FINAL REPORT
Decebmer 21, 2015 Weimar Germany
HYDROFRAC

Summary

The project was carried out from July 1, 2014 and was requested terminate on November 30, 2015. During the 17-months course of the project, most of the objectives have been achieved as planned in the proposal while certain task remains to be accomplished. This report will summarise the works that have been carried out successfully and also refer to the part of the tasks which were originally planned but will remain for the future development with the scientist. The deliverable that occurred during the project as the outcome of the research is also listed in a file that is attached to this final report.

1 Work Progress and Achievements

1.1 A summary of progress towards objectives and details for each task

The main objectives of this project were to

1. develop of a fully 3D computational multiphysics framework to gain better understanding of the HF process and
2. to apply this framework to a specific shale to shed light on the following issues:
   a. The resulting wellbore pressure variation due to the fracture network evolution, for a given injection flow rate and geostructural model.
   b. The effect/interaction of an existing fracture network due to a previous stage of HF treatment on the fracture network evolution in succeeding, adjacent stages.
   c. The possibility of the fracture network encroaching into adjacent layers of rock.
   d. The interaction of fractures with existing natural faults that intersect the shale seam.
   e. Determination of key input parameters (material parameters, boundary conditions, etc.) for a certain output (e.g. pressure drop).

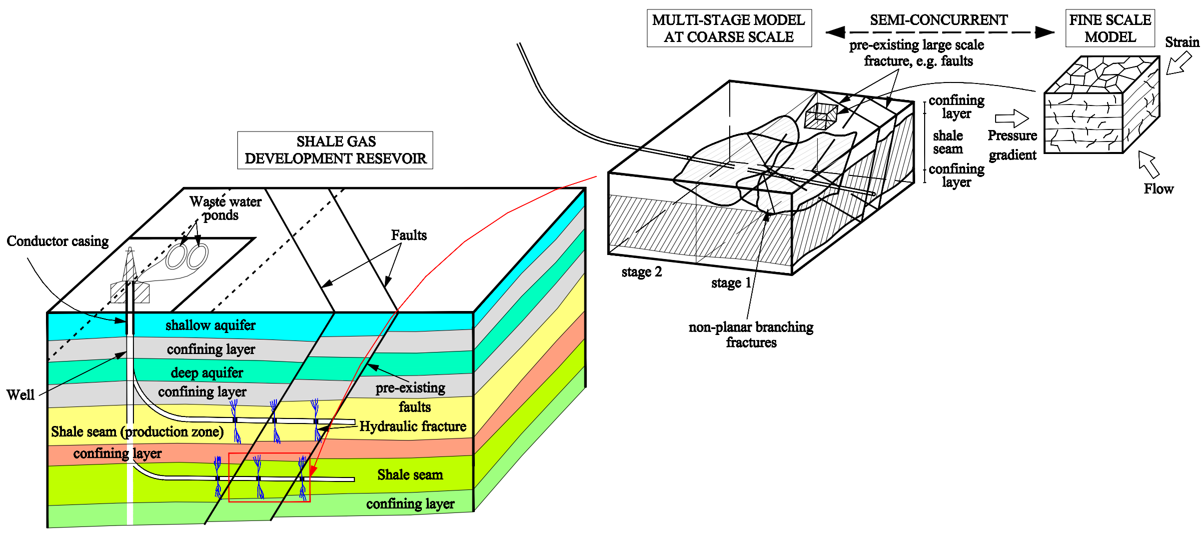


Figure 1: Multiscale framework for 3D simulation of hydraulic fracturing in naturally fractured reservoirs

In the first part of the project, we developed a fully computational multiphysics framework in *two dimensions*. This framework has been verified and tested and will be described in more detail below. It followed basically the steps as outlined in the research proposal and an extension of this method to 3D is currently in progress. Furthermore, the first manuscript which will contain the results as outlined below is currently in preparation and will be submitted to an international SCI journal soon. There have been some changes in the implementation of the workplan due to the pregnancy of the Marie-Curie fellow as reported to the project officer. The baby of the Marie-Curie fellow was born on December 20, 2014 and in agreement with the project officer, the project has been suspended for two months. Note that according to German regulations, a woman is not allowed to work for two months after giving birth to her baby. Besides, excellent progress towards the final research objectives have been achieved so far. For the two-dimensional case, the MC-fellow already developed and implemented

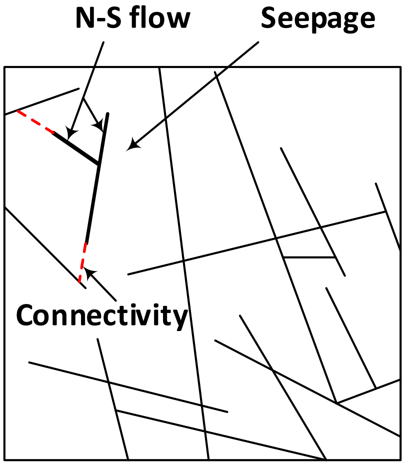
1. the coarse-scale model for fluid flow in fractured porous media.

2. the fine scale model, which is similar to the coarse-scale but contains more detailed features.

1.1.1 Coarse-scale Model for fluid flow in fractured porous media

The developed coarse scale model is in essence a combination of a porous media model with fluid flow through evolving fracture patterns. It consists of the following three ingredients:

- Model for the solid in the bulk as porous media using Biot's type model.
- Fracture model that consists of a fracture criterion and a method to describe the fractures and their evolution. In our approach, the extended finite element method (XFEM) has been exploited for this purpose.
- Model for fluid transportation which includes the seepage and channel flow through a discrete evolving 3D fracture network.



NS-GD model

Figure 2: Model for flow through fractured porous media

The model in the bulk is based on the mechanics of unsaturated porous media. The stress relation is based on modified effective stress, $\boldsymbol{\sigma}' = \boldsymbol{\sigma} + \alpha \mathbf{m} p$, where $\boldsymbol{\sigma}'$ is the effective stress, $\boldsymbol{\sigma}$ is the total stress, and p is the mean pore pressure applied to the solid skeleton applied by the fluids (i.e. the water) and $\mathbf{m}$ is an identity vector. The capillary pressure has been considered in our unsaturated porous media model. It arises from the difference between the wetting phase (such as water) and non-wetting phase (such as oil or gas), $p_c = p_g - p_w$ where p_c denotes the capillary pressure, p_w and p_g denote the pore pressure resulting from water and gas, respectively.

At the beginning of the project, it was not clear if such a model is needed since for tight oil/gas reservoir there are controversial points of view at present regarding the need of a liquid phase in the pores (not the fractures). Theoretical models for tight shale have been developed in [1] to include two-phase flow in the porous matrix. On the other hand, experimental studies on nano- to micro-scale imaging of shale and mercury porosimeter analysis show that **80%** of the pores have sizes less than 5 nanometers[2]. Owing to the high porosity and the gas slippage effect, the gas permeability in organic matter is significantly higher than that in the nonorganic matrix. The organic matter holding gas is oil wet, and associated pores work as nanofilters for hydrocarbon flow, suggesting that fluid flow in organic matter is predominantly single phase, and only gas flow needs to be considered [3]. The same conclusion of single phase flow in matrix is supported by [4]. The influence of the liquid phase on a specific output of interest, e.g. fracture density, will be quantified late in this project. We used a phenomenological curve of capillary pressure with dependency on the saturation $p_c(S)$ based on experimental calibration.

The constitutive behaviour of the solid phase has been based on effective stress, i.e. $\mathrm{d}\boldsymbol{\sigma}' = \mathbf{C}^{\tan}\mathrm{d}\boldsymbol{\varepsilon}$, $\mathbf{C}^{\tan}$ being the consistent tangent stiffness matrix of the solid skeleton. We have implemented a nonlinear poro-elast damage model which consists of three stages: 1. linear elastic (transverse isotropic) response, 2. the evolution of "micro"-cracks and 3. the formation of "macro"-cracks. The material loses stability before the third stage which requires regularization techniques. Note that the macro-cracks and the associated discrete fluid flow has been modeled with XFEM in our project.

The "micro"-crack dependent permeability of the porous media has been modeled by a phenomenological model so far. The evolution of the permeability $\mathbf{K}$ has therefore been expressed as a function of the pore volume ratio ϕ, i.e. $\mathbf{K}(\phi) = K_0 + \mathbf{K}_{\mathrm{mc}}(\phi)$; K_0 is the initial permeability[1]. The porosity $\phi = \phi(\mathbf{D})$ accounts

[1]Note that permeability of intact shale is $K_0 = 10^{-13}$–10^{-9}m/s.

for the increase of the permeability due to the "micro"-crack evolution in terms of an anisotropic damage tensor $\mathbf{D}$. In the future, a multiscale approach should be used for extracting the permeability depending on the damage state of the next smaller length scale.

Fracture is modelled by the extended finite element method. Three types of "fractures" (discontinuities) in the geostructural model are currently considered:

- The main body of layered rock formations describing the geometry of strata formation, Fig. 1.
- The major discontinuities such as faults cutting through layers, Fig. 1.
- The evolving fracture network due to HF.

We aligned the discretization to the boundaries of the rock layers and model only the evolving fractures as well as existing coarse-scale (fracture-related) features such as faults with the extended finite element method (XFEM) [5]. For the discretisation of the (solid) displacement field, only a Heaviside-enrichment (no crack front enrichment)has been used:

$$\mathbf{u}^h(\mathbf{X}) = \sum_{I \in \mathcal{S}} N_I(\mathbf{X})\mathbf{u}_I + \sum_{K=1}^{M} \sum_{I \in \mathcal{S}_c} N_I(\mathbf{X}) H_I^M(f(\mathbf{X}))\mathbf{a}_I^M \tag{1}$$

$\mathcal{S}$ being the set of all nodes in the discretisation, $\mathcal{S}_c$ are the set of nodes influenced by the crack, $\mathbf{u}^h(\mathbf{X})$ is the displacement field and $\mathbf{u}_I$ and $\mathbf{a}_I$ are degrees of freedom for displacement and jump term coefficient; $N_I(\mathbf{X})$ are the finite element shape functions, M the number of cracks that influence node I, $H_I(f(\mathbf{X})) = H(f(\mathbf{X})) - H(f(\mathbf{X}_I))$ is the shifted Heaviside step function and $f(\mathbf{X})$ is a level set function that can be used to implicitly describe the crack topology. Omitting the crack front enrichment tremendously facilitates the implementation (simpler integration strategies, better conditioning, no special treatment of blending elements, etc.). The capillary pressure p_c has been enriched to capture a local pressure increase in the vicinity of the crack

$$p_c = \bar{p}_c + \hat{p}_c = \sum_{I \in \mathcal{S}} N_I(\mathbf{X})\bar{p}_{cI} + \sum_{K=1}^{M} \sum_{I \in \mathcal{S}_c} N_I(\mathbf{X})\psi_I^M(\mathbf{X})\hat{p}_{cI}^M \;, \tag{2}$$

$\bar{p}_c$ being the capillary pressure of matrix, $\hat{p}_c$ denotes the pressure change due to the crack and $\psi_I^M(\mathbf{X})$ is a nonlinear decaying distance function derived from analytical solution of consolidation problem.

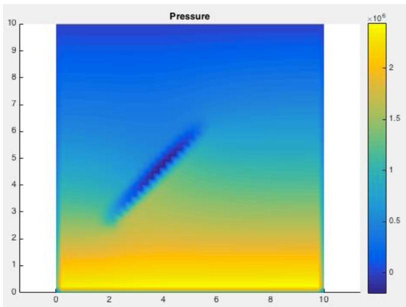


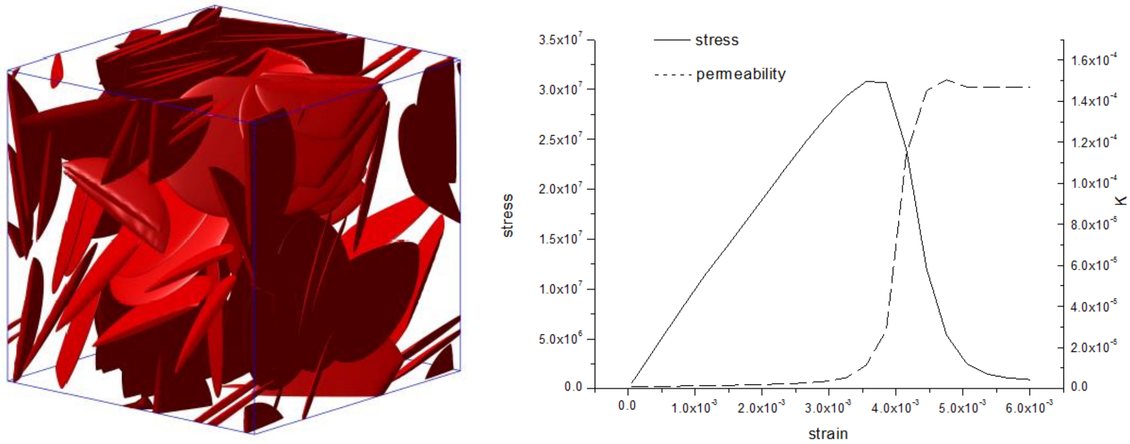
Figure 3: Pressure distribution in the coarse-scale

The model for fluid flow through fractured porous media consists of the solution of the Navier-Stokes equation and generalized Darcy's law (NS-GS). The concept of this approach is depicted in Fig. 2. The NS-GS model solves the Navier-Stokes equation and continuity equation for the flow through explicit fractures combined with seepage through matrix using Darcy's model. The mechanical coupling is enforced by the continuity of the traction applied to the bulk matrix and the fluid pressure in between the cracks. The mass balance is coupled by the continuity of the flow in tangential direction to the crack and a difference term normal to the crack depending on the pressure gradient. The fluid is assumed to be a Newtonian fluid model.

First results of our coarse-scale model are shown in Figure 3 which illustrates the pressure distribution for a fluid-driven crack.

1.1.2 Fine scale model

In order to better understand the role played by small-scale fractures in the overall crack propagation, we proposed to introduce another fine-scale model wherein all fine-scale fractures are modelled as discrete (or smeared) cracks. The information of the fine-scale will be passed to the coarse scale. Note that our fine-scale model is already fully three-dimensional as fluid flow through the crack surfaces are not to be modelled explicitly as described in the proposal. One key challenge is the design of the RVE structure. The fine scale model includes porous structures of shale and constituent materials. Note that the fine scale structure is case specific for a given reservoir geology and rock composition. Stochastic micro-cracks and pores have been inserted at the fine scale model. A probability weighted moments (PWMs) based



(a) Fine-scale model with small fractures (b) Upscaled sress-strain and permeability-strain curve

Figure 4: Fine-scale model and upscaled stress-strain and permeability-strain curve

on Maximum Entropy quantile functions and L-moment has been used to generate the fractures as also pointed out in the proposal. A typical fine-scale structure is shown in Figure 4a. We were able to extract the permeability by a semi-concurrent multiscale approach (FE^2) as outlined in the proposal. Figure 4b shows the upscaled stress-strain and the associated permeability-strain curve. An increased permeability is observed once the stress drops which is also observed experimentally. In other words: The drop in stress is equivalent in an increased damage which is in turn related to cracking. Hence the permeability increases. This feature is a natural outcome of the upscaling procedure and no empirical model is needed. Note that we have also implemented such an empirical model in our coarse-scale model as discussed in our proposal. Contour plots of the damage, velocity and pressure field at the end of the simulation are illustrated in Figure 7. The micro-cracks, i.e. the micro-damage, can be clearly seen in the figure. Also the relation associated higher velocity inside the cracks is well captured.

More studies are now conducted for a sensitivity analysis. Subsequently, a manuscript about the semi-concurrent multiscale approach will be prepared and submitted.

1.1.3 Periodic random packing of ellipsoids for fine-scale model generation

To improve the efficiency and physical meaning of fine-scale mode, a molecular dynamics based method is applied to generate the periodic random packing of ellipsoids. It is known that the shapes of the inclusions in the micro-structure are various. In this case, the ellipsoids with variable aspect ratios can describe a wide range of shapes. It is impractical to describe the shape precisely for all the part the material while taking care of the computation efficiency. Therefore a stochastic method needs to be implemented in fine-scale model generation. On the other hand, the fines-scale model should be able to capture a wide range of porosity of rock. The algorithms based growing and moving ellipsoids are devised which can be used to accomplish the aforementioned goal. The flow chart of the algorithms is shown in Fig. 6.

The work has been completed which can generate high porosity model as shown in Fig. **??**.

1.2 A summary of the progress of the researcher training activities/transfer of knowledge activities/integration activities

Before the start of her Marie-Curie fellowship, Dr. Zhuang has been involved in training events of the host institution, in particular as lecturer in the ITN-INSIST which is coordinated in Weimar (transfer of knowledge). This gave her already an excellent opportunity to get familiar with the host institute. She has been fully integrated even before the start of the project.

Furthermore, she attended all weekly group seminars. The Marie-Curie fellow also attended a German language course from April 2015 to end of July 2015. Originally, this course was intended at the beginning of the project. However, due to the pregnancy of Dr. Zhuang, she decided to first focus on the project and attend the language course at a later stage. Due to her pregnancy, the completion of her manuscripts have been delayed. Besides the excellent progress, she was not able to write up her results yet. The first manuscript is currently in preparation and the second manuscript will follow subsequently.

As also mentioned in the proposal, Dr. Zhuang intended to establish her future career in Europe. When this substantially happens, the transfer of knowledge is a direct investment in ERA. In fact, Dr. Zhuang was successful in obtaining an offer as research group leader in a prestigious Computational Mechanics Group at the Leibniz University in Hannover. This will guarantee a long-term future in Germany.On the other hand due to this new appointment, she has to terminate the project at the end of November. An early termination application has been submitted.

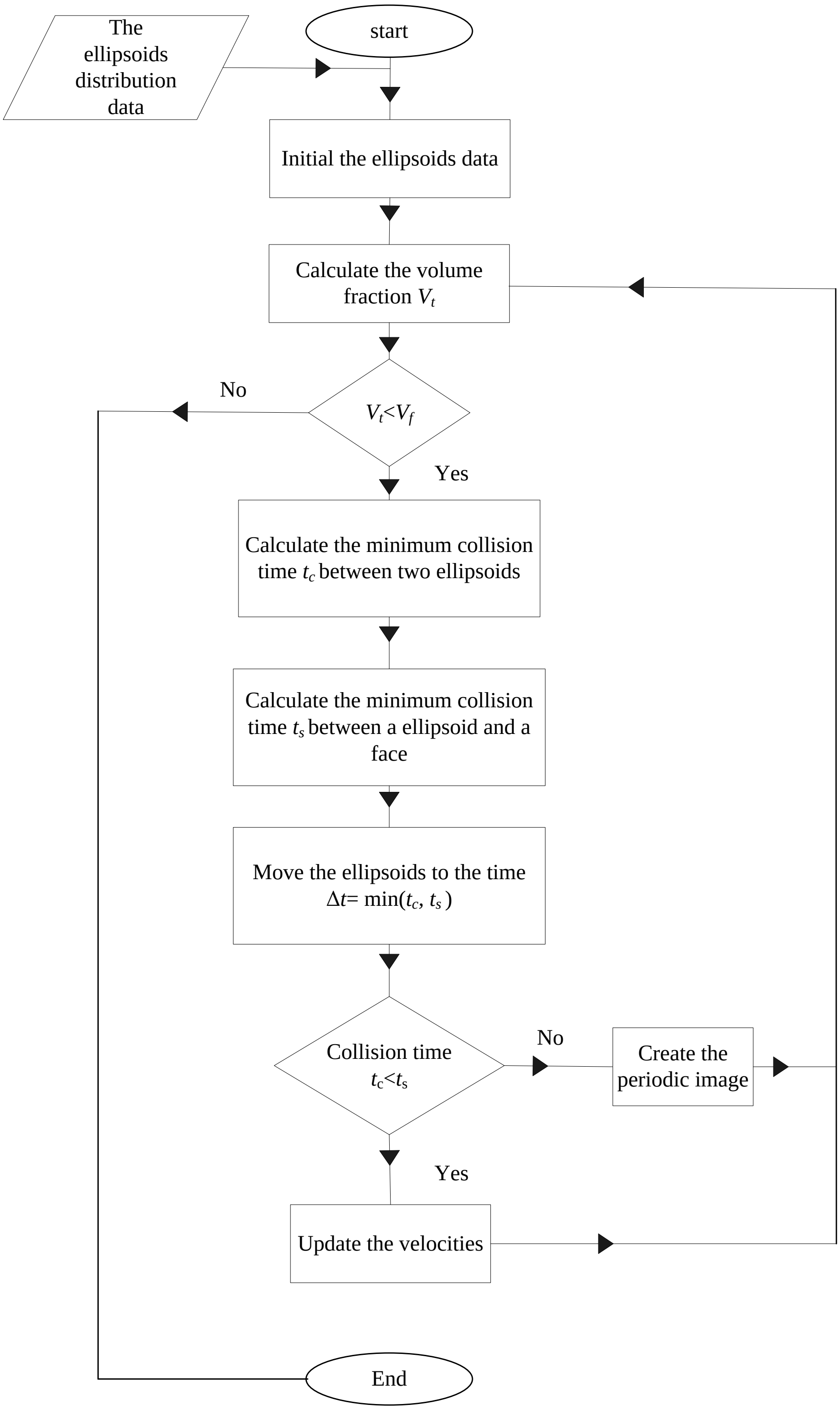


Figure 5: Flowchart of generation of the periodic random packing of ellipsoids

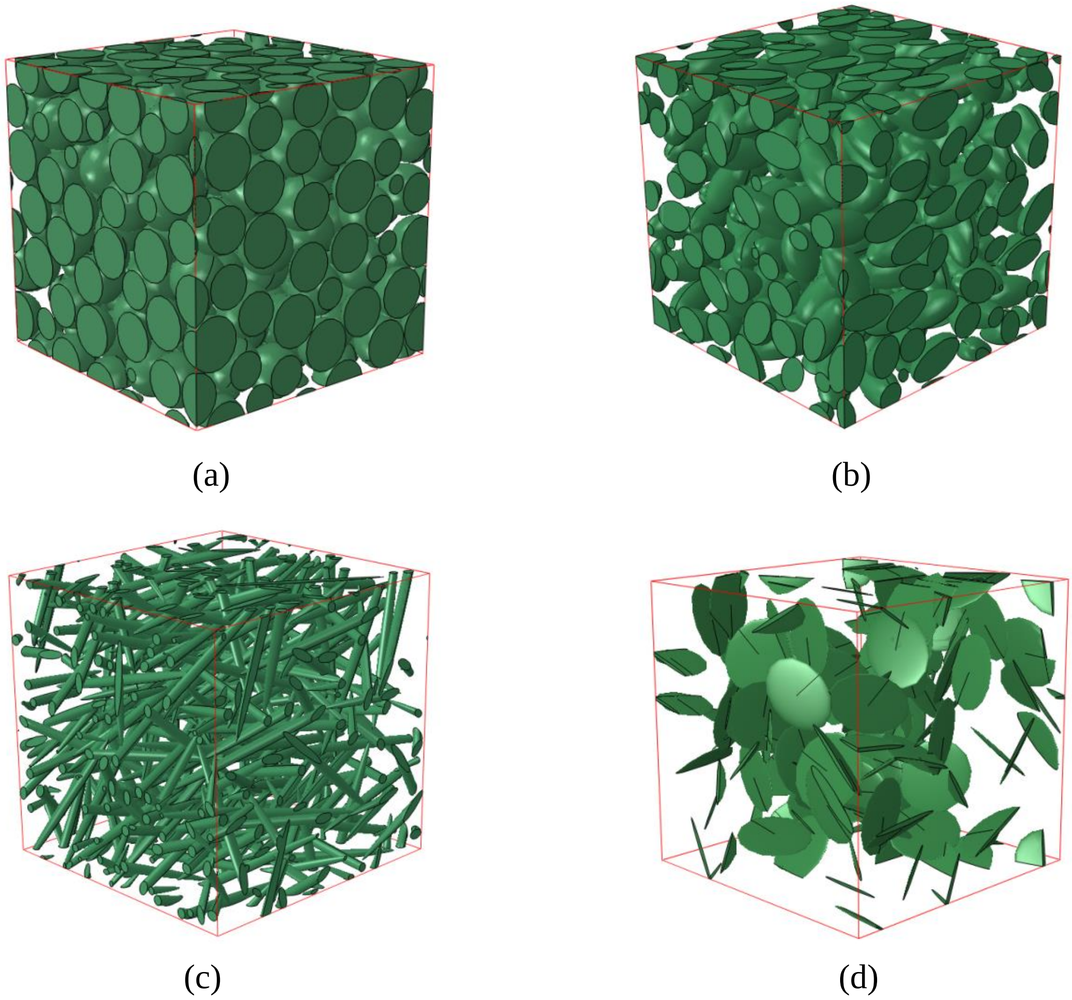
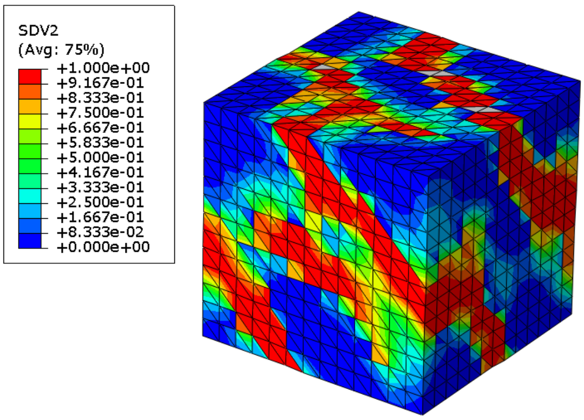
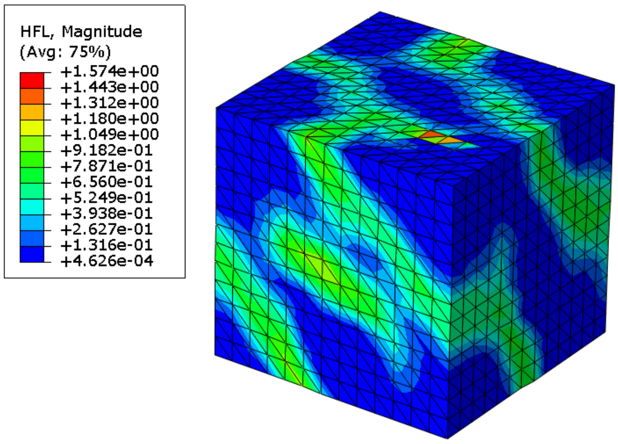


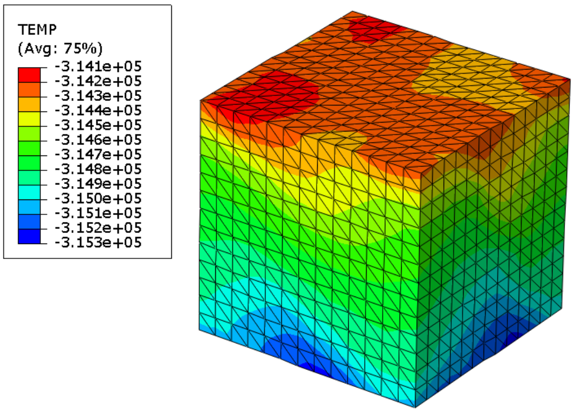
Figure 6: RVE samples of different aspect ratio and volume volume fraction. $(a)R1 = R2 = 1, N = 200, V_f = 60\%; (b)R_1 = R_2 = 200, N = 200, V_f = 40\%; (c)R_1 = R_2 = 20, N = 200, V_f = 10\%; (d)R_1 = R_2 = 1/20mN = 100, V_f = 50\%$



(a) Damage



(b) Velocity



(c) Pressure

Figure 7: Contour plots at the fine scale

References

[1] Y-S Wu, J Li, D Ding, C Wang, and Y Di. A generalized framework model for the simulation of gas production in unconventional gas reservoirs. *SPE Journal*, page artile ID: 163609, 2014.

[2] E Ozkan. Releasing shale-gas potential with fractured horizontal wells. In *SPE Distinguished Lecture Program, Colorado School of Mines*, 2011. URL `www.spe.org/dl`.

[3] FP Wang and RM Reed. Pore networks and fluid flow in gas shales. *SPE Journal*, page article ID: 124253, 2009.

[4] RJ Ambrose, RC Hartman, M Diaz-Campos, IY Akkutlu, and CH Sondergeld. New pore-scale considerations for shale gas in place calculations. *SPE Jouanl*, 2010:131772, 2010.

[5] N Möes, J Dolbow, and T Belytschko. A finite element method for crack growth without remeshing. *International Journal for Numerical Methods in Engineering*, 46:131–150, 1999.