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RESEARCH PAPER

Calculation method of proppant embedment depth in hydraulic fracturing

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Abstract: For the issue of proppant embedment in hydraulic fracturing, a new calculation method of embedment depth considering elastic-plastic deformation was proposed based on the mechanism of proppant embedment into rocks by combining proppant embedment constitutive equations and contact stresses on the rock-proppant system. And factors affecting embedment depth of proppant were analyzed using the new method. Compared with the elastic embedment model, the results calculated by the new method match well with the experimental data, proving the new method is more reliable and more convenient to make theoretical calculation and analysis. The simulation results show the process of proppant embedment into rocks is mainly elastic-plastic. The embedment depth of monolayer proppants decreases with higher proppant concentration. Under multi-layer distribution conditions, increasing the proppant concentration will not change its embedment depth. The larger the proppant embedment ratio, the more the stress-bearing proppants, and the smaller the embedment depth will be. The embedment depth under higher closure stress is more remarkable. The embedment depth increased with the drawdown of fluid pressure in the fracture. Increasing proppant radius or the ratio of proppant Young's modulus to rock Young's modulus can reduce the proppant embedment depth.

Key words: hydraulic fracturing; proppant; embedment depth; constitutive equation; contact stress; elastic-plastic deformation; proppant concentration

Introduction

Volume fracturing of horizontal wells has become a primary technology for the development of tight reservoirs, such as shale, tight sandstone, and coalbed reservoirs[1]. Proppant slug injection and small size proppant are usually used in the technology, which often result in partial distribution of proppant in fractures and in the intersection of main fracture and branch fracture. Proppant partially distributed in the fracture and the intersection of main fracture and branch fracture may bears higher external stress, making the proppant embed deeper into the fracture planes, and causing decline of productivity and even failure of the fracture[2–3]. Therefore, predicting the behavior of proppant embedment is of great significance for the design of volume fracturing.

Methods for proppant embedment study include experiment, numerical simulation, and theoretical model analysis. Many researchers have conducted experiments to investigate the proppant embedment in different kinds of rock and obtained some basic understandings on the embedment[4–8]. However, the experimental studies aimed at a specific kind of rock, making their results difficult to apply to other types of rock. Alramahi et al.[9] studied the indentation of proppant into hydraulic fractures by using the finite element method, and found that proppant embedment mainly occurred in the plastic deformation stage of the surface of rock fractures. Deng et al.[10] numerically simulated shale–proppant interaction using a newly developed discrete element method, and reached the finding that the higher the concentration of the proppant, the smaller the embedment depth of the proppant was. Although numerical simulation can be used to solve the embedment of proppant, large in computation workload, it is not convenient for engineering design. The theoretical model, simpler and easier, is still the most widely method used to describe the behavior of proppant embedment.

The theoretical model has experienced the development

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from the empirical formula, to semi empirical formula and theoretical solution. Huitt et al.[11] derived a model to calculate the depth of proppant embedment based on the empirical relation from metal penetration–hardness experiment. In the model, two characteristic constants for each penetrated specimen need to be obtained from laboratory penetration–hardness test. Volk et al.[12] proposed empirical expressions for predicting embedment depth based on their experimental results. An analytical model was derived by Li et al.[13] based on Hertzian contact theory. However, the model cannot predict the embedment occurring in non-elastic regions because Hertzian contact theory is an elastic solution.

In this study, a new theoretical model was proposed to predict proppant embedment. The new model considers the elastic, elastoplastic, and plastic deformation of rock fracture surfaces, thus eliminating the limitation of the elastic model. Moreover, the solution of the embedment depth and the proppant embedment period was obtained by a trial method because the rock deformation includes three regions. The new model and previously published elastic model were compared with experimental results of Lacy et al., Guo et al., and Lu et al. to verify the feasibility and accuracy of the new model. Factors affecting the embedment depth of proppant were analyzed by using the new model.

1. Mathematical model

1.1. Rock–proppant contact stress

Fluid pressure in the hydraulic fracture p_f and proppant contact stress σ_p act on the A cross section with the total cross-sectional area A_t (including the area of proppants and pores)[14] (Fig. 1). According to the force–balance relationship, we can obtain:

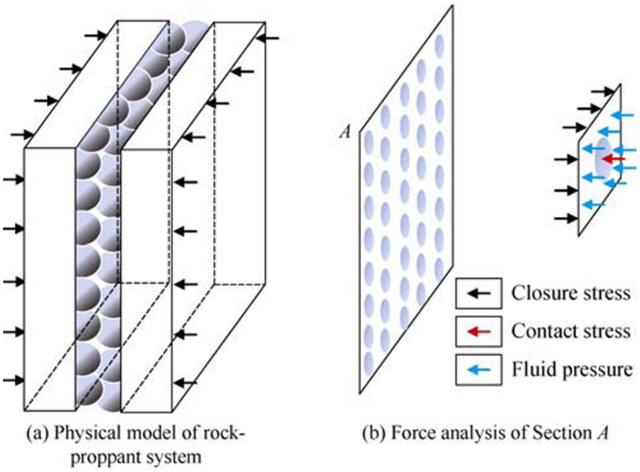
$$\sigma_\mathrm{c} A_\mathrm{t} = \sigma_\mathrm{p} A_\mathrm{p} + p_\mathrm{f}\left(A_\mathrm{t} - A_\mathrm{p}\right) \tag{1}$$

Identifying the distribution of proppants that contact with the rock fracture surface is necessary for analyzing the stress on a single proppant in the rock–proppant system. The three forms of proppant layout in the rock fracture surface are loose monolayer, dense monolayer, and multilayer distributions (Fig. 2)[15]. Proppants are in compacted state in the multilayer distribution due to the closure pressure. Hence, the layout of these proppants contacting with the fracture surface is equal to the dense monolayer distribution. Therefore, the contact stress analysis of the proppant under the multilayer distribution is equal to the stress analysis of proppants under the dense monolayer distribution.

We used surface density to quantify proppant distribution state. Proppant surface density is defined as the number of proppants contacting with rock fracture surface per unit area. It can be written as:

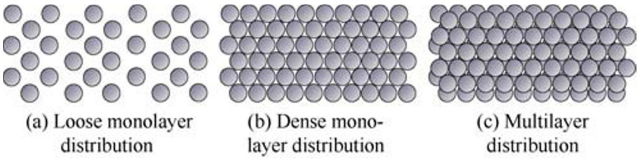
$$n_\mathrm{t} = \frac{N_\mathrm{t}}{A_\mathrm{t}} \tag{2}$$

Given the influence of fracture surface roughness and the proppant size distribution, the real number of proppants embedded into the fracture surface is less than the apparent number of proppants contacting with the fracture surface[16–17]. We defined embedment ratio ε as the ratio of the number of embedded proppants to the number of proppants contacting with the fracture surface. It can be expressed as:



(a) Physical model of rock-proppant system (b) Force analysis of Section A

Fig. 1. Force analysis of the rock–proppant system.



(a) Loose monolayer distribution (b) Dense monolayer distribution (c) Multilayer distribution

Fig. 2. Proppant distribution patterns.

$$\varepsilon = \frac{N}{N_\mathrm{t}} = \frac{n}{n_\mathrm{t}} \tag{3}$$

The average embedded area of a single proppant is given by:

$$A_\mathrm{pe} = \frac{A_\mathrm{p}}{N} \tag{4}$$

Eqs. (1)–(4) are combined to derive the average contact stress on a single proppant, which is written as follows:

$$\sigma_\mathrm{p} = \frac{\sigma_\mathrm{c} - \left(1 - \varepsilon n_\mathrm{t} A_\mathrm{pe}\right) p_\mathrm{f}}{\varepsilon n_\mathrm{t} A_\mathrm{pe}} \tag{5}$$

Eq. (5) shows that the contact stress is a function of the embedded area, embedment ratio, external load, and internal fluid pressure in the hydraulic fracture. The key to solving the contact stress is to calculate the embedded area, because the external load, the fluid pressure, and the proppant distribution are known or given parameters.

1.2. Constitutive model for proppant embedment

In this study, proppant deformation was not considered in the analysis of proppant embedment depth. Therefore, proppant embedment into rock fracture surface can be interpreted by the contact mechanism of the rigid sphere embedment into a semi-infinite space under a normal load. With the increase of proppant embedding depth, the local deformation of the contact position between the rock and the proppant goes