространения гидроразрыва.

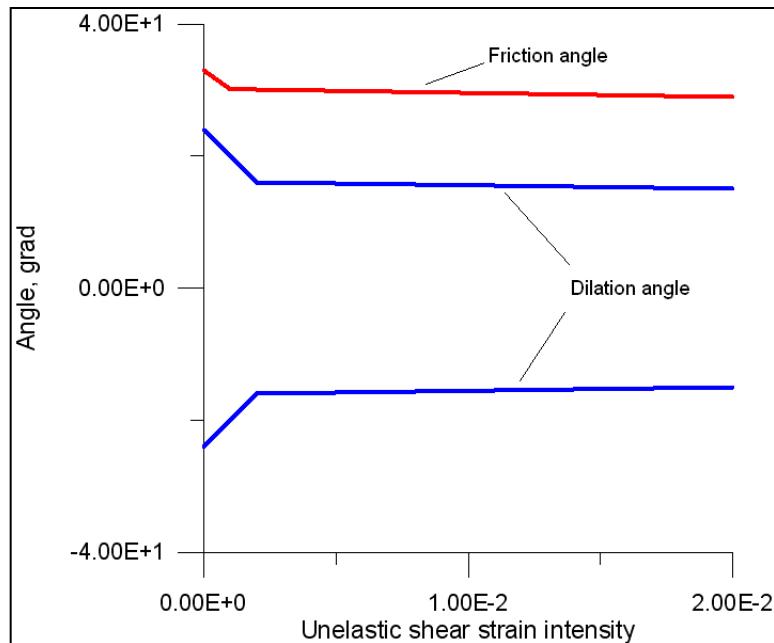
Рассмотрено два варианта – с горизонтальным и вертикальным распространением разрыва.

Горизонтальный разрыв**Вертикальный разрыв**

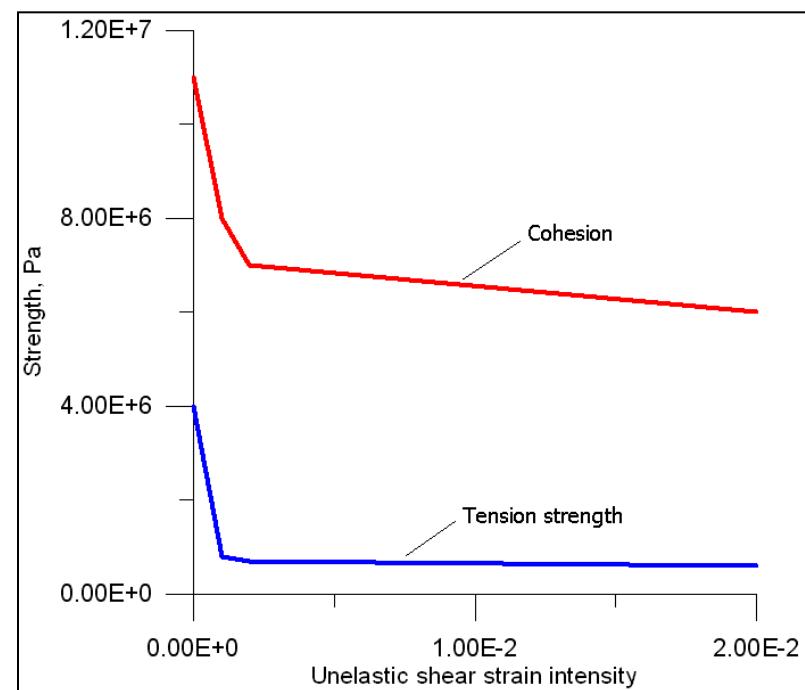
Кривая деформирования с разупрочнением



Изменения углов внутреннего трения и дилатансии в зависимости от накопленной пластической деформации



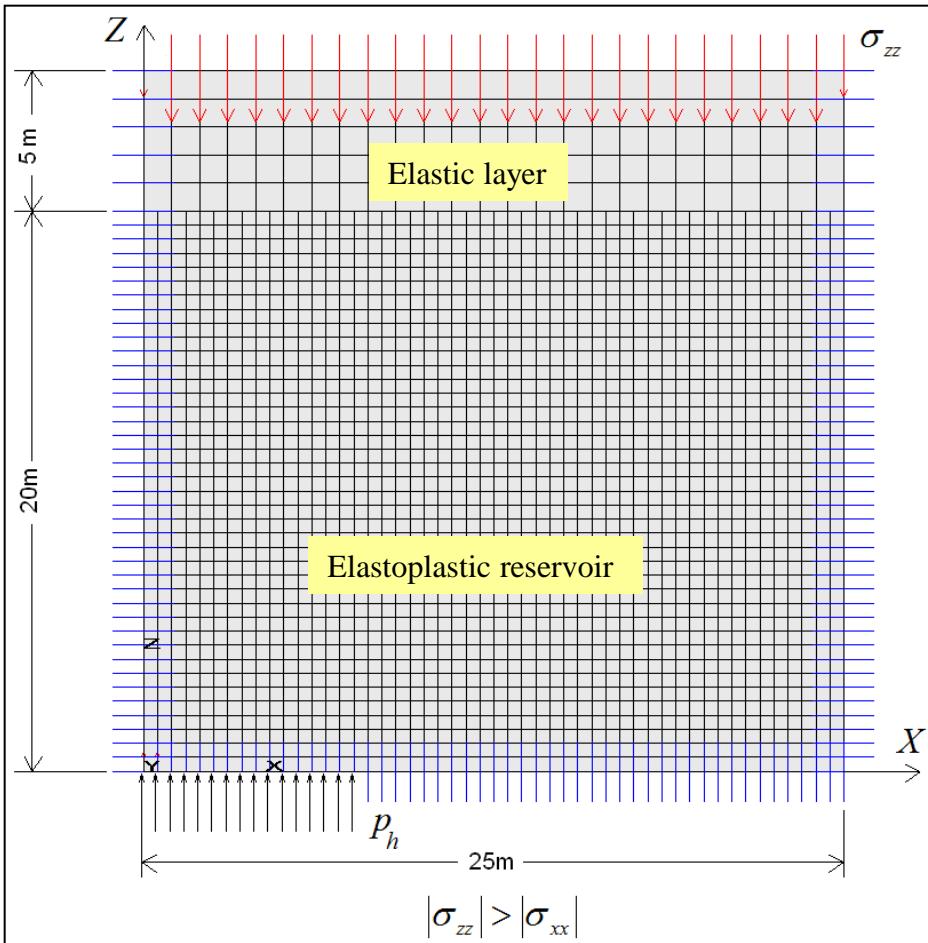
Изменения сцепления и прочности на растяжение в зависимости от накопленной пластической деформации



Горизонтальный разрыв

Свойства упругого слоя

$$\rho = 2340 \text{ kg/m}^3 \quad G = 2.1 \cdot 10^9 \text{ Pa} \quad K = 2.5 \cdot 10^9 \text{ Pa}$$



2125 elements

Свойства упругопластического коллектора

$$\rho = 2340 \text{ kg/m}^3 \quad G = 8.8 \cdot 10^9 \text{ Pa} \quad K = 2.02 \cdot 10^{10} \text{ Pa}$$

$$c = 1.1 \cdot 10^7 \text{ Pa} \quad \phi_s = 33^\circ \quad \sigma^t = 4 \cdot 10^6 \\ \psi_s = 24^\circ \quad \text{or} \quad \psi_s = -24^\circ$$

Фильтрационные свойства коллектора

$$p = 2.5 \cdot 10^7 \text{ Pa} \quad \text{- pore pressure}$$

$$\kappa = 5 \cdot 10^{-12} \text{ m}^2 / (\text{Pa sec}) \quad \text{- filtration coefficient}$$

$$n = 0.24 \quad \text{- porosity}$$

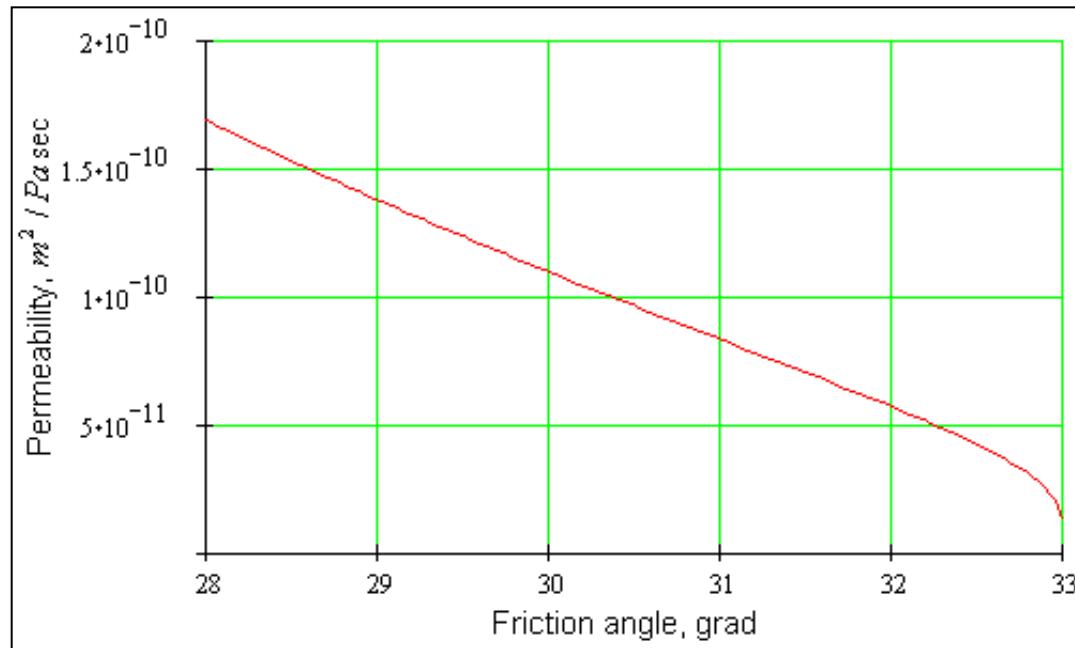
Полные начальные напряжения

$$\sigma_{xx} = -3 \cdot 10^7 \text{ Pa} \quad p_h = 9 \cdot 10^7 \text{ Pa}$$

$$\sigma_{yy} = -6 \cdot 10^7 \text{ Pa}$$

$$\sigma_{zz} = -4 \cdot 10^7 \text{ Pa} \quad p_h = 6 \cdot 10^7 \text{ Pa}$$

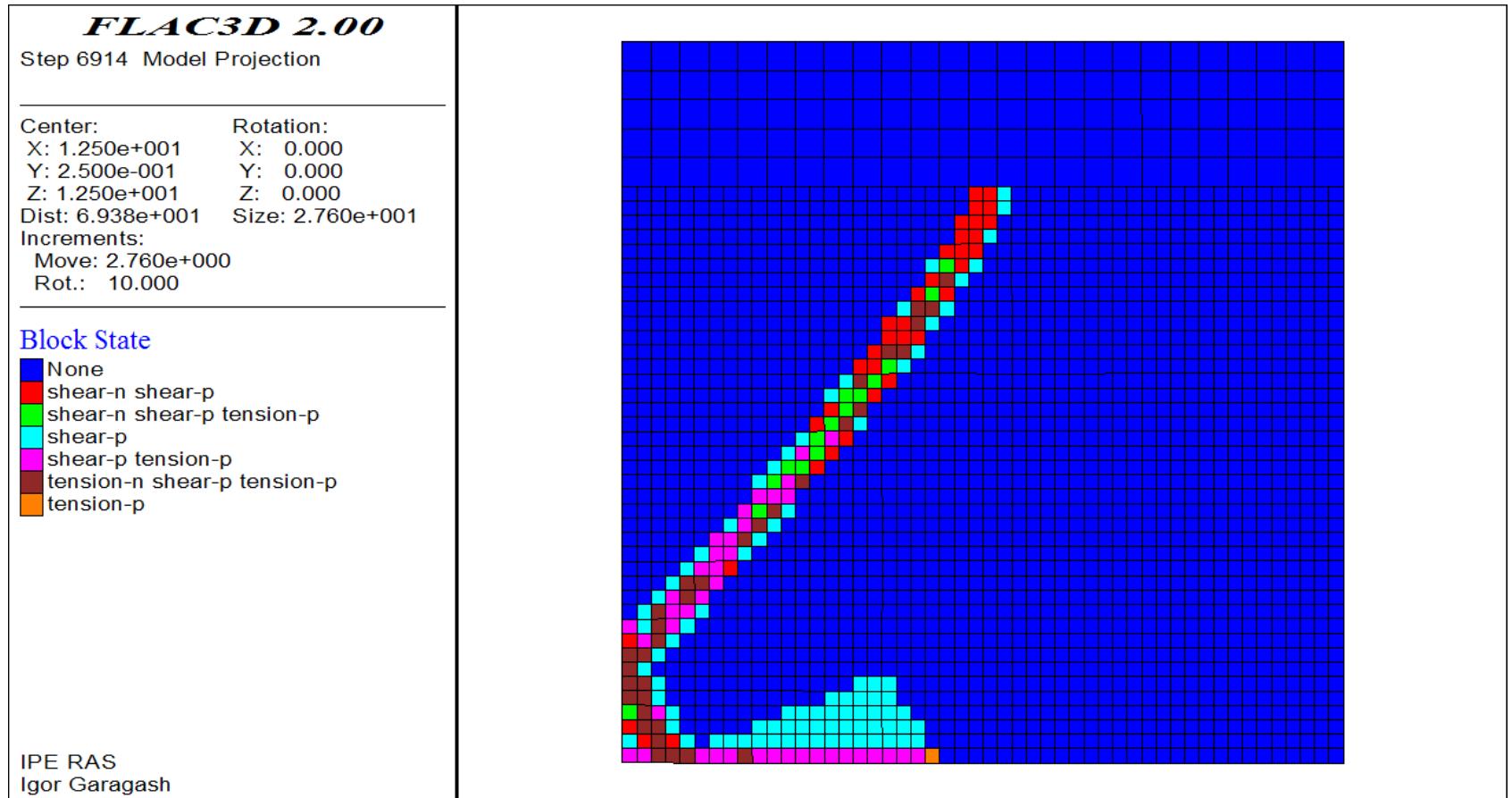
$$\kappa = \kappa^0 \left\{ 1 - \left[\frac{(\phi_s - \phi)}{\phi_s} \right]^{0.1} \right\}^{-2}$$



Зависимость коэффициента фильтрации от угла трения

Порядок расчета следующий. Сначала на левой границе сетки создается разрез, равный длине одной ячейки (0.5м), к поверхности которой прикладывается давление $p_h = 9 \cdot 10^7 \text{ Pa}$. Как только в конце разреза напряжения в определенный момент превышают предельное напряжение на растяжение $\sigma^t = 4 \cdot 10^6$, разрез увеличивается на одну ячейку и к образовавшейся свободной поверхности прикладывается давление. Затем процедура повторяется. В результате разрез движется, моделируя процесс гидроразрыва. При этом предполагается, что гидроразрыв происходит быстро и фильтрация не успевает развиться. Затем, когда разрыв достигает десяти метров , давление сбрасывается до величины $p_h = 6 \cdot 10^7 \text{ Pa}$ и движение прекращается. Далее включается фильтрация и считается связанная задача до времени $t = 3 \text{ min}$.

$$\psi_s = -24^\circ$$



Plastic zones created on the moment when the fracture propagation was stopped

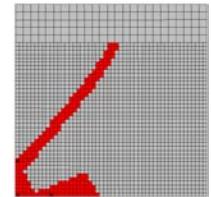
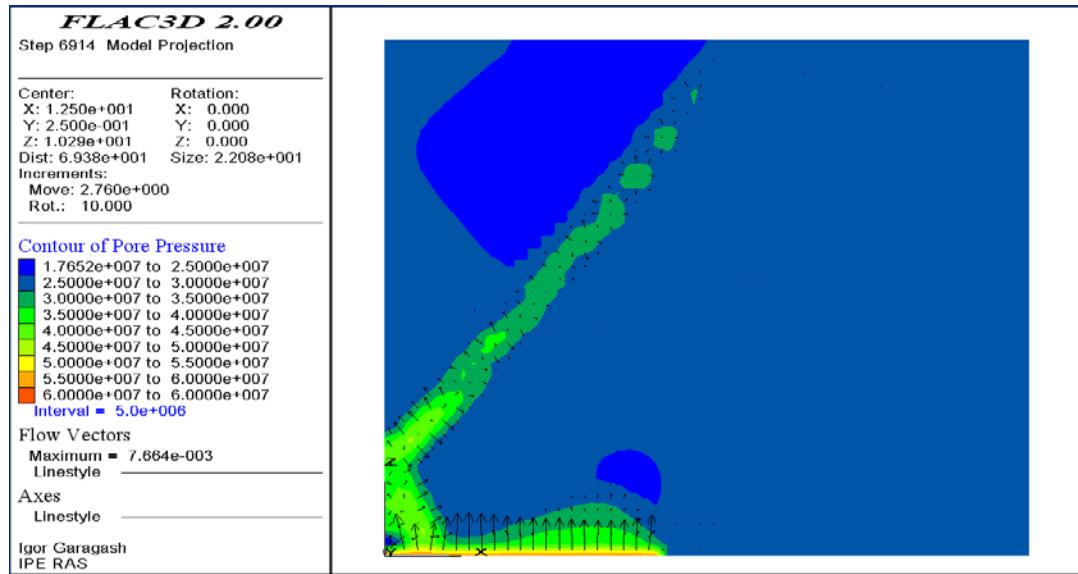
$$p_h = 9 \cdot 10^7 \text{ Pa}$$



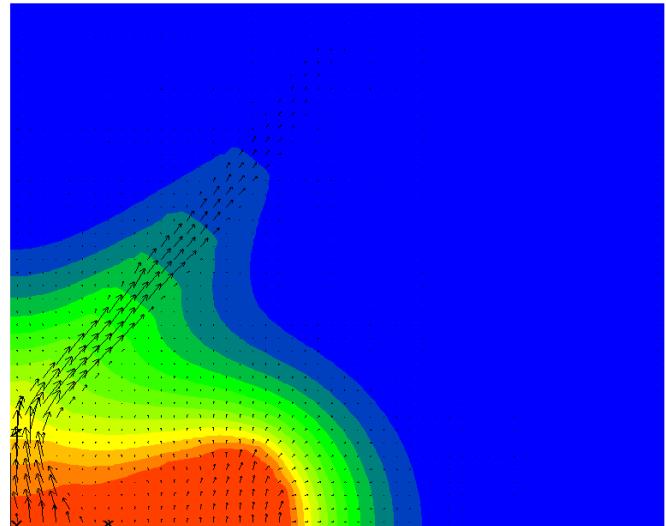
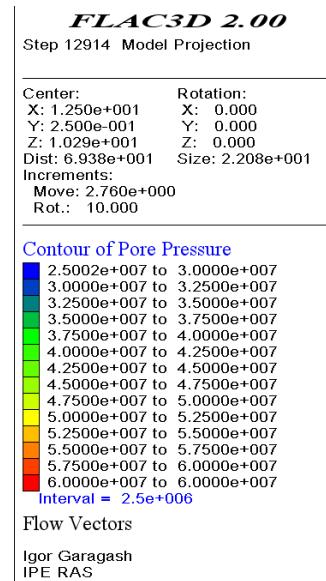
$$p_h = 6 \cdot 10^7 \text{ Pa}$$

Pore pressure pattern and fluid flow velocity at the stop moment

$$\psi_s = -24^\circ$$

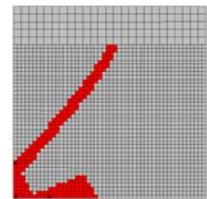
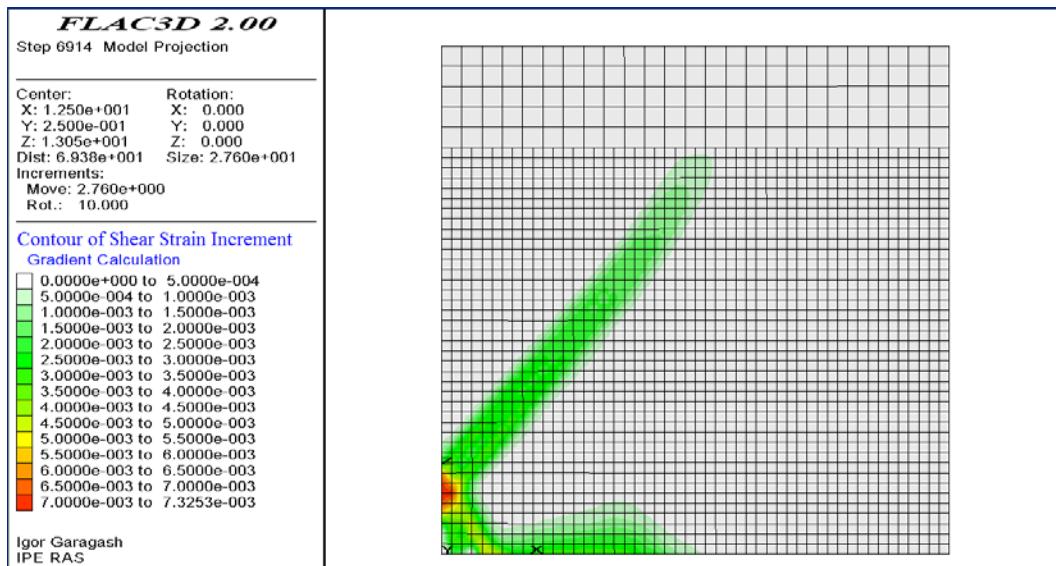


Pore pressure field and flow velocity after three minutes of filtration

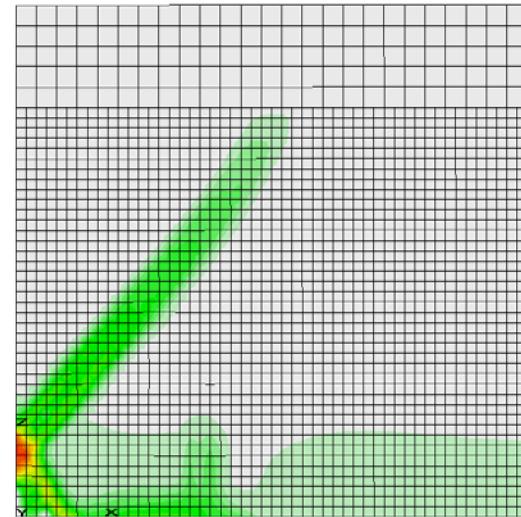
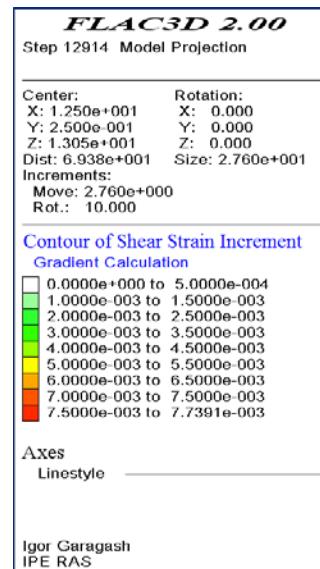


Shear strain intensity at the moment of the stop of hydrofracturing

$$\psi_s = -24^\circ$$

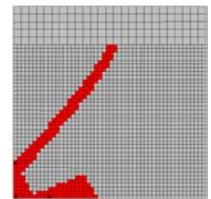
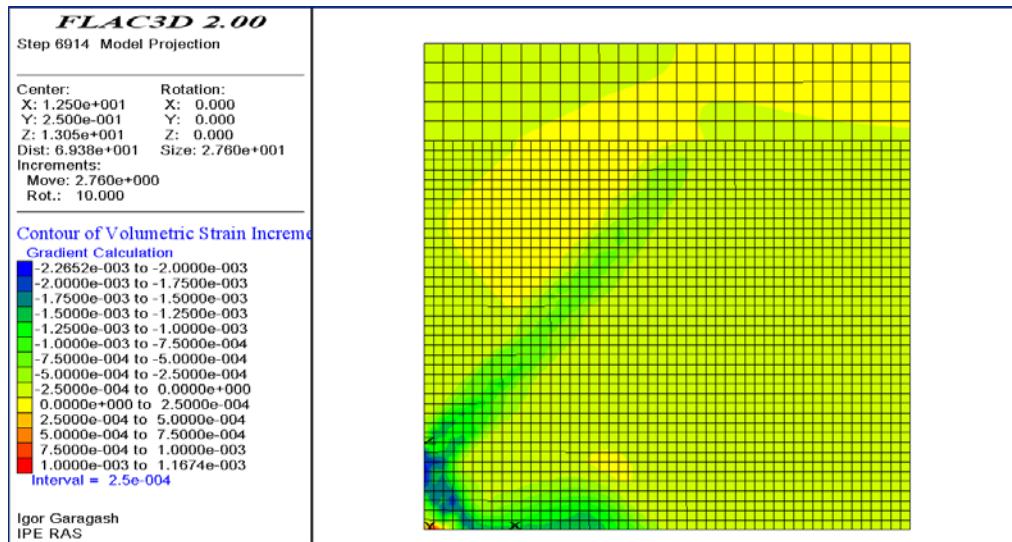


Shear strain intensity after three minutes of the filtrations

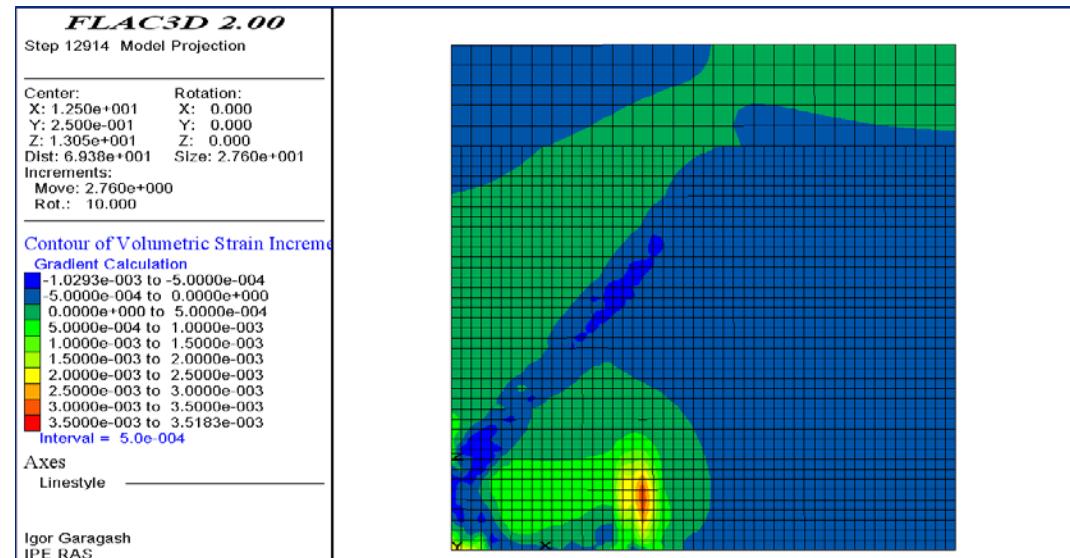


Volume strain field at the stop of hydrofracturing

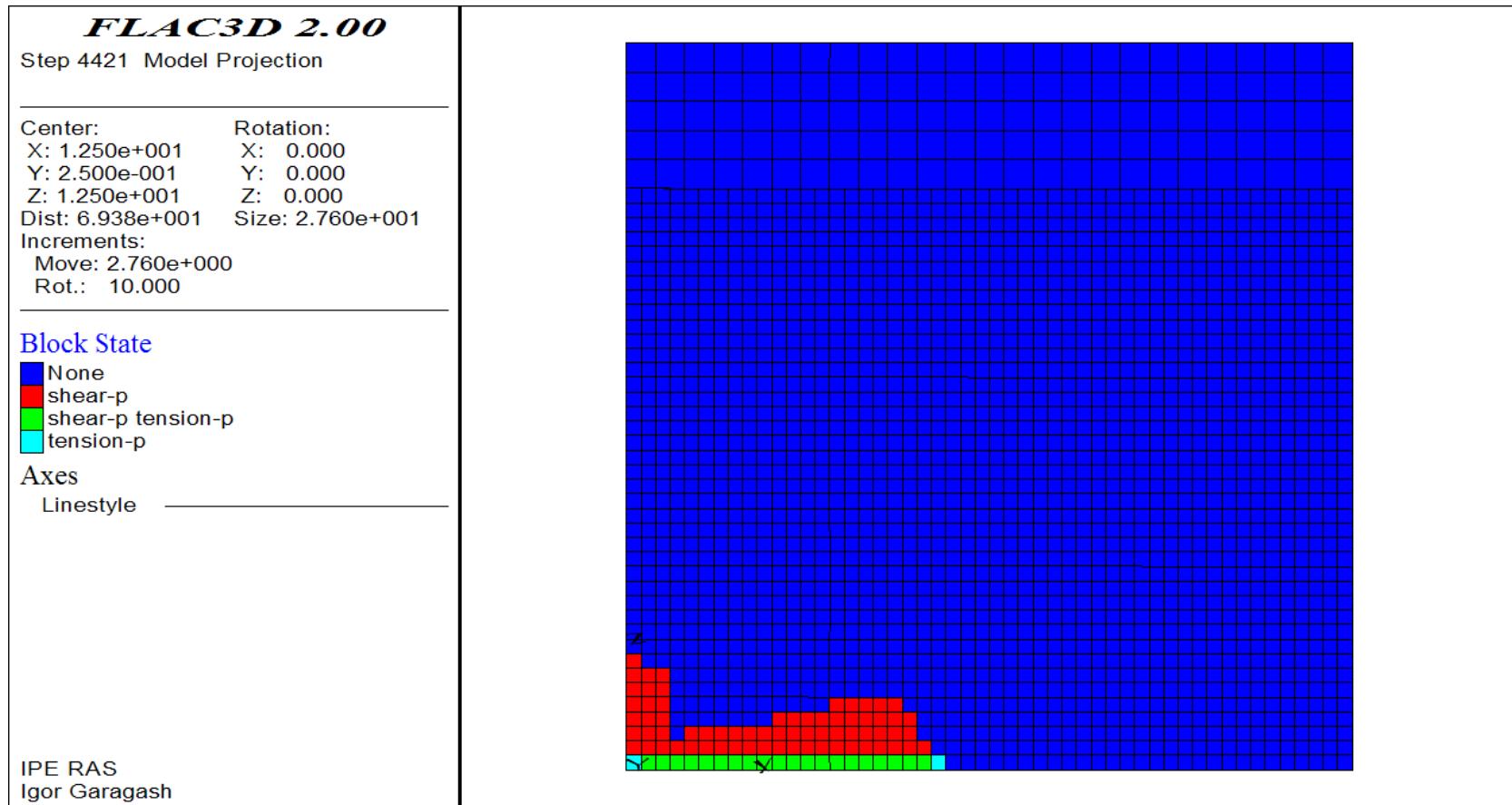
$$\psi_s = -24^\circ$$



Volumetric deformation after three minutes of the filtration

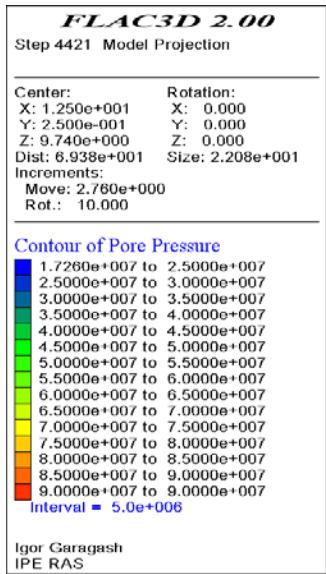


$$\psi_s = 24^\circ$$

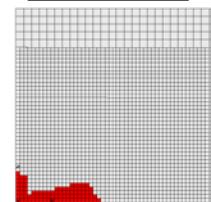


Plastic zones created on the moment when the fracture propagation was stopped

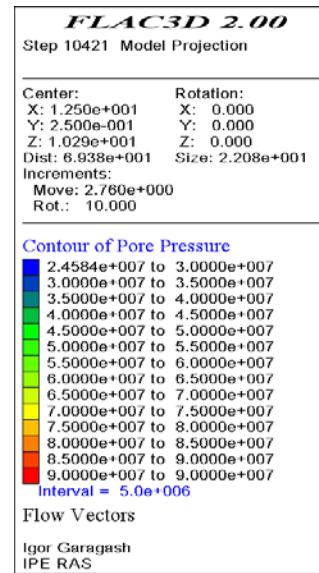
Pore pressure field and fluid velocity at the stop hydrofracturing



$$\psi_s = 24^\circ$$

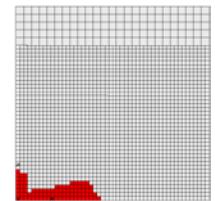
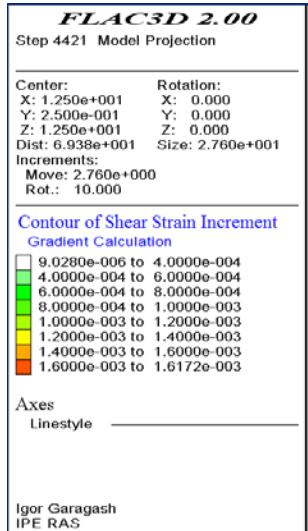


Pore pressure field after three minutes of the filtration beginning

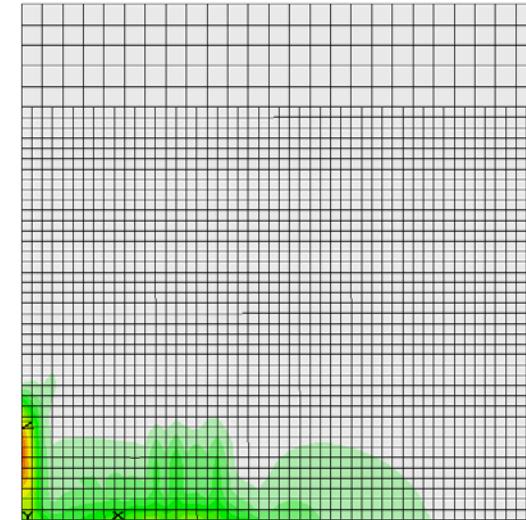
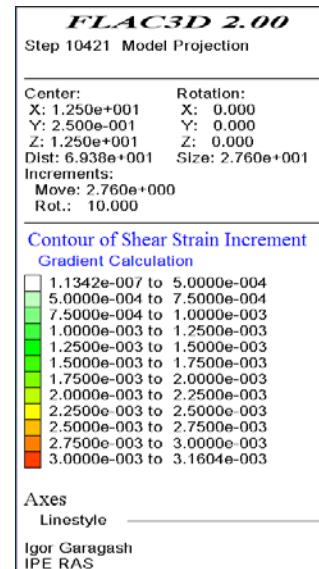


Plastic strain intensity at the stop of hydrofracturing

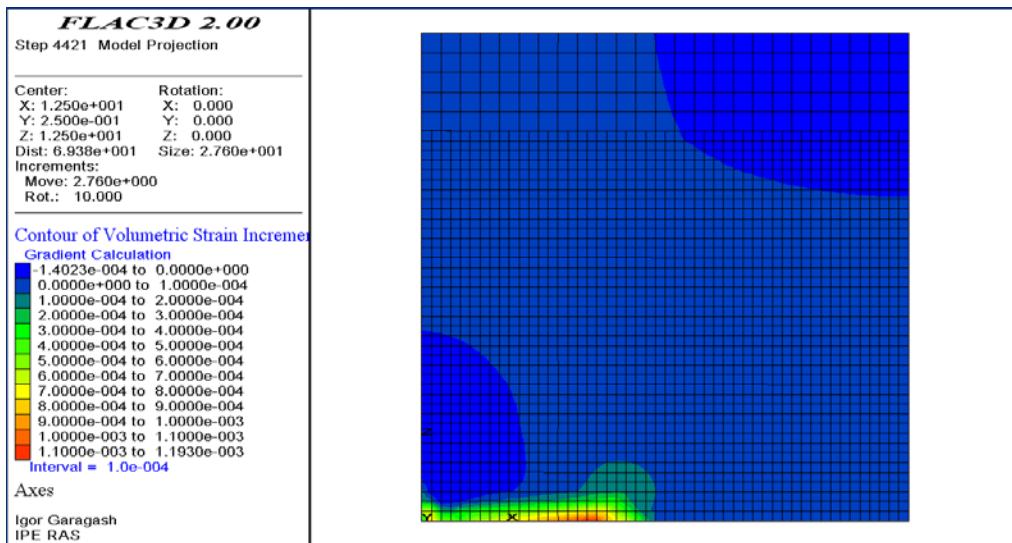
$$\psi_s = 24^\circ$$



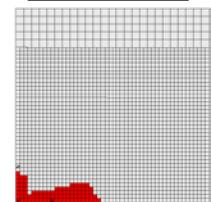
Plastic strain intensity field after three minutes of filtration process



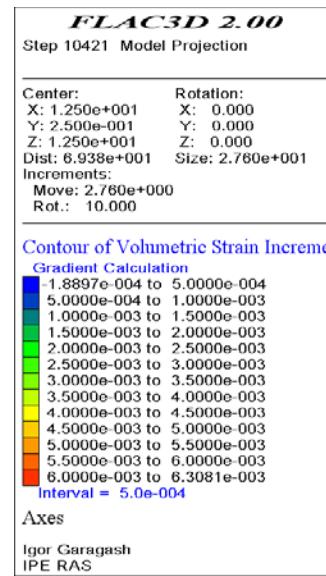
Volume strain field at the stop of fracturing

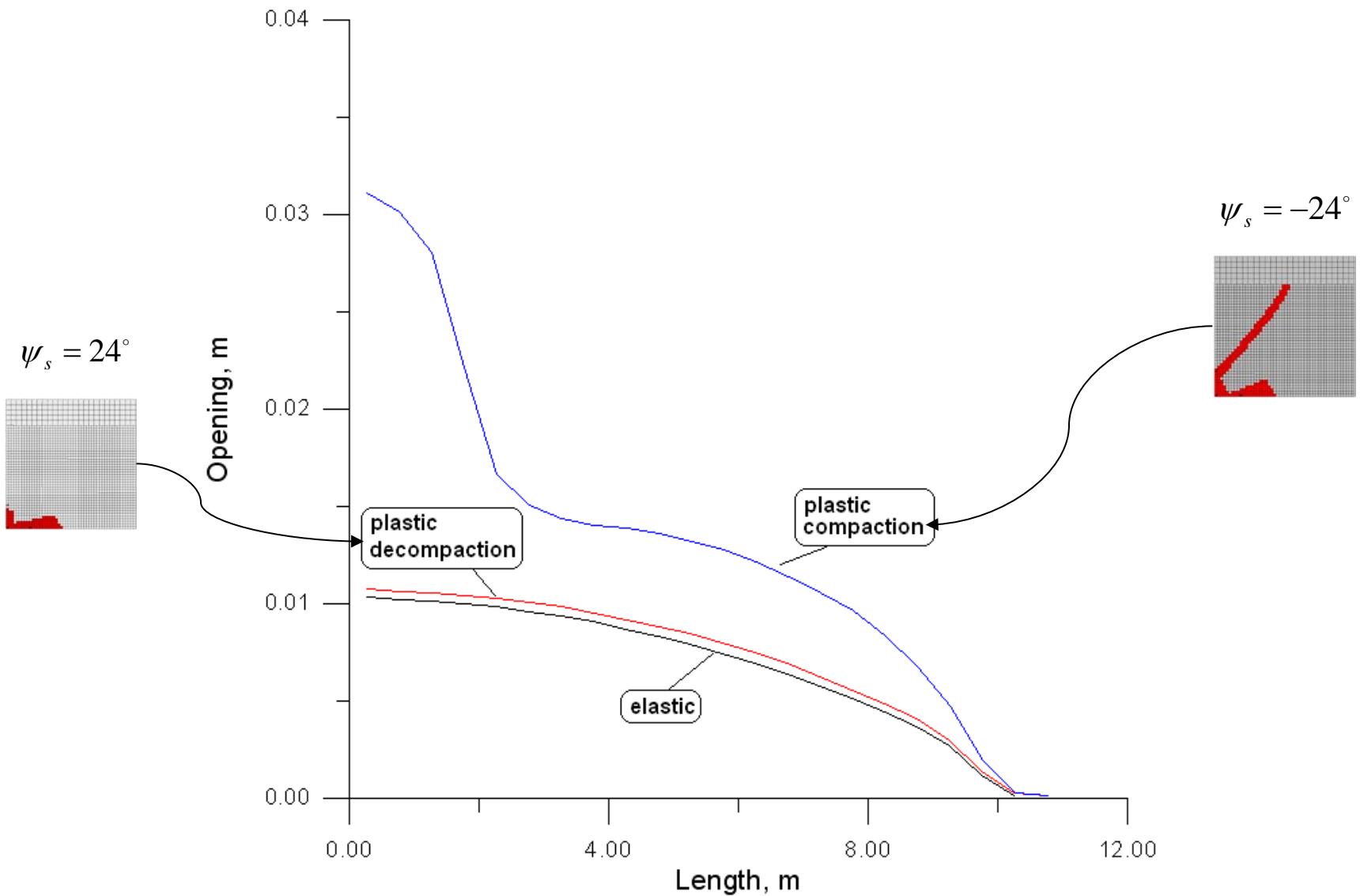


$$\psi_s = 24^\circ$$



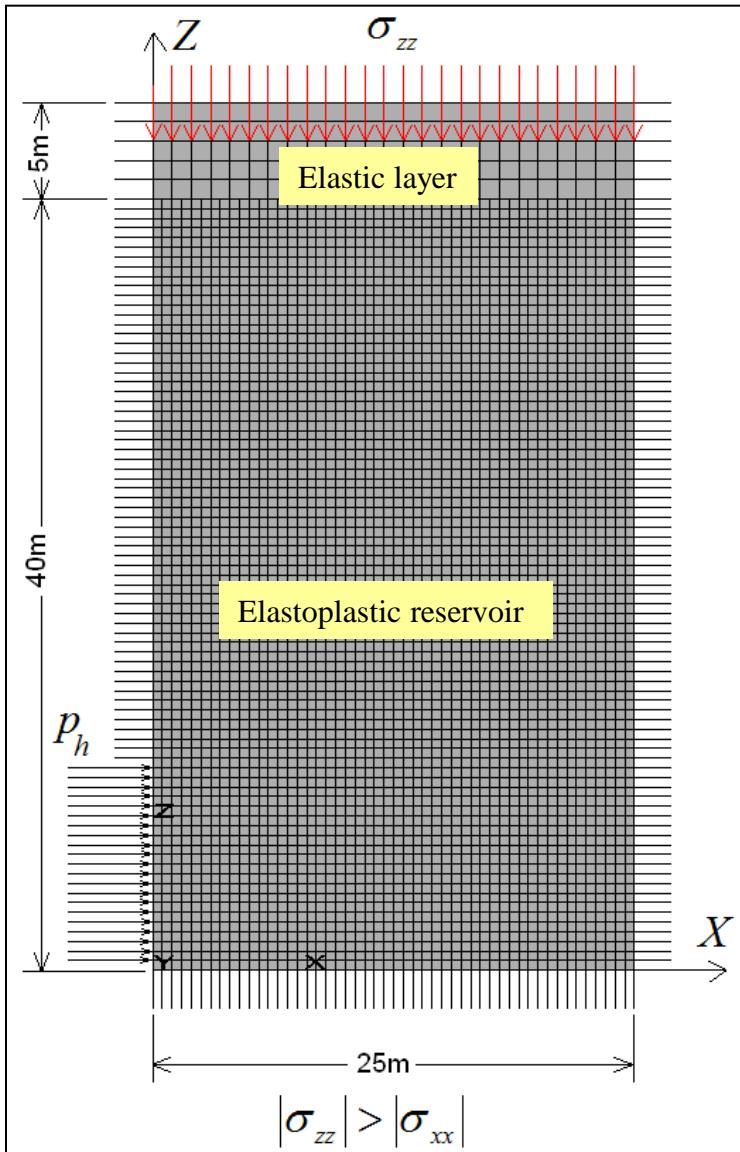
Volume strain field after three minutes after three minutes
of filtration process





Crack opening is shown for the elastic and elastoplastic cases at the stop after pressure drop

Vertical rupture



4125 elements

Properties of elastic layer

$$\rho = 2340 \text{ kg/m}^3 \quad G = 2.1 \cdot 10^9 \text{ Pa} \quad K = 2.5 \cdot 10^9 \text{ Pa}$$

Properties of elastoplastic reservoir

$$\rho = 2340 \text{ kg/m}^3 \quad G = 4 \cdot 10^9 \text{ Pa} \quad K = 7 \cdot 10^9 \text{ Pa}$$

$$c = 8 \cdot 10^6 \text{ Pa} \quad \phi_s = 33^\circ \quad \sigma^t = 5 \cdot 10^5$$

$$\psi_s = 24^\circ \quad \text{or} \quad \psi_s = -10^\circ$$

Filtration properties of elastoplastic reservoir

$$p = 2.5 \cdot 10^7 \text{ Pa} \quad \text{- pore pressure}$$

$$\kappa = 5 \cdot 10^{-12} \text{ m}^2 / (\text{Pa sec}) \quad \text{- filtration coefficient}$$

$$n = 0.24 \quad \text{- porosity}$$

Initial total stresses

$$\sigma_{xx} = -3 \cdot 10^7 \text{ Pa}$$

$$\sigma_{yy} = -6 \cdot 10^7 \text{ Pa}$$

$$\sigma_{zz} = -4 \cdot 10^7 \text{ Pa}$$

$$p_h = 6 \cdot 10^7 \text{ Pa}$$



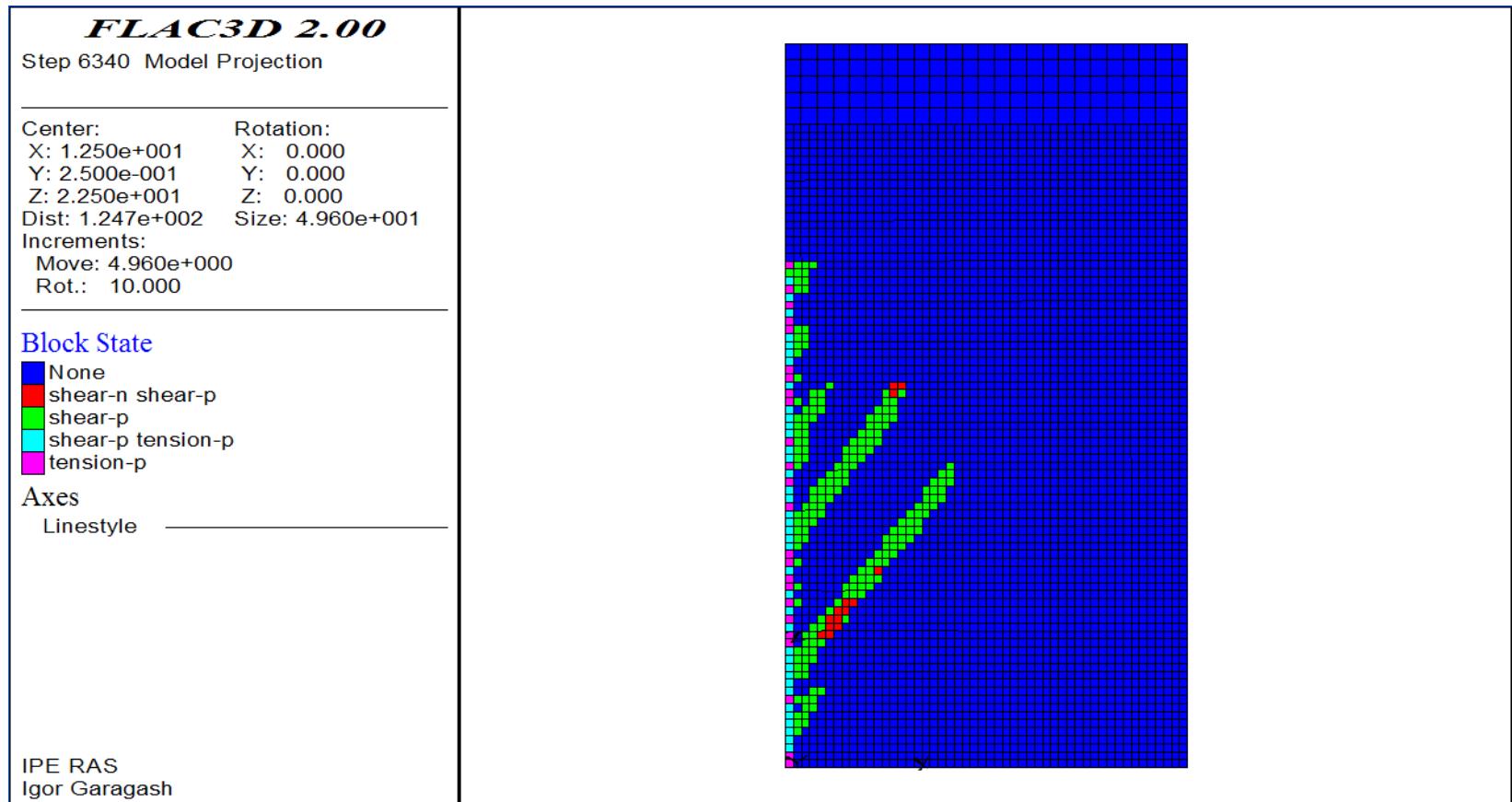
$$p_h = 3 \cdot 10^7 \text{ Pa}$$

Strain intensity	0	$1 \cdot 10^{-3}$	$2 \cdot 10^{-3}$	$2 \cdot 10^{-2}$	1
Cohesion, Pa	$8 \cdot 10^6$	$4 \cdot 10^6$	$2 \cdot 10^6$	$1 \cdot 10^6$	$1 \cdot 10^6$
Tension, Pa	$5 \cdot 10^5$	$1 \cdot 10^5$	$8 \cdot 10^4$	$7 \cdot 10^4$	$7 \cdot 10^4$
Friction angle	33	31	30	29	29
Dilation angle	-10 (24)	-8 (20)	-6 (16)	-5 (15)	-5 (15)

The calculation procedure is the following one. Firstly, along the left border of a grid the vertical cut, equal to length of one cell (0.5 m), is created to which surface the pressure $p_h = 6 \cdot 10^7 \text{ Pa}$ is applied. As soon as at the end of the cut the stress exceeds a limit stress for tension, the cut is increased by one cell and the pressure is applied to the formed free surface. Then the procedure repeats.

As the result, the moving cut simulates the hydrofracturing process. Thus it is supposed that hydrofracturing occurs quickly and the filtration has not time to be developed. When the crack reaches thirty meters length, the pressure is dropped to the value $p_h = 3 \cdot 10^7 \text{ Pa}$ and the motion is stopped. Then filtration process is included and the connected problem is solved up to the moment $t = 3 \text{ min}$.

$$\psi_s = -10^\circ$$



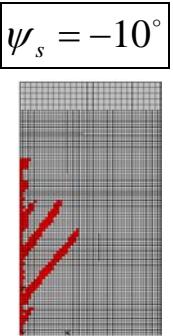
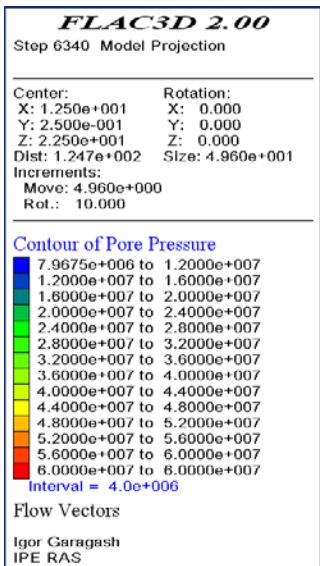
Plastic zones created on the moment when the fracture propagation was stopped

$$p_h = 6 \cdot 10^7 \text{ Pa}$$

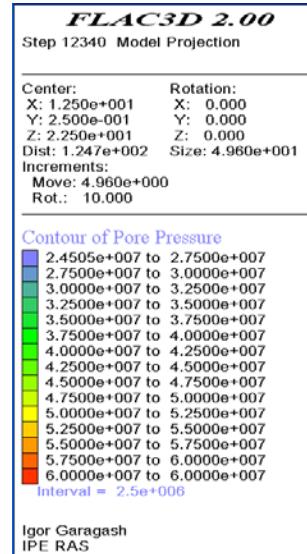


$$p_h = 3 \cdot 10^7 \text{ Pa}$$

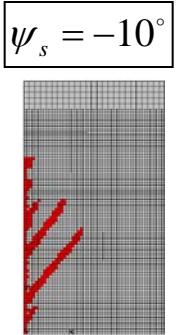
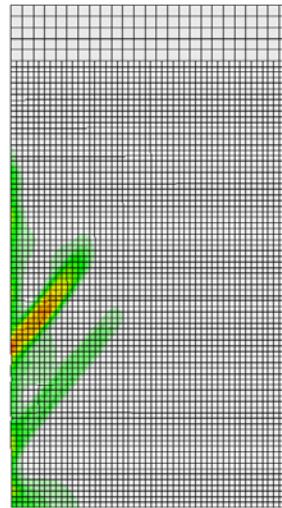
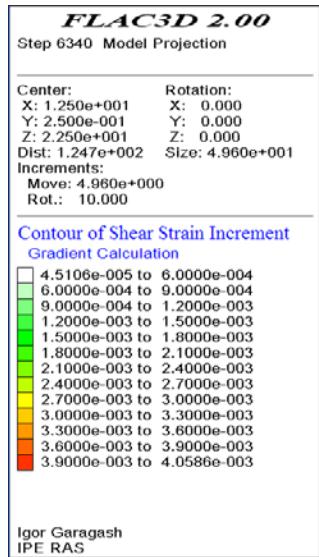
Pore pressure field and fluid velocity at the stop hydrofracturing



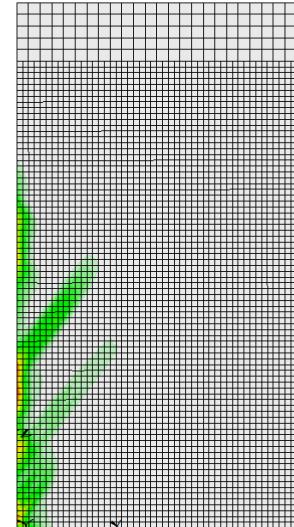
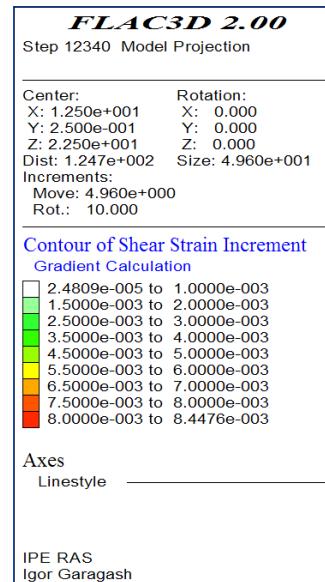
Volumetric deformation after three minutes of the filtration



Plastic strain intensity at the stop of hydrofracturing

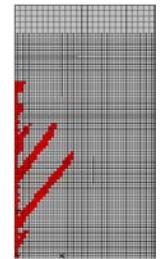
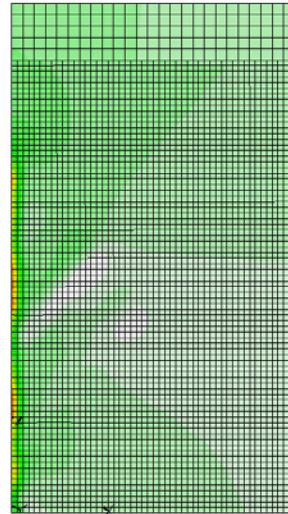
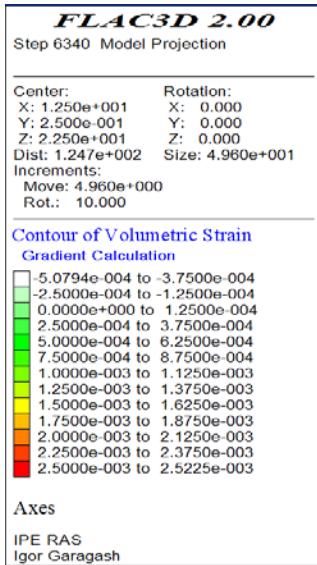


Plastic strain intensity field after three minutes of filtration process

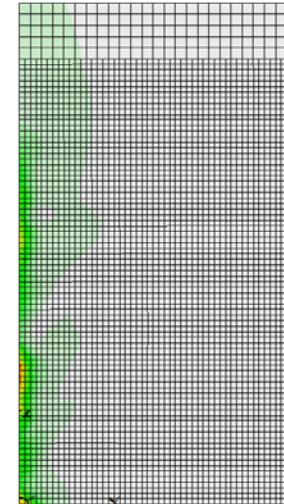
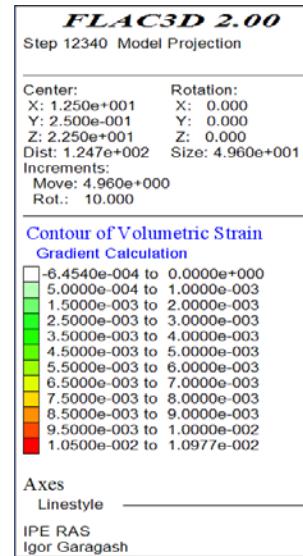


Volume strain field at the stop of fracturing

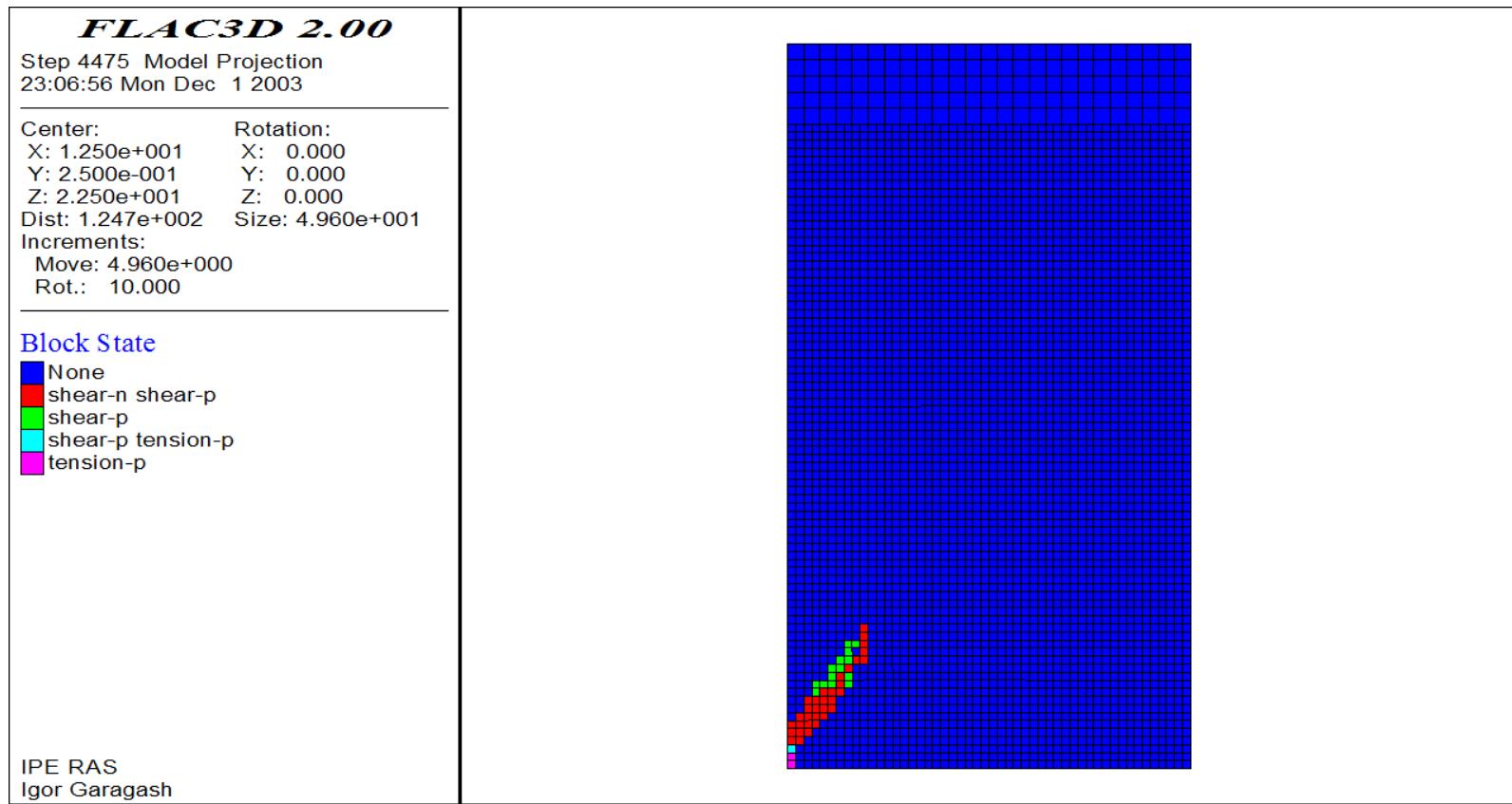
$$\psi_s = -10^\circ$$



Volume strain field after three minutes after three minutes
 of filtration process



$$\psi_s = 24^\circ$$



Plastic zones created on the moment when the fracture propagation was stopped

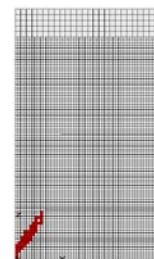
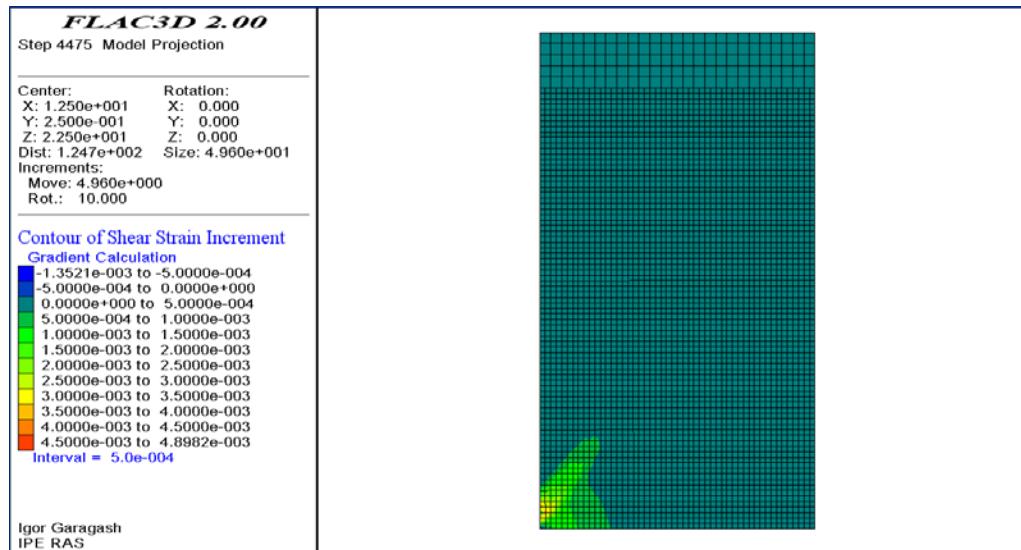
$$p_h = 6 \cdot 10^7 \text{ Pa}$$



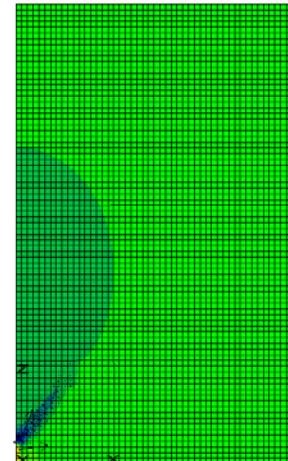
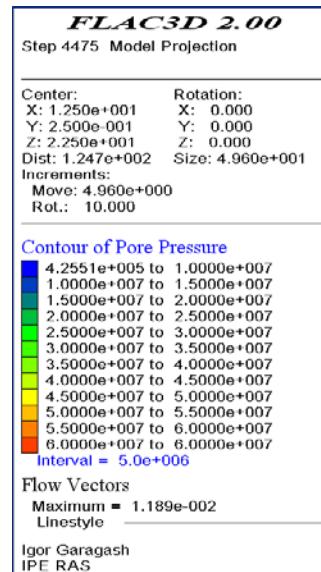
$$p_h = 3 \cdot 10^7 \text{ Pa}$$

Plastic strain intensity at the stop of hydrofracturing

$$\psi_s = 24^\circ$$



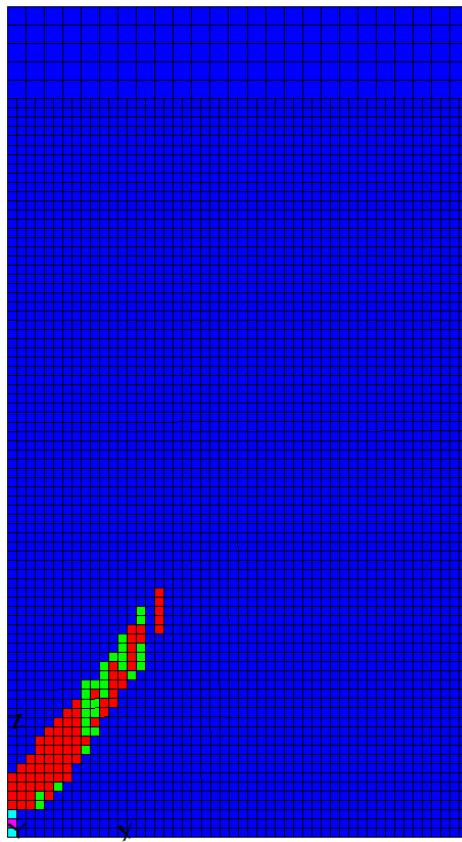
Plastic strain intensity field after three minutes of filtration process



Plastic zones created when the fracture propagation was stopped

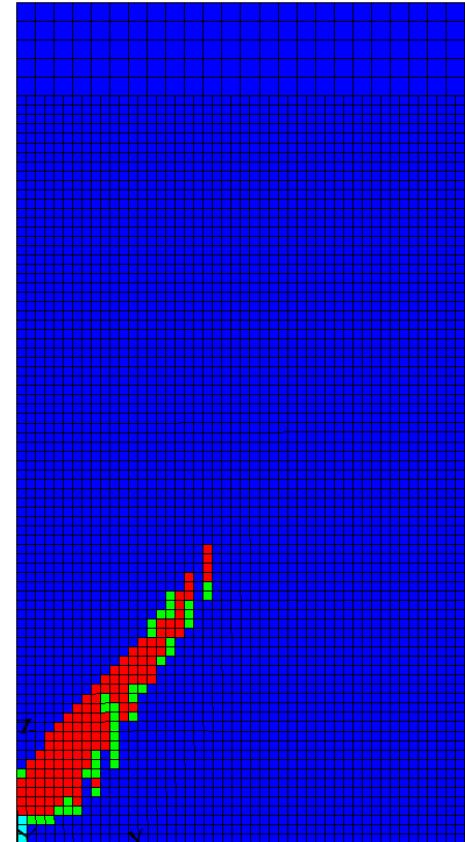
Block State
None
shear-n shear-p
shear-p
shear-p tension-p

$$\psi_s = 24^\circ$$



$$p_h = 9 \cdot 10^7 \text{ Pa}$$

$$\psi_s = 24^\circ$$

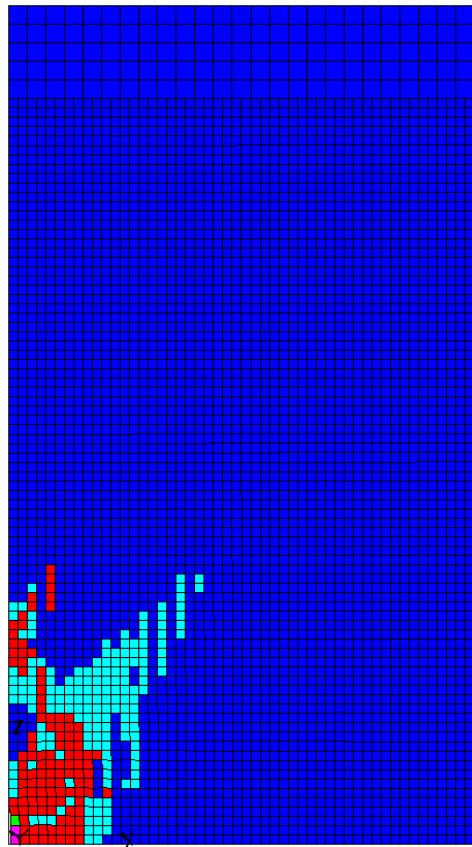


$$p_h = 13 \cdot 10^7 \text{ Pa}$$

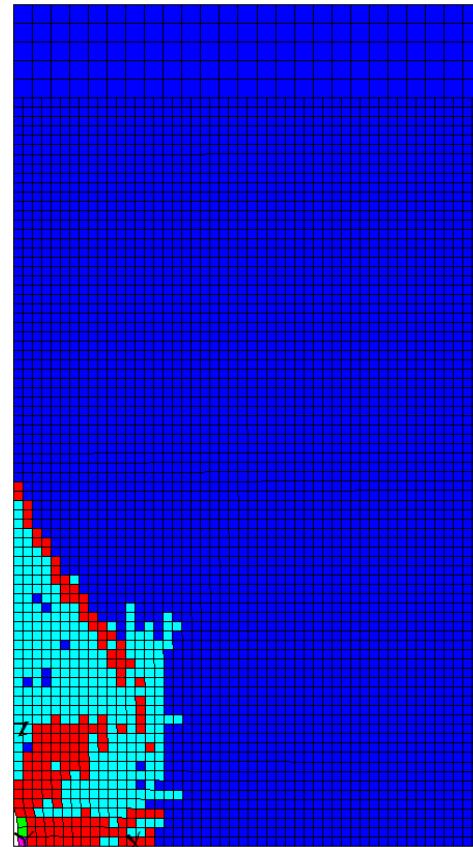
Plastic zones created when the fracture propagation was stopped

Block State
None
shear-n shear-p
shear-n shear-p tension-p
shear-p
shear-p tension-p

$$\psi_s = 24^\circ$$



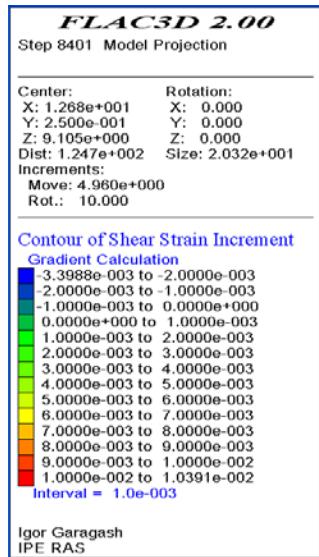
$$\psi_s = 24^\circ$$



$$p_h = 21 \cdot 10^7 Pa$$

$$p_h = 31 \cdot 10^7 Pa$$

Plastic strain intensity at the stop of hydrofracturing



$$p_h = 9 \cdot 10^7 \text{ Pa}$$

$$\psi_s = 24^\circ$$

Plastic strain intensity at the stop of hydrofracturing

$$p_h = 13 \cdot 10^7 \text{ Pa}$$

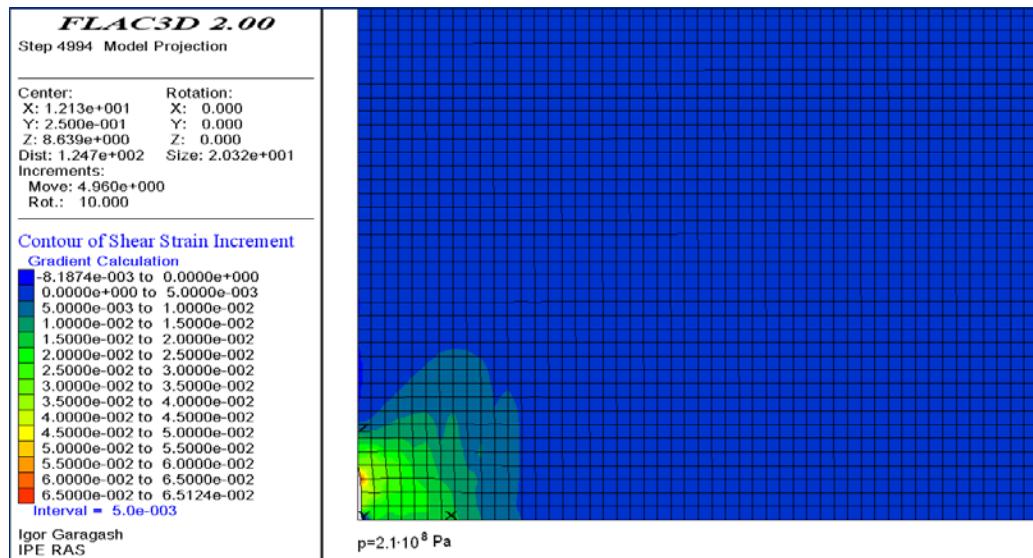
$$\psi_s = 24^\circ$$



$$p_h = 9 \cdot 10^7 \text{ Pa}$$

$$\psi_s = 24^\circ$$

Plastic strain intensity at the stop of hydrofracturing



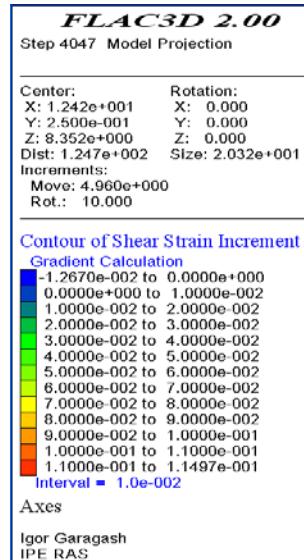
$$p_h = 21 \cdot 10^7 \text{ Pa}$$

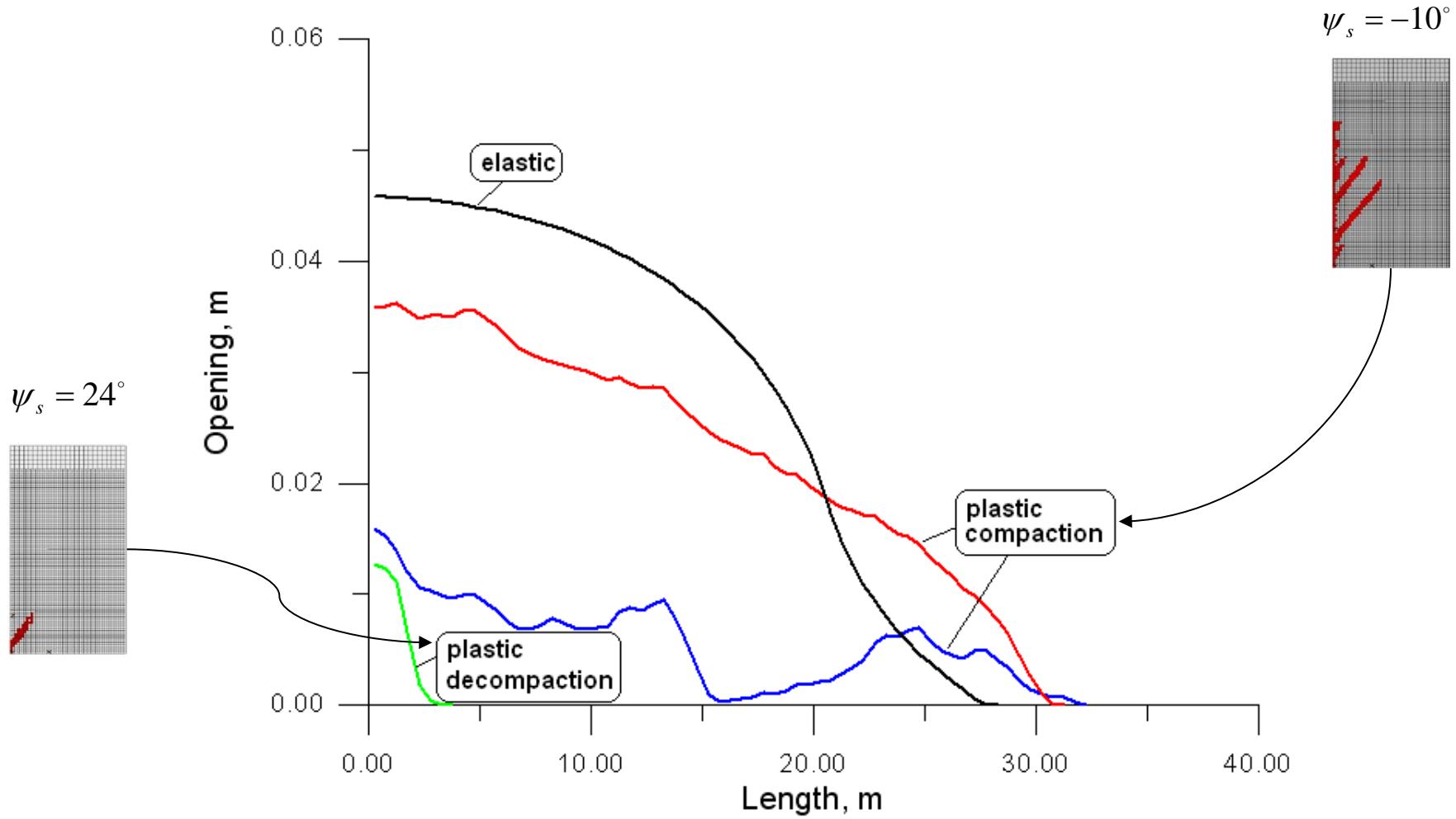
$$\psi_s = 24^\circ$$

Plastic strain intensity at the stop of hydrofracturing

$$p_h = 31 \cdot 10^7 \text{ Pa}$$

$$\psi_s = 24^\circ$$





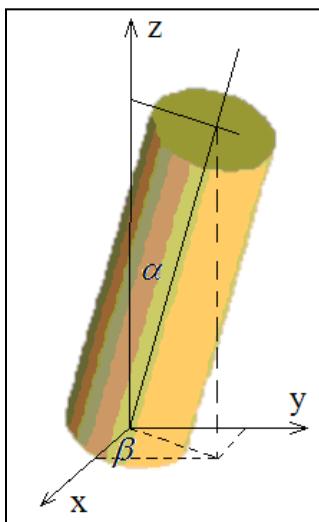
Hydrofracture openings at the stop after pressure drop
(blue line is opening of crack after three minutes of filtration)

We show from this preliminary work that hydraulic fracturing in soft rocks is accompanied by the localization of plastic deformations. Influence of the type of plastic volumetric variation (compaction or dilation) and the softening behavior results in essentially different pictures of deformation fields and pore pressure in the reservoir. The profiles of crack openings and, hence, work spent on their creation, are essentially different. In one case, the fracture cannot propagate in tension.

Further work, to confirm the role of localization in fracturing soft rocks and analyze in details the influence of input parameters (rock properties, including mesh size which is given the length scale, and in-situ stress), will include an improved fracture propagation criterion and the influence fluid leak-off during propagation. Removing the symmetry along the crack line is also necessary to get more realistic slip lines which are generally breaking the symmetry.

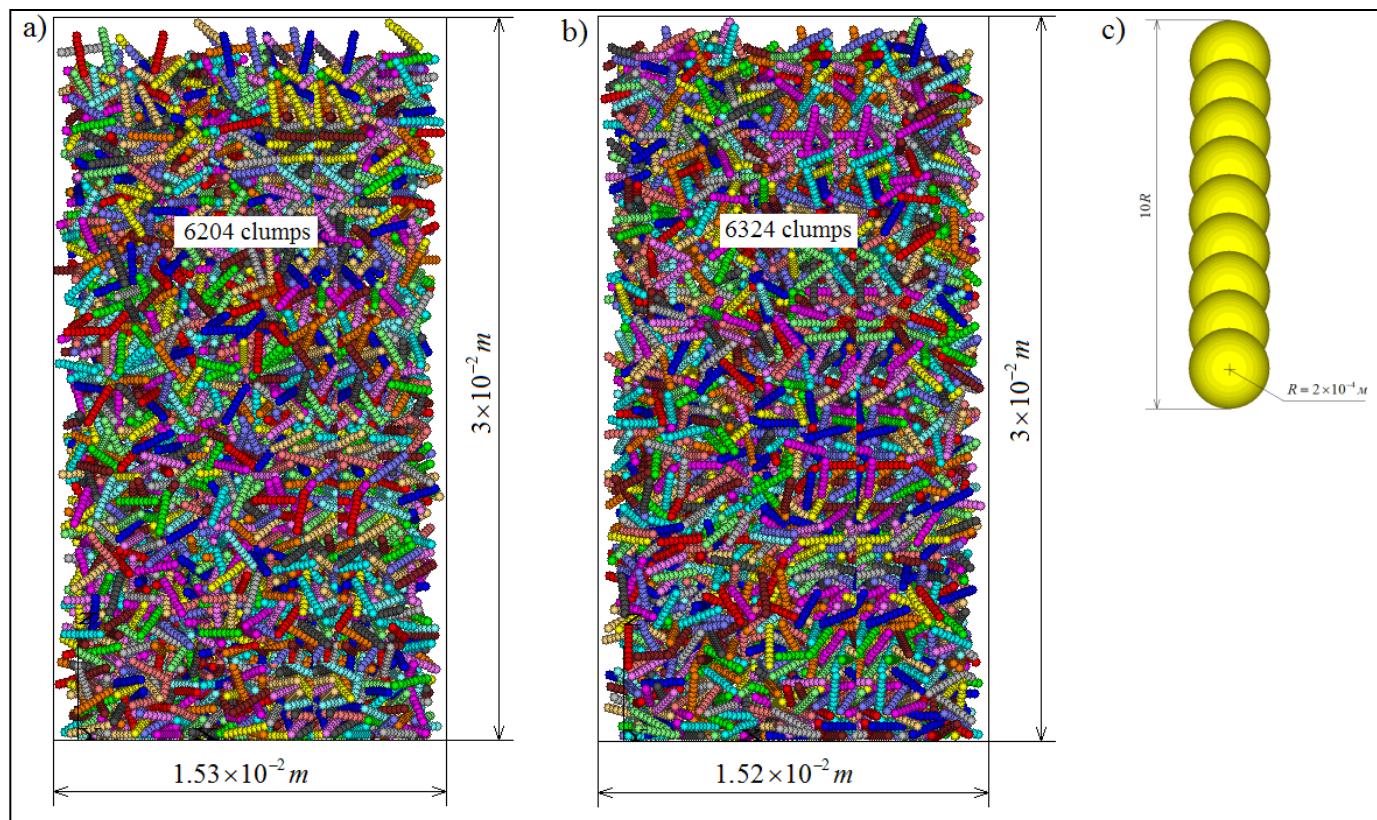
Particle Flow
Code in 3 Dimensions

Cylindrical particle



Initial porosity equal 0.8,
very loose material

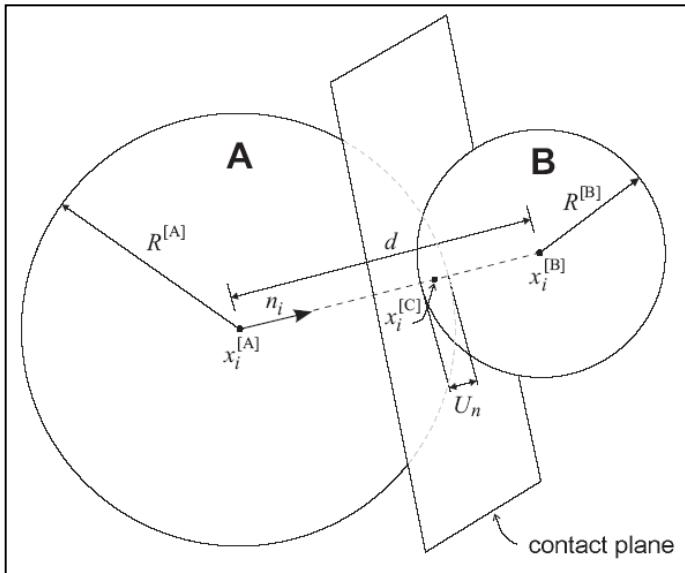
First (a) and second (b) initial ensembles of particles, (c) - analogue of cylindrical particle



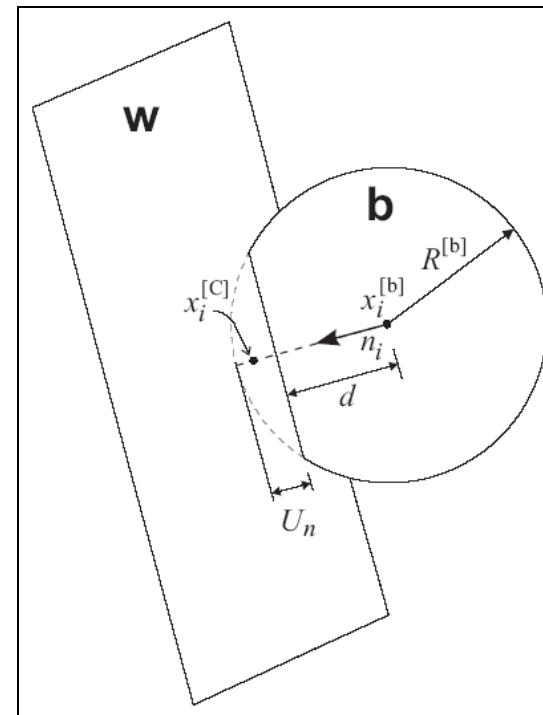
The length of the cylindrical particle is equal to its ten radii. For modeling of such ensembles we shall use the clump logic supports the creation of super-particles of arbitrary shape. Each clump consists of a set of overlapping spheres that acts as a rigid body with a deformable boundary.

rigid ball with a deformable boundary

Ball-ball contact



Wall-ball contact



Contact-Stiffness Models

$$P_n = K_n n_i U_n \quad K_n = \frac{k_n^{[A]} k_n^{[B]}}{k_n^{[A]} + k_n^{[B]}}$$

$$\Delta P_s = K_s \Delta U_s \quad K_s = \frac{k_s^{[A]} k_s^{[B]}}{k_s^{[A]} + k_s^{[B]}}$$

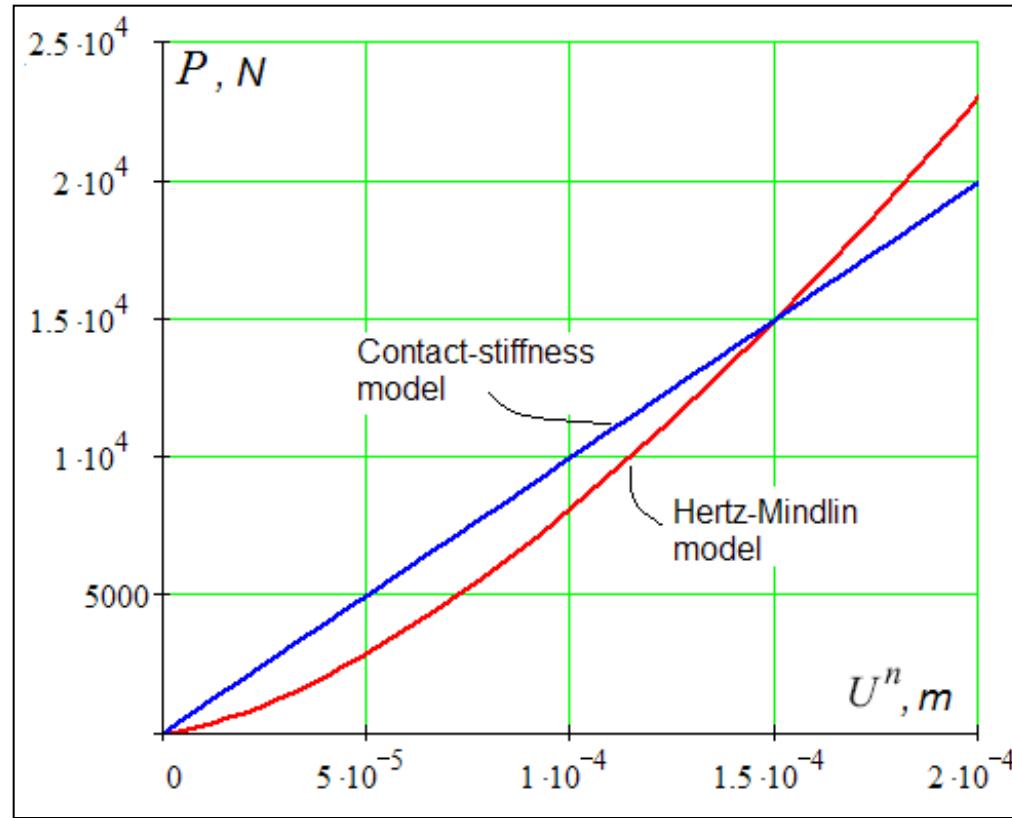
interaction of particles is linear

The Hertz-Mindlin Contact Model

$$P = U_n^{3/2} \frac{\sqrt{2}}{3} \frac{E}{1-\nu^2} \sqrt{R}$$

nonlinear law of interaction of the particles

- . Dependence of contact force from overlapping in case of Hertz-Mindlin model (a red line) and contact-stiffness model (a dark blue line)



Contact-Stiffness Models

Spheres stiffness

$$K_n^{ball} = 1 \cdot 10^8 N/m$$

$$K_s^{ball} = 1 \cdot 10^8 N/m$$

Wall stiffness

$$K_n^{wall} = 1 \cdot 10^8 N/m$$

$$K_s^{wall} = 0$$

The Hertz-Mindlin Contact Model

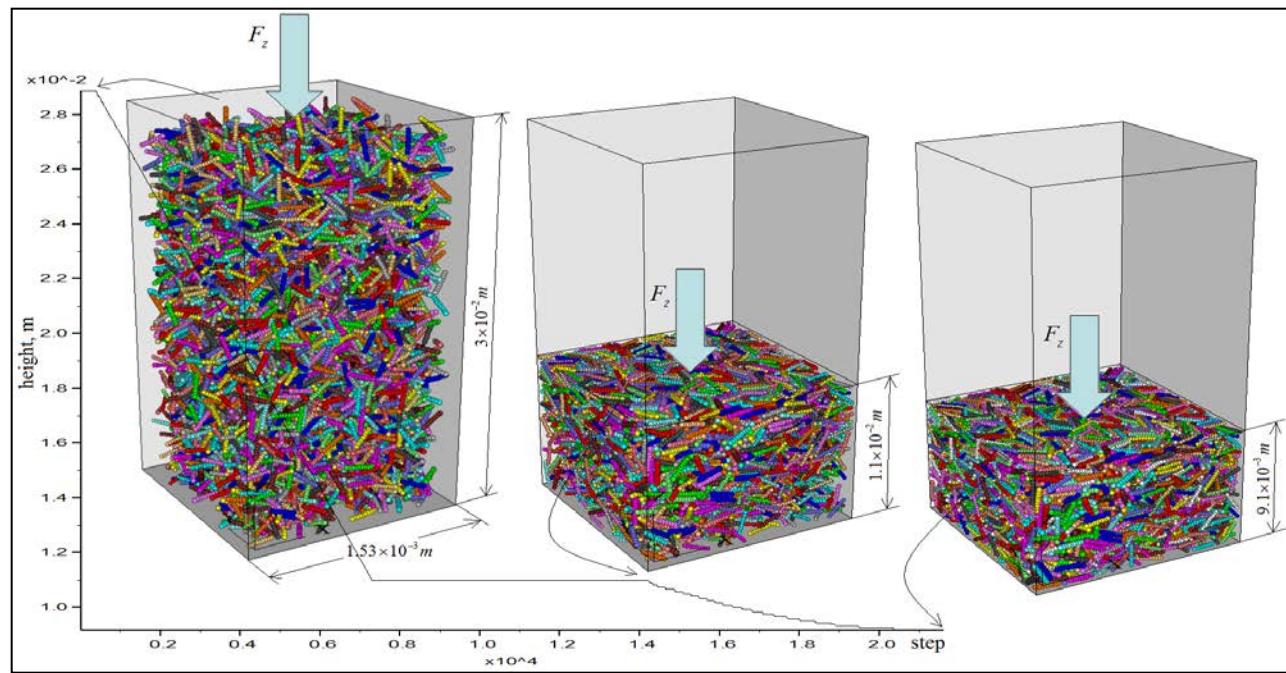
Spheres properties

$$G_{ball} = 4.6 \cdot 10^{11} Pa$$

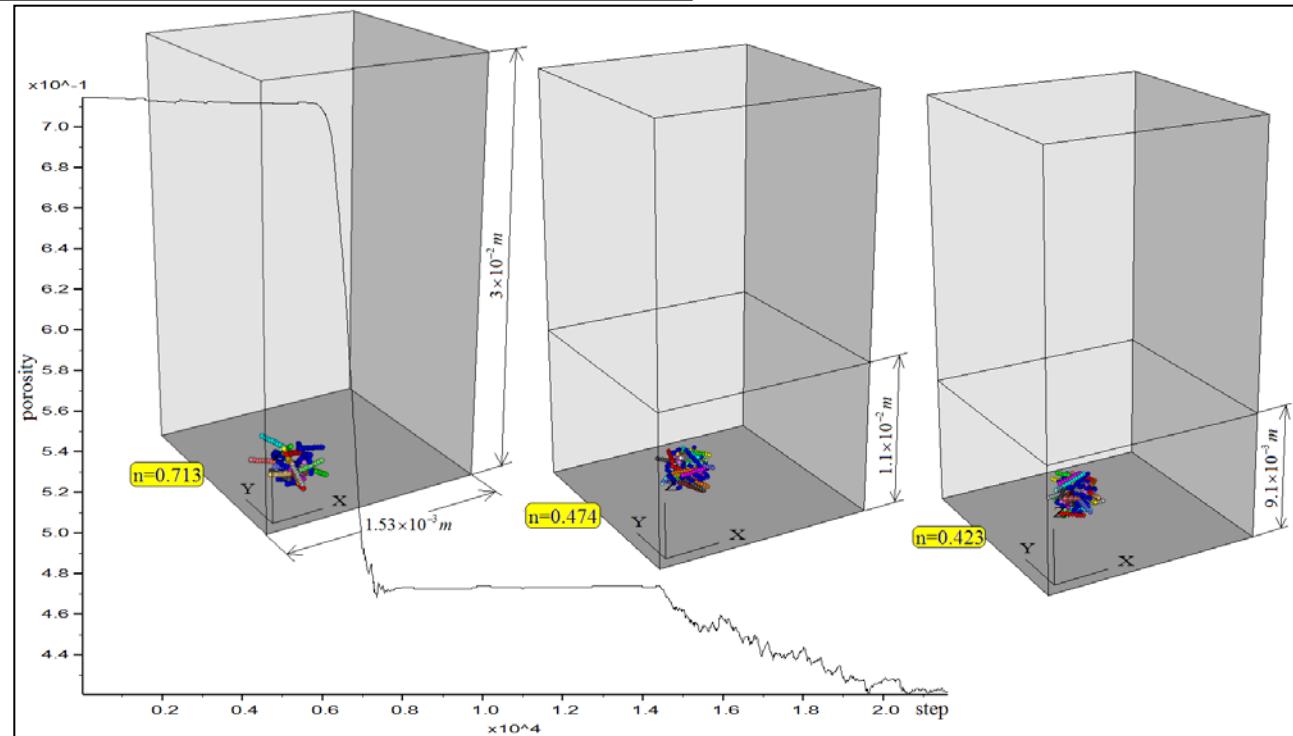
$$\nu_{ball} = 0.25$$

Loading is made by movement of the top wall. In the initial state the porosity of ensembles of particles n is closed to value 0.7. Therefore at first more dense ensembles of particles with density $n \approx 0.47$ are formed. Then the loading proceeds until the average vertical stress in samples will not reach the preset vertical value $\sigma_{zz} = -2.4 \cdot 10^7 \text{ Pa}$ that corresponds to depth about one kilometer.

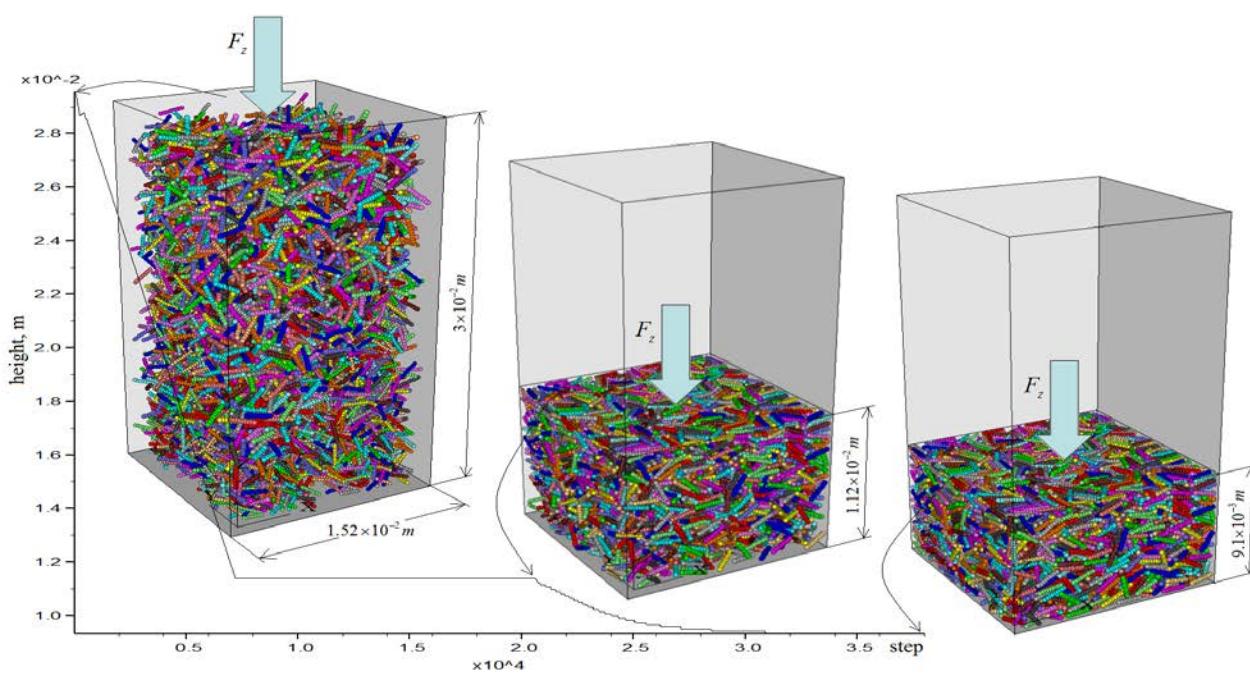
Loading process similar the compaction of particles in a rigid glass and also it is known under the name uniaxial compaction test.



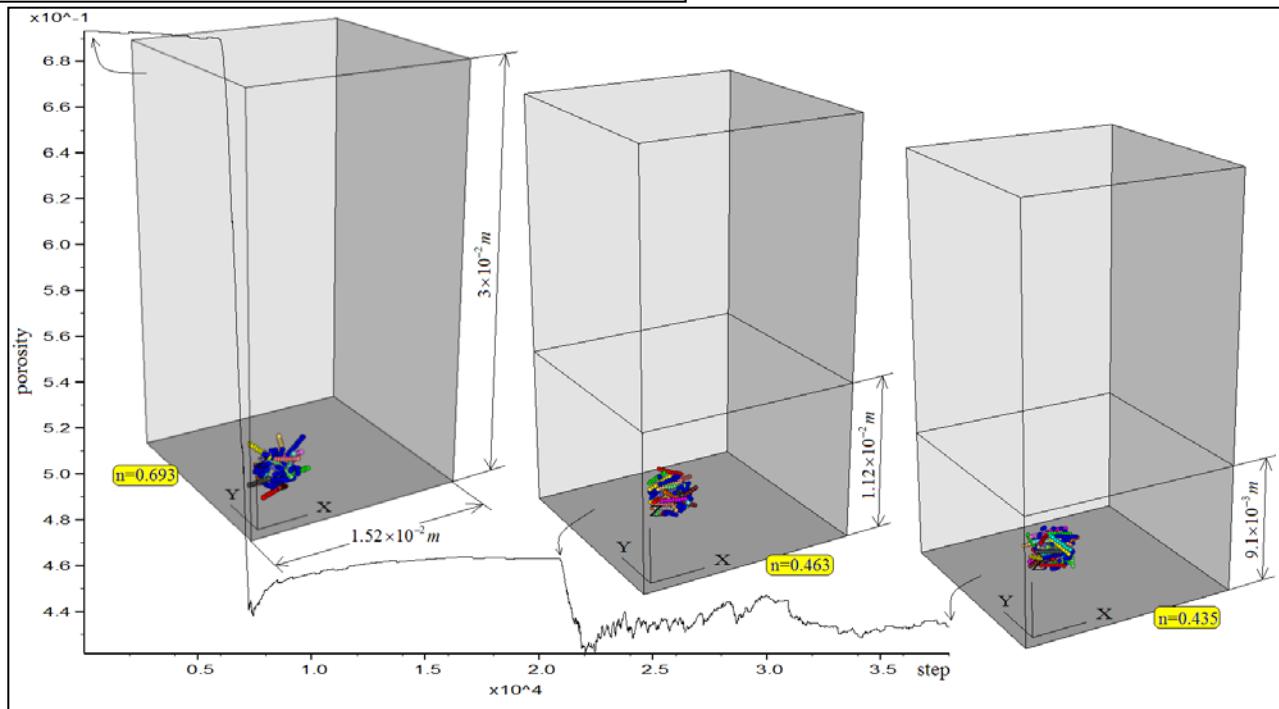
The graph of displacement of the upper wall during compaction of the 1-st ensemble of cylindrical particles.



Graph of porosity change inside of sphere volume during the compaction of the 1st particle ensemble

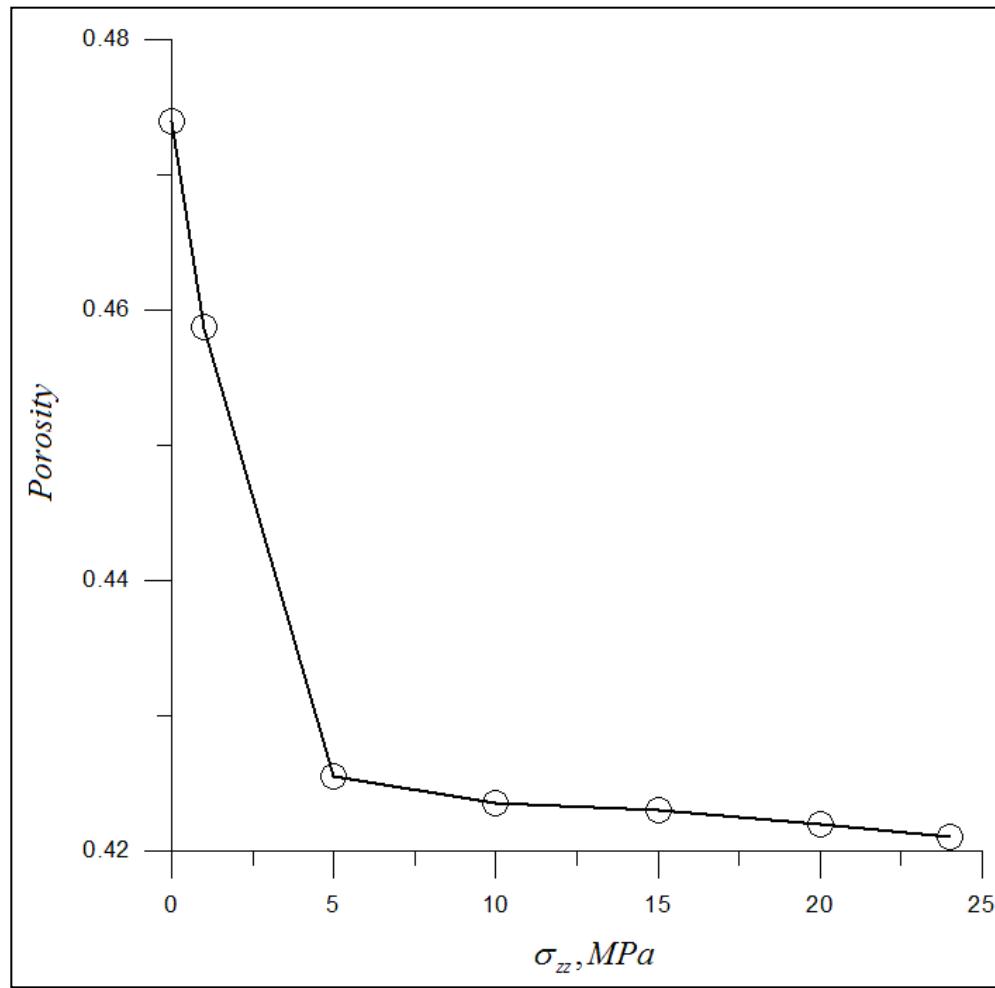


The graph of displacement of the upper wall during compaction of the 2nd ensemble of cylindrical particles.



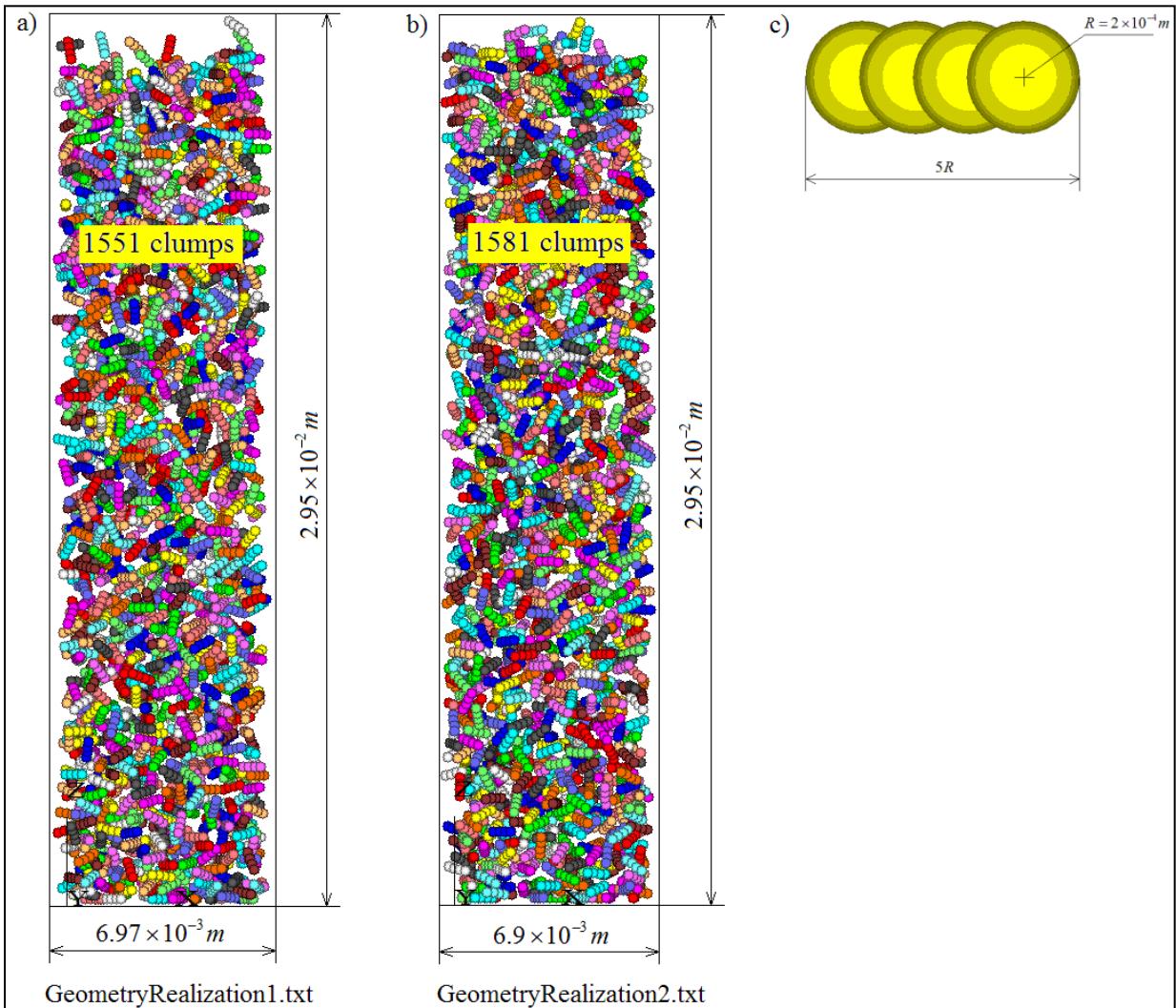
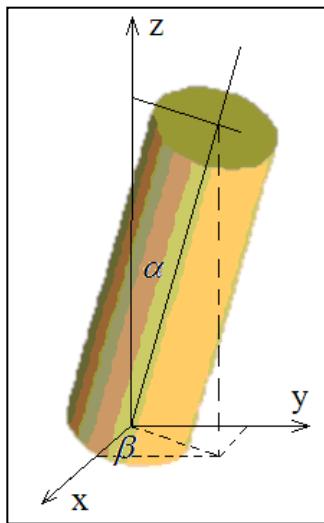
Graph of porosity change inside of sphere volume during the compaction of the 2nd particle ensemble

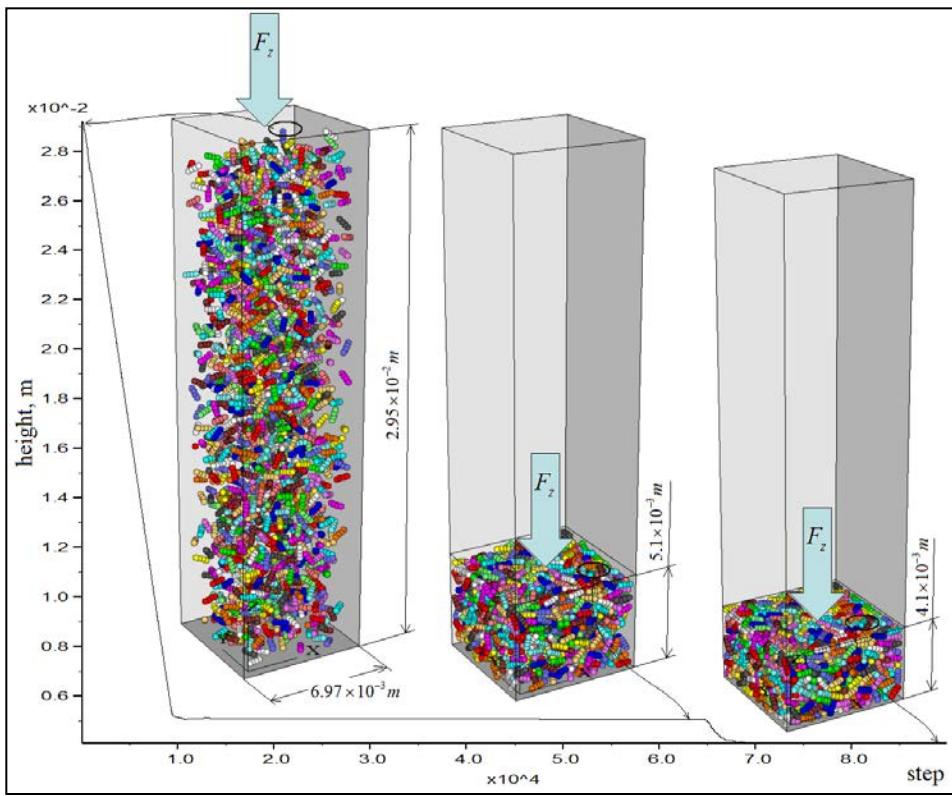
The graph of porosity versus vertical load



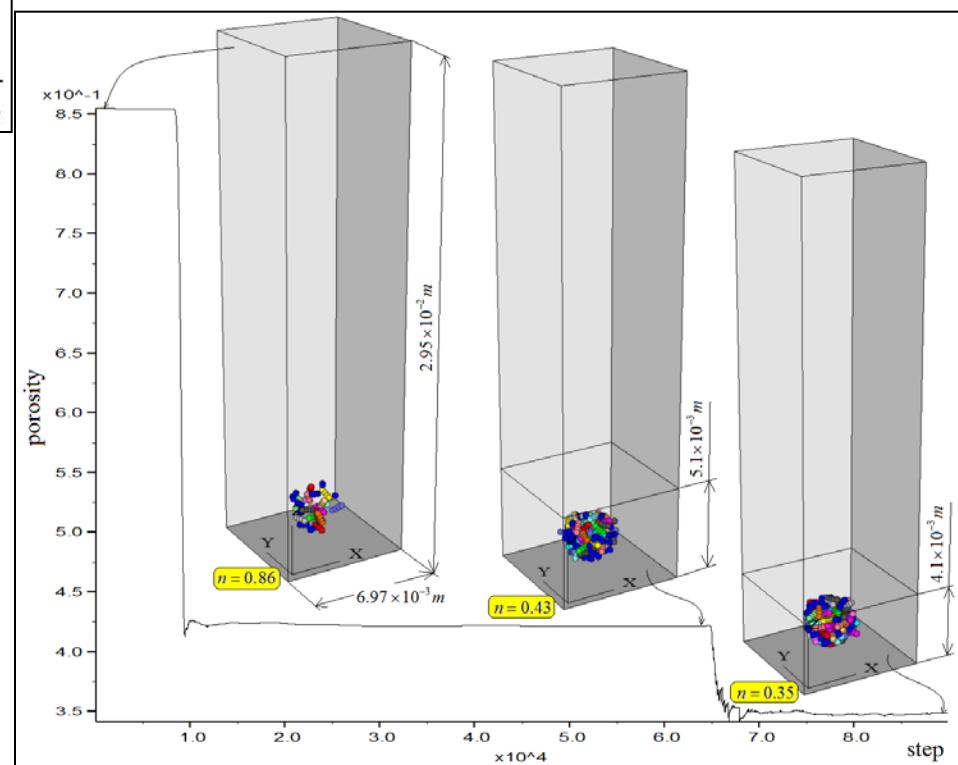
First (a) and second (b) initial ensembles of particles, (c) - analogue of cylindrical particle

Cylindrical particle

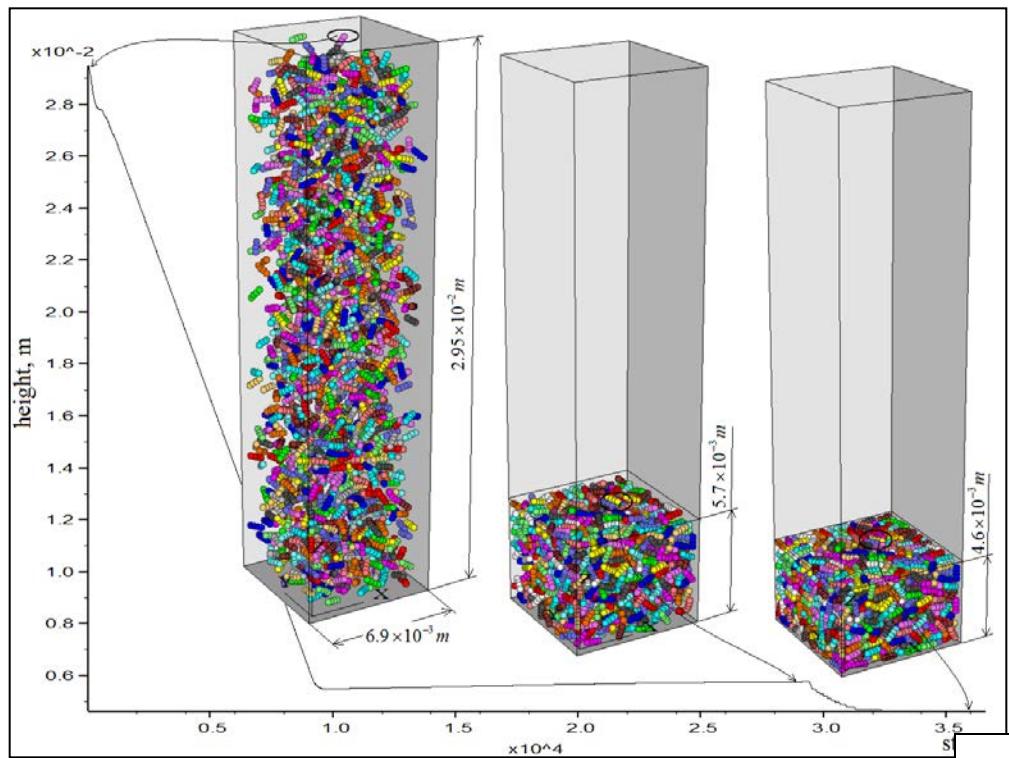




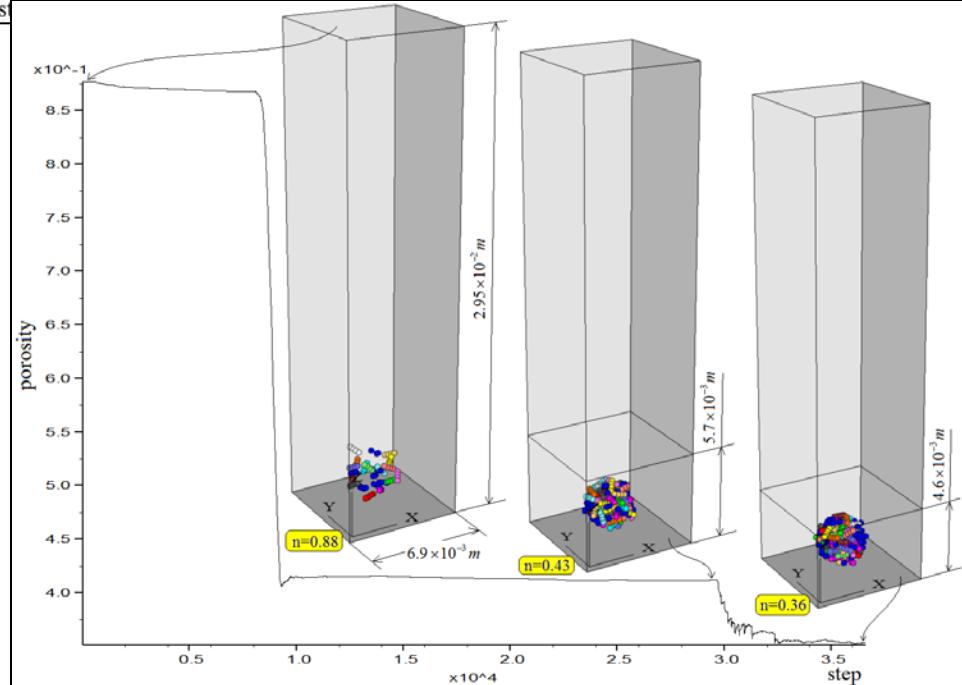
The graph of displacement of the upper wall during compaction of the 1st ensemble of cylindrical particles.



Graph of porosity change inside of sphere volume during the compaction of the 1st particle ensemble

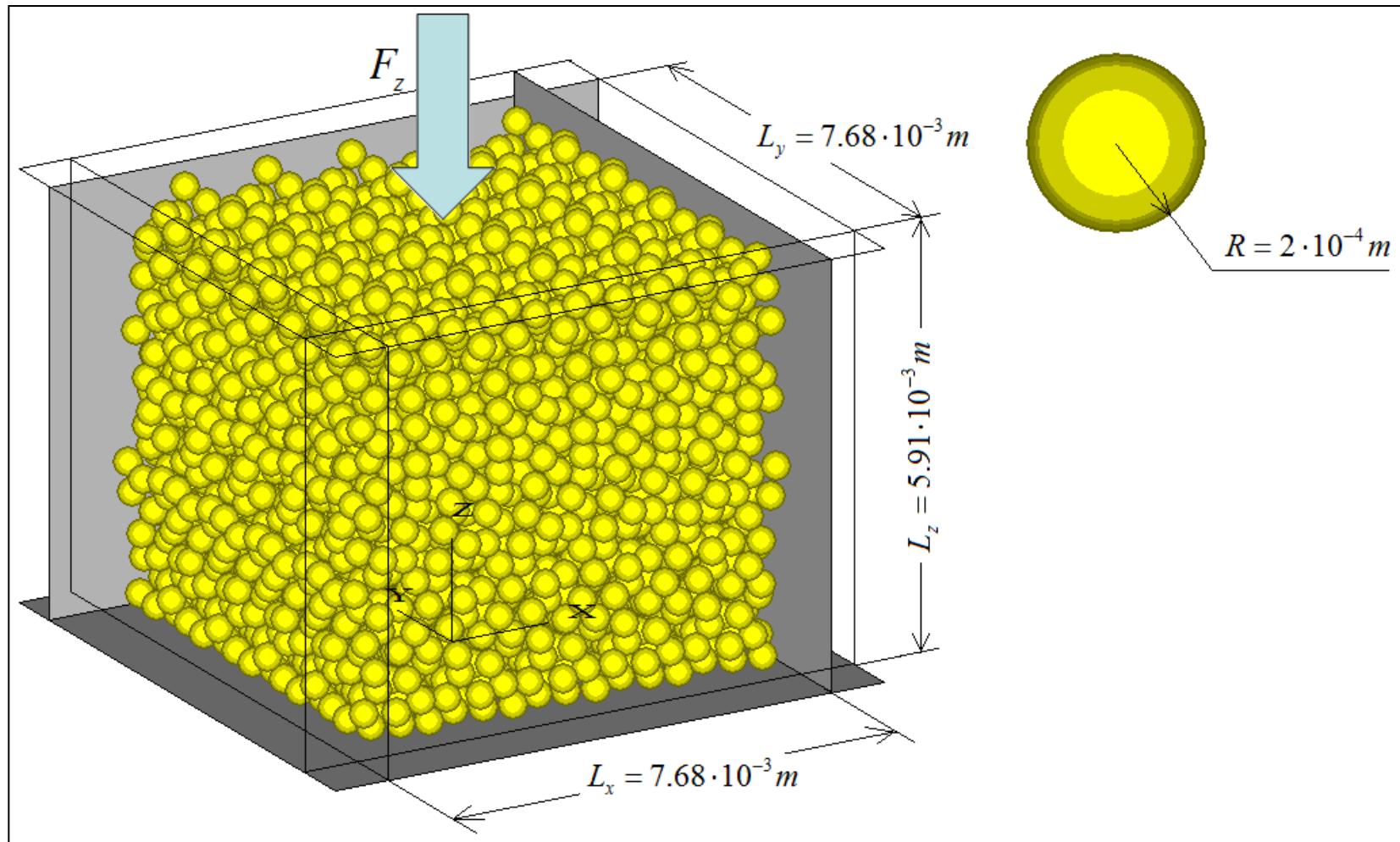


The graph of displacement of the upper wall during compaction of the 2nd ensemble of cylindrical particles.

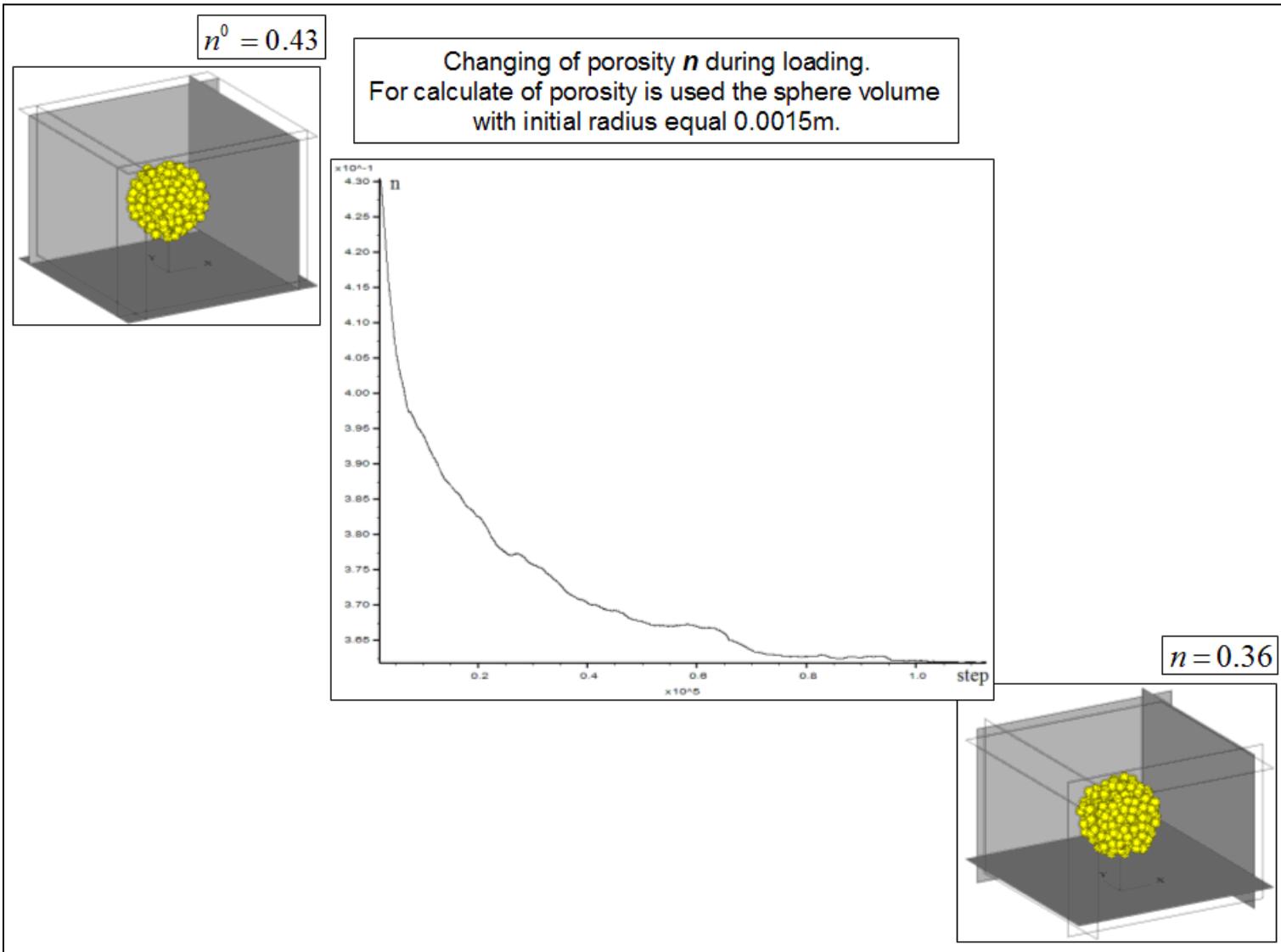


Graph of porosity change inside of sphere volume during the compaction of the 2nd particle ensemble

Ensemble of spherical particles

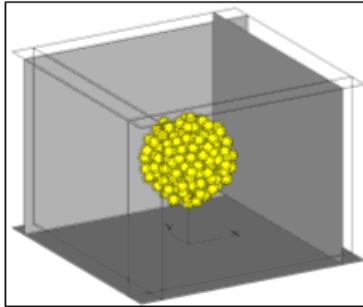


The graph of porosity changing in case of contact-stiffness model

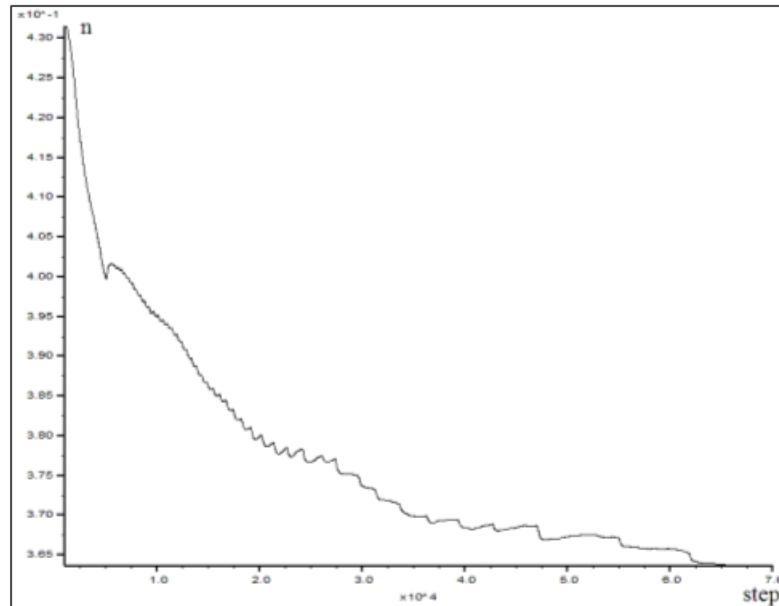


The graph of porosity changing in case of Hertz-Mindlin model

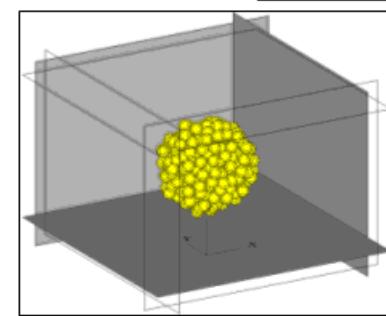
$$n^0 = 0.43$$



Changing of porosity n during loading.
For calculate of porosity is used the sphere volume
with initial radius equal 0.0015m.



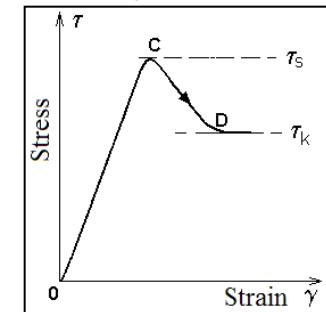
$$n = 0.36$$



In FLAC^{3D} realized an explicit calculation scheme. This ensure that the numerical modeling is stable when the physical system being modeled is unstable. In this case strain energy in the system is converted into kinetic energy, which then radiates away from the source and dissipates. FLAC models this process directly, because inertial terms are included - kinetic energy is generated and dissipated.

For each time step sequence of calculations can be represented as:

1. Calculation of new strains used the node velocities.
2. To calculate the new stresses used the strains and stresses in the previous moment of time used the constitutive relations.
3. To determine the new nodal velocities and displacements using the motion equations.



The calculation cycle

$$\sigma_{ij,j} + M_i = \rho \frac{\partial^2 u_i}{\partial t^2}$$

