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DETERMINATION OF MICROMECHANICAL PARAMETERS OF PROPPANT PARTICLES

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Abstract— The purpose of hydraulic fracturing is improving well productivity by creating fractures, which are propped with a propping agent. The success of this process depends highly on the achieved fracture conductivity, which is the product of the fracture width and the apparent permeability of the proppant within the fracture. After hydraulic fracturing treatment, well productivity is definitely affected by the interaction between the proppants and the fracture surface. As the fracture again closes, the resulting pressure deforms the proppants and embeds them in the surrounding rock, which significantly reduces fracture conductivity. In our prior work, the analytical method pointed out proppant size, Young's modulus and Poisson's ratio of proppant as well as formation, closure pressure as factors which influence proppant embedment and fracture aperture. However, the discrete element method could provide with a more precise result considering the random characteristic of the phenomenon. In this paper we introduce the determination method of micromechanical properties of proppant particles by using EDEM Academic discrete element software and YADE DEM freeware software.

Keywords— Proppant; hydraulic fracturing; discrete element method;

I. INTRODUCTION

Hydraulic fracturing is a stimulation treatment used in the upstream division of the petroleum industry. The goal of the treatment to enhance well productivity that results higher inflow and so production as well. This treatment is a multi-disciplinary process [1] and is acclaimed as the most effective reservoir-scale stimulation technique. The treatment is initiated at the surface but indeed performed in the formation close to the bottom of the well. Hydraulic fluid, which contains water in 99 % and additives in 1 % to increase dynamic viscosity, is pumped into the well to achieve the formation breakdown pressure that indicates fracture propagation (Fig. 1. shows the schematic hydraulic fractures in a well). After the fracture is created proppant is mixed into the hydraulic fluid to operate as a propping agent when pumping stops [2].

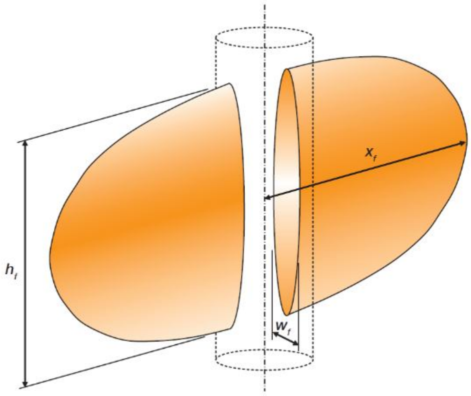

Fig. 1 Schematic representation of hydraulic fractures in a well [3]

The situation, which is aimed to simulate, takes place after pumping stopped and there is no more extra pressure energy which would exceed the formation's breakdown pressure, so the fracking fluid leaks off and the hydraulic pressure drops. Finally, the in-situ stress of the given rock overcomes the fluid pressure resulting a closure action (closure pressure can be interpreted at this point) that is prevented by proppant particles that are propping the fracture.

The analytical solution, applied in our previous work [4], is based on only mathematical and physical considerations. It was used for investigation of change in fracture aperture by Li et. al. [5], and it is derived from the Hertzian contact theory [6]. The main benefit of the analytical solution is the simplicity and the applicability; however it is based on relatively generous assumptions that mean limitations involving inaccuracy. Considering the fact that the analytical solution is derived from the contact theory, proppant placement is considered as perfect spheres situated ideally on each other that assumes perfectly uniformed stress distribution and non-real deformation and embedment. Taking into account the phenomenon's random characteristic, one can definitely conclude that numerical solution can provide a much more reasonable solution. DEM (Discrete Element Method) can handle the non-uniform proppant placement and it can also handle proppant shape as not a perfect sphere but clumps or another more real shape that approximates the reality more precisely. The first step of the discrete element modeling technique is to determine the micromechanical parameters of proppants as accurate as it is possible.

II. DISCRETE ELEMENT MODELING TECHNIQUE

The discrete element method (DEM) is a new numerical method for computing the motion and effect of a large numbers of small particles. A numerical model is called a discrete model if it consists of separate, finite sized bodies ("discrete elements") each of them being able to displace independently of each other; the displacements of the elements can be large (i.e. not infinitesimally small) the elements can come into contact with each other and loose contact, and these changes of the topology are automatically detected during the calculations [7].

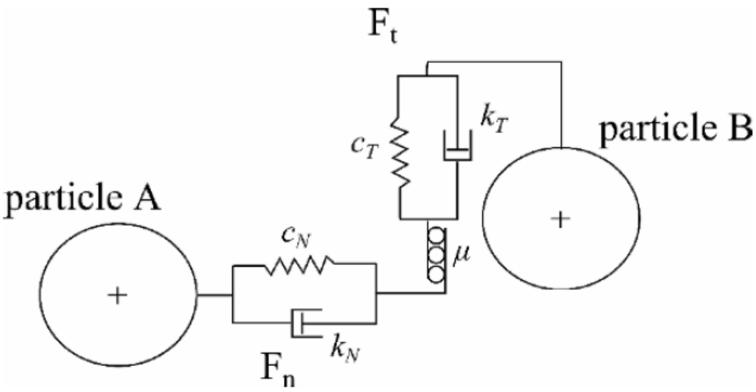

Fig. 2 A Simplified Hertz-Mindlin no slip contact model [9].

The result of the discrete modeling depends partly on the geometrical characteristics (the geometry of the particles and the structural elements) and partly on the mechanical characteristics of the relation of the discrete elements. The DEM solvers apply contact models for the calculation of contact forces and moments created by the interaction of elements. The constants of the contact model are called micromechanical parameters. In the case of discrete modeling, one of the most difficult tasks is to determine these micromechanical parameters, since in many cases they cannot be directly measured. Some of these parameters (such as powders or cohesion granular materials) cannot be measured at all. In these cases, parameter identification techniques may be used [8].

Determining the micromechanical parameters of granular assemblies makes numerical modeling very complicated and time consuming because in most cases, the calibration procedure takes more time and research than creating and solving a discrete element model. For determination of the micromechanical parameters of non-cohensive proppant particles the EDEM Academic and YADE freeware software were used. In EDEM environment the Hertz-Mindlin "no slip" contact model was applied (Fig 2.), which models interactions in the system using damped oscillation systems. The description of Herzt-Mindlin contact theory can be found at [9].

The micromechanical parameters used in discrete modeling of non-cohesion granular assemblies are thus: - Poisson-ratio (ν): defined as ratio of transverse contraction strain to longitudinal extension strain in direction of stretching force

- Shear modulus (G): defined as ratio of shear stress to shear strain.
- Density (ρ): defined as "weight" per unit volume
- Coefficient of restitution (Cr): ratio of speed of separation to speed of approach in a collision
- Coefficient of static friction (μ_0)
- Coefficient of rolling friction (μ_r).

In YADE environment perfectly rigid BALL type model was used (Fig. 3.). The code commonly used in YADE computes normal interaction stiffness as stiffness of two springs in serial configuration with lengths equal to the sphere radii.

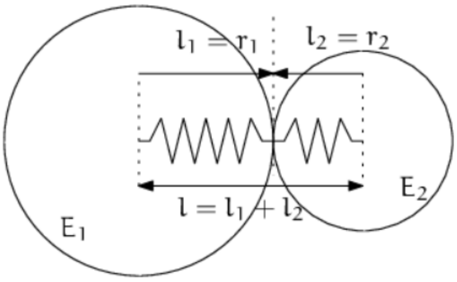

Fig. 3 BALL type model in YADE: series of 2 springs representing normal stiffness of contact between 2 spheres [10]

The description of Ball type model theory can be found at [10]. The micromechanical parameters used in YADE are thus:

- Young modulus (E)
- Poisson-ratio(ν)
- Density(ρ)
- Friction angle (φ)
- Coefficient of rolling friction (μ_r).

During the simulations, the linear- and angular momentum theorem is used to write the equation of motion for all the individual particles resulting multiple number of differential equations to be solved in a sufficiently large number of time steps. The used time step has a great impact on the stability of the numerical model.

III. EXPERIMENTAL INVESTIGATIONS

Silo outflow was selected to the base of parameter identification technique.

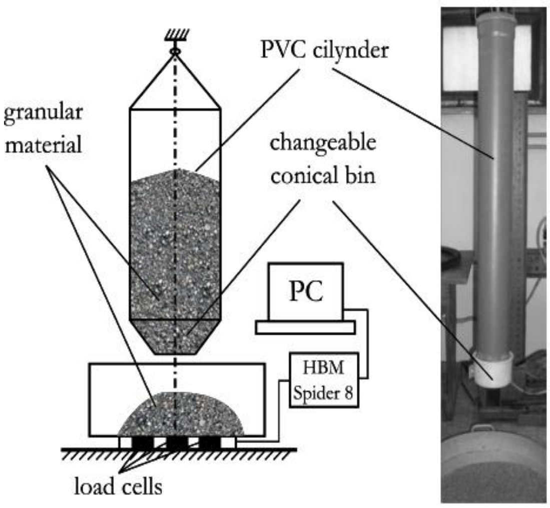

Fig. 4 Measuring arrangement for examination of gravitational discharge of cylindrical silos [11]

Experimental investigation of the outflow of cylindrical silos was performed with a model silo equipped with a data measuring and processing system. The body of the model silo is a 110 mm diameter, 700 mm long PVC cylinder with a removable conical hopper with a 35 mm diameter outlet (Fig 4.). The cone half angle of the bin was 60°. The total mass of the proppant particles was 1.7 kg.

During the experimental investigations the discharged mass was measured by three HBM (Hottinger Baldwin Messtechnik) C9Bforce transducers. An HBM Spider8 measuring amplifier was responsible for data processing. The sampling rate was 50 Hz in all case off measurements. During the data processing, the related mass-time data were plotted in a common coordinate system and in each case the average outflow mass flow was determined. Due to the linear nature of the phenomenon, the use of linear regression was a straightforward solution to determine directly and quickly the average outflow mass flow rate (slope of the linear mass-time function) (Fig. 5). The measurement was repeated five times and 0.47±0.02 kgm^{-1} discharge rate was obtained.

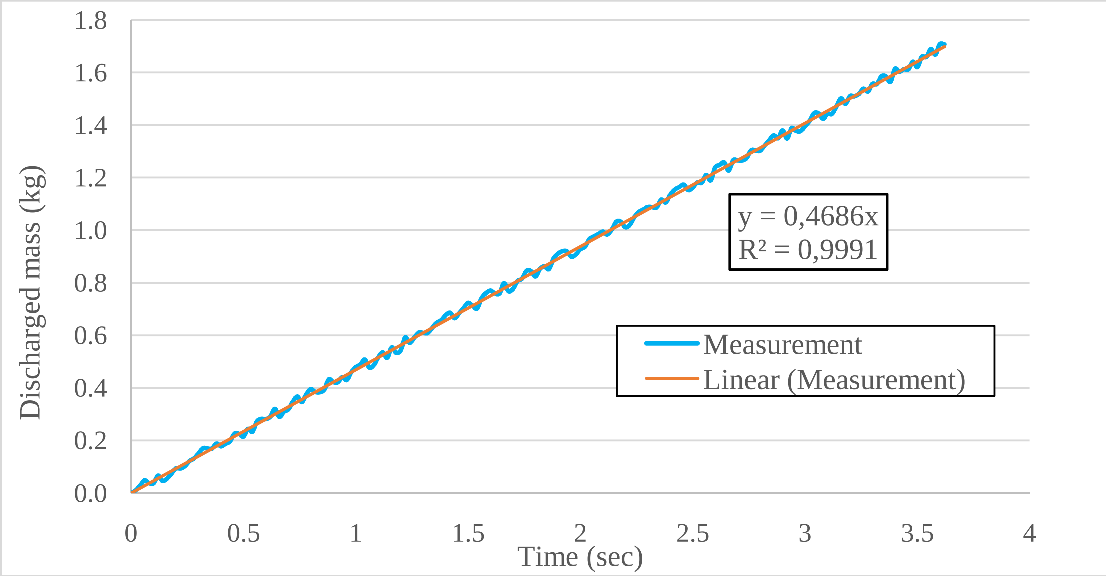

Fig. 5 The measured mass-time function

IV. DISCRETE ELEMENT SIMULATIONS

The steps of the simulation process were the same for both discrete element software. First, the particles were randomly created inside the silo. In the next step the particles felt down under gravity. It was necessary to wait that the granular assembly reach the quasi-static state. This step was required because the contact models presented - and used for modeling - describe the interaction of particles with damping spring-dashpot system, and it will take some time for the vibrations damped. After reaching the quasi-static state, the outlet of the silo opened and the particles flowed out of the silo (Fig. 6). During solution of the numerical model mass of the particles remained in the container was recorded. First step of the modeling is to define the shape, size and the size distribution of the particles. The proppant particles sphericity is nearly90%, therefore the particles were modeled as perfect spheres. The diameter of the spheres was 1 mm (Fig. 7-8.).

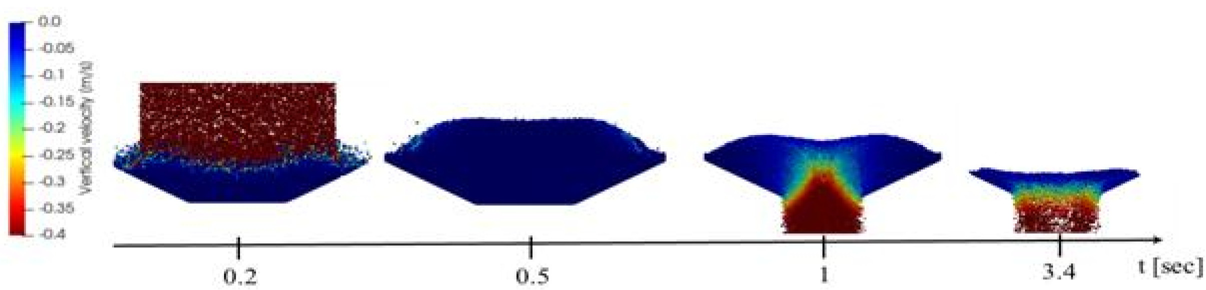

Fig. 6 The simulation process

The proppant particles were characterized by a relatively uniform size distribution, so during the calculations we worked with the same size.

In EDEM software environment the coefficient of restitution, static friction and rolling friction are interpreted between interacting bodies, so these must be given within particle-assembly as well as the interaction between the elements and the boundary walls. Rayleigh time is taken by an energy wave to transverse the smallest element in the granular system. Time step must be so short, that the disturbance of particle's motion could only propagate to the nearest neighbors [9]. The final time step value was $\Delta t = 1.214 \cdot 10^{-5}$ s. The grid size in all simulation was $2R_{min}$, where R_{min} is the minimal radius of particles. The simulation was repeated three times. The initial simulations were calculated with some of the micromechanical parameters used in our prior work [12]. However using these parameters it can be found that the calculations and measurements results did not show a good agreement. Modification of the parameter values was necessary. The mechanical behavior of the proppant particles highly depends on the internal friction conditions of the material. Due to this fact it was enough to modify the values of static friction and the density of the particles. Table 1 shows the initial and the modified micromechanical parameters of the particles.

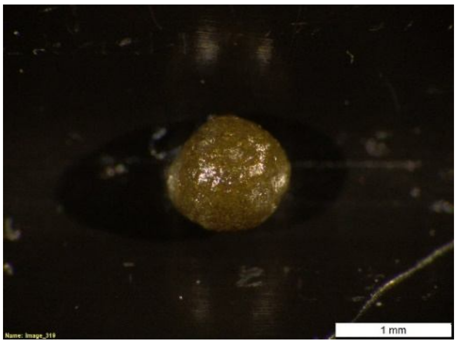

Fig. 7Microscope photo of the proppant particle

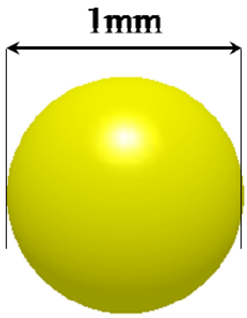

Fig. 8Discrete element model of a proppant particle

TABLE I - MICROMECHANICAL PARAMETERS OF PROPPANT IN EDEM SOFTWARE ENVIRONMENT

Micromechanical parameter	Initial		Modified	
	proppant	silo	proppant	silo
Poisson-ratio (ν)	0.25	0.3	0.25	0.3
Shear modulus (G), Pa	$3.58 \cdot 10^8$	$8 \cdot 10^8$	$3.58 \cdot 10^8$	$8 \cdot 10^8$
Density (ρ), kg/m³	3400	7500	2000	7500
Coefficient of restitution (Cr)	proppant: 0.5 silo: 0.6	proppant: 0.6 -	proppant: 0.5 silo: 0.6	proppant: 0.6 -
Coefficient of static friction (μ_0).	proppant: 0.3 silo: 0.25	proppant: 0.25 -	proppant: 0.3 silo: 0.25	proppant: 0.3 -
Coefficient of rolling friction (μ_r)	proppant: 0.01 silo: 0.01	proppant: 0.01 -	proppant: 0.01 silo: 0.01	proppant: 0.01 -

TABLE III - MICROMECHANICAL PARAMETERS OF PROPPANT IN YADE SOFTWARE ENVIRONMENT

Micromechanical parameter	Initial		Modified	
	proppant	silo	proppant	silo
Poisson-ratio (ν)	0.25	0.3	0.25	0.3
Young's modulus (G), Pa	$5 \cdot 10^{10}$	-	$5 \cdot 10^{10}$	-
Density (ρ), kg/m³	3400	-	5100	-
friction angle (φ), °	2.8	2.8	10	1
Coefficient of rolling friction (μ_r)	$1 \cdot 10^{-4}$	-	$1 \cdot 10^{-4}$	-

In Table 2 the initial and modified parameters can be seen in YADE. The applied time step in YADE was $1.27749 \cdot 10^{-5}$sec. In YADE there is a useful tool to track dynamic behavior of the particulate assembly by computing the ratio of summarized force on bodies and mean force magnitude on interactions. For perfectly static equilibrium, summary force on all bodies is zero thus the above-mentioned ratio will tend to zero as simulation stabilizes. Zero value can be never reached because of finite precision computation. When the particles reach the quasi-static state the bin was opened and total mass in the container was calculated by a python script. When all of the particles discharged from the bin discharged mass – time function was plotted and linear regression was carried out by an automatized procedure. By this approach iterative modification of micromechanical parameters was possible thus the calibration process was significantly faster compared to EDEM.

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For post processing ParaView [13] was utilized for indicating particles, facets or velocity field during the discharge. According to our expectations funnel flow formed and linear mass – time relationship was observed (Fig. 9).

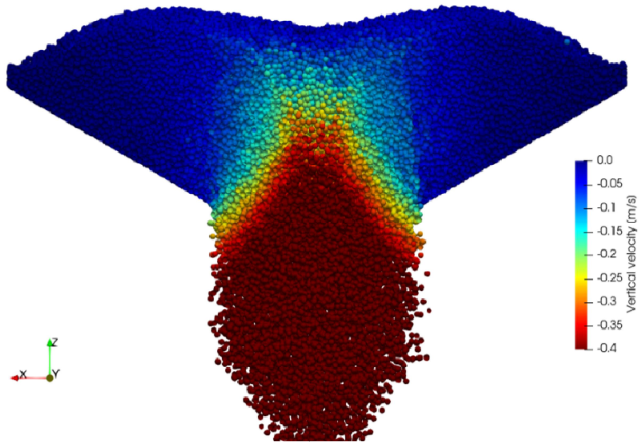

Fig. 9 Funnel flow discharge of proppant particles

Fig. 10 shows comparison of the simulated and experimental results. It can be seen that both numerical models describe the phenomenon adequately.

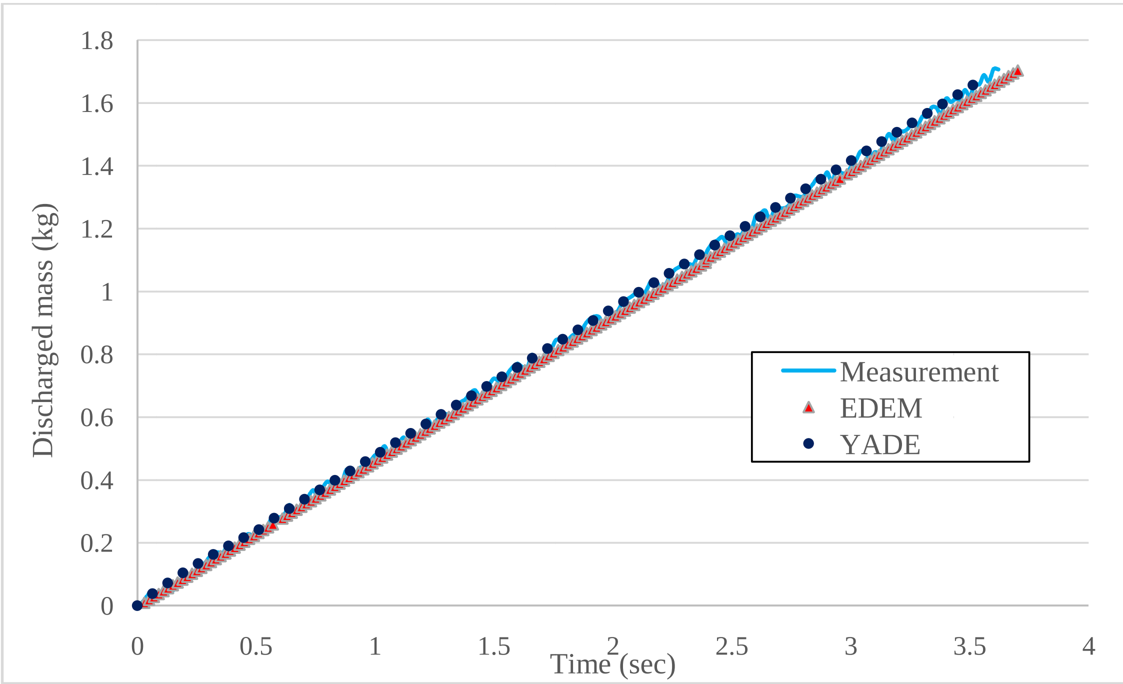

Fig. 10 Comparison of simulated and measured results

V. CONCLUSION

In this paper we proved that discrete element modeling technique is capable to determine the micromechanical parameters of hydraulic fracturing proppant particles. Silo outflow was selected as a parameter identification technique. It can be found that by application of different contact models and by various combinations of micromechanical parameters can be accurately described the micromechanical behavior of the proppant particles. For this reason, further investigations are planned to find universally applicable set of micromechanical parameters. During our work we used in EDEM Academic and YADE DEM freeware software, because we would like to utilize the advantages of both software in our next research. These results provide helps for the future investigations, where the performance of hydraulic fracturing process will be investigated.

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