MODELING OF HYDRAULIC FRACTURING ON THE BASIS OF THE PARTICLE METHOD

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Abstract. A technique of calculating the deformation of the soil environment when it interacts with a liquid on the basis of the particle method is realized. To describe the behavior of the solid and liquid phases of the soil, a classical two-parameter Lennard-Jones interaction potential and its modified version proposed by the authors were chosen. The model problem of deformation and partial destruction of a soil massif under strong pressure from the liquid pumped into it is solved. Analysis of the results shows that the use of the modified Lennard-Jones potential for describing the solid phase of the soil environment makes it possible to describe the process of formation of cracks in the soil during hydraulic fracturing of the formation.

1. Introduction

One of the two basic technologies for the production of shale gas is the technology of hydraulic fracturing. Hydraulic fracturing of a formation is a process that involves the introduction of a mixture of water, sand and chemicals into the gas-bearing rocks under extremely high pressure (500-1500 atm). However, during hydraulic fracturing of the formation, consequences arise which pose a greater threat to the environment. There is a contamination of groundwater chemical reagents. There are destructive processes in the soil and even up to seismic activity. It is also worth mentioning the contamination of the soil from the drainage of waste water and a lot of other technological factors, as well as subsidence of the soil in the areas of hydraulic fracturing. It should be noted that it is very difficult to safely model and understand the danger of hydraulic fracturing in a given area, since the soil is a complex heterogeneous medium. It is possible that we will lose more from the consequences of hydraulic fracturing of the formation. However, it is also necessary to extract resources, especially in the current needs of mankind.

Nevertheless, modern methods of mathematical modeling allow us to investigate heterogeneous media. One of the methods that are capable of modeling destruction, mixing of different types of particles is the particle method. Thus, we will be able to predict the consequences of hydraulic fracturing of the formation for the environment and in advance, if possible, exclude them by reducing the pressure of hydraulic fracturing of the formation, by introducing any substances into the soil, which will increase its connectivity, or completely eliminate hydraulic fracturing in this place, etc.

At present, most of the computational methods are based on the discretization of the domain, and most often finite element and finite difference methods are used [1-12]. Such an approach has perfectly proved itself in solving problems of deformation of complex heterogeneous media of various
natures. However, there is a wide class of problems in which loaded media are accompanied by multiple destruction and slippage of fragments, medium cracking, intense mass transfer, including mass mixing effects, etc. When solving such problems, the use of the grid approach is very difficult. A promising class of numerical methods for mechanics of a deformable solid body, adapted for modeling fracture processes, and in principle for the modeling of heterogeneous media, such as soil, is particle methods [13-18]. The theoretical basis for calculating the resulting crack, as well as known analytical models of the hydraulic fracturing process, are given in [19-24]. It should be noted that in the modern sense the term "particle methods" is collective and includes very diverse numerical methods, both relating to the classical representatives of the discrete approach in mechanics, and the meshless algorithms for numerical solution of the equations of continuum mechanics. Moreover, at present, some modern implementations of traditional numerical methods, such as the particle finite element method, are often referred to as particle methods. It should be noted that the particle methods were formed on the basis of the well-known molecular dynamics method used to study the response of the medium at the atomic level. At the same time, the possibilities of atomic description for modeling the behavior of a solid body on the spatial and temporal scales interesting from the point of view of engineering applications are extremely limited, and this description was used for modeling in most of the liquid and gaseous media. At present, the potentials of interatomic interaction for most materials are known. This can not be said about the potentials for describing the behavior of deformed continuous media, especially shear ones. Therefore, it is very important to model soil masses and interacting fluids based on the particle method with different pair interaction potentials for different phases. To describe the behavior of the liquid phase, the Lennard-Jones potential is used in this paper [17], and to describe the deformation of the soil massif, the "modified" Lennard-Jones potential introduced by the authors [25-27].

2. The problem statement
The fundamentals of the particle method, based on the use of pair interaction potentials, are as follows. Let's consider a collection of $N$ material particles interacting with each other in a potential field. The motion of the particles is described on the basis of the following equation of motion:

$$m \ddot{r}_k = \sum_{n=1}^{N} \Phi(r_{kn}) \ddot{r}_{kn} + \phi(r_{kn}),$$

where $\ddot{r}_k$ and $\ddot{v}_k$ are the position and velocity vectors of the $k$-th particle

$$r_{kn} = r_k - r_n, v_{kn} = \ddot{v}_k - \ddot{v}_n, r_{kn} = |r_{kn}|, v_{kn} = |v_{kn}|,$$

$m$ is the mass of the particle, $\Phi(r)$ describes the conservative component of the interaction between the particles, $\phi(r)$ describes the external conservative force field. Conservative component of the interaction $\Phi(r)$ can be found by the formula:

$$\Phi(r) \overset{\text{def}}{=} \frac{1}{r} f(r), f(r) \overset{\text{def}}{=} -\Pi(r),$$

where $f(r)$ is the scalar potential force, $\Pi(r)$ is the interaction potential.

Two potentials for pair interaction are used to describe continuous media. In the first case, this is the Lennard-Jones potential [17]

$$a = 0.4r, \Pi(r) = D \left[ (a/r)^{12} - 2(a/r)^6 \right].$$

In the second case, the modified Lennard-Jones potential [29-31] was used

$$\Pi(r) = D \left[ 48.97(a/r)^{12} - 93.55(a/r)^6 + 35.11(a/r)^6 + 9.93(a/r)^6 \right], a = 0.4 \times 1.28r.$$
To solve the problems of mechanics by the particle method, one has to deal with a large amount of data and computations. Therefore the most promising technology for solving these problems is heterogeneous computing clusters with the use of graphic accelerators (GPU). One GPU-device is equivalent to solving the problems of seismic wave propagation to about 50 central Xeon processors. However, this technology has certain limitations on the amount of available memory, since the internal memory of GPU devices is much smaller than the RAM of traditional cluster nodes. To implement calculations on graphics accelerators, the open source library VexCL is used. This library simplifies the development of applications using OpenCL technology and allows using intuitive notation for writing basic operations of linear algebra. The calculations were performed on a heterogeneous computing cluster [28-31]. Each of the seven cluster nodes has three AMD Radeon HD 7970 GPUs installed.

3. Numerical results and discussion

In the work in two-dimensional formulation, two model problems of hydraulic fracturing of the reservoir were solved. The calculation area is shown in figure 1. Yellow is a soil environment in which a fluid enters the vertical channel, which is shown in lilac color. Both the soil and the fluid are a collection of material particles, the number of which is horizontally and vertically indicated in figure 1 in thousands. In the first, the Lennard-Jones potential was used to describe the motion of soil and fluid particles. In the second problem, the Lennard-Jones potential was used only to describe the fluid, and to describe the motion of the soil, the "modified" Lennard-Jones potential was used.

At the initial moment of time, the soil is in a position of equilibrium in the potential field of gravity and is stationary. The fluid is immobile and weightless. Further, the fluid is also placed in the gravitational potential field and it starts moving (as a set of material particles) down the channel and, interacting with the soil, leaving the channel. On the interaction front between the particles representing the soil and the fluid, they are partially mixed, and in the soil, cracks can appear.

Figures 2 and 3 show the configurations that the soil mass becomes in the process of fracturing and further mixing of the media, partial fracture and cracking of the soil for the first and second model tasks, respectively.
Figure 2. The final state of the formation after soil fracturing with its modeling using the Lennard-Jones potential.

Figure 3. The final state of the formation after soil fracturing with its modeling using the “modified” Lennard-Jones potential.

It should be noted that when modeling a layer of soil using the Lennard-Jones potential, the mixing of fluid particles and soil occurred in the front of their interaction. The use of the "modified" Lennard-Jones potential for soil modeling allows obtaining cracks in the soil, and in general allows obtaining more realistic picture of the fracturing.

4. Conclusions
The method of particles was realized in the work, which makes it possible to investigate the interaction of continuous media of different physical nature (fluid and soil). Based on the Lennard-Jones potential and the previously introduced "modified" Lennard-Jones potential, modelling the problem of deformation and partial destruction of a soil massif under strong pressure from the fluid side was solved. Analysis of the results shows that the use of the "modified" Lennard-Jones potential for describing the soil environment makes it possible to realize the process of brittle fracture in the soil during fracturing, whereas the Lennard-Jones potential allows reproducing only viscous destruction of the soil environment.

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