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Research advance of numerical simulation methods for sand production prediction of unconsolidated sandstone

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1 Introduction

With the rapid development of global economy, the demand for oil and gas resources keeps rising, unconsolidated sandstone reservoirs occupy a very important position in China's oil and gas resources (Wang et al., 2010) (Zhang, 2021) (Yan et al., 2021). In the process of drilling and producing oil in unconsolidated sandstone reservoir, the stress and pore pressure around the oil production cavity will be redistributed, which will cause serious problems such as sand production in the production stage (Wang et al., 2022). Sand production not only damages borehole integrity, but also leads to reduced oil and gas production, equipment corrosion and impact on production safety during production (Ahad et al., 2020) (Song et al., 2021). Due to the existence of the above negative effects, the exploitation cost of unconsolidated sandstone reservoir is further improved, so it is particularly important to conduct reliable sand production prediction research (Shabdirova et al., 2019) (Zivar et al., 2019).

At present, the research on sand production prediction of unconsolidated sandstone mainly focuses on two aspects, namely laboratory experimental research and numerical simulation research. Laboratory experimental studies mostly use a single large cylindrical artificial sandstone specimen for diagenesis and combine electrorheological probes (ER Probes) or high-pressure consolidation system (HPCS) to simulate the sand behavior, from the overall or macro perspective to simulate the sand law, but it is difficult to reveal the microscopic nature and mechanism of particle migration and sand production process (Zhang et al., 2015; Kozhagulova et al., 2020a; Kozhagulova et al., 2020b). Meanwhile, sand production in oil wells is closely related to mechanical behavior and rock properties of sandstone reservoir (Fattahpour et al., 2012). Because of the complex mineral composition and low cementation strength of unconsolidated sandstone reservoir, it is more difficult to predict sand production by laboratory experiments.

To better simulate and predict sand production, many scholars have shifted their research focus to numerical simulation methods (Cao et al., 2021; Liu et al., 2022). Therefore, this article discussed the current research status of numerical simulation methods for prediction of sand production in unconsolidated sandstone, analyzes the shortcomings of various methods, and puts forward suggestions for further research, so as to provide reference and theoretical support for sand production prediction and sand control design in the development of unconsolidated sandstone reservoirs.

2 Numerical simulation methods for sand production prediction

The accurate prediction of unconsolidated sandstone sand production in the production process plays a significant role in the level of oil and gas production. There are four kinds of numerical simulation methods, namely finite element method, finite difference method, discrete element method and discrete element-finite element hybrid method.

2.1 Finite element method

The finite element method mainly includes critical drawdown pressure difference evaluation, equivalent plastic strain analysis, thick wall cylinder calculation and prediction of sand production (Papamichos et al., 2010; Liu and Liu, 2018) (Garolera et al., 2020; Li et al., 2018).

2.1.1 Critical drawdown pressure difference evaluation

This method uses the true triaxial stress chamber (TTSC) to simulate the single-hole sanding behavior under true triaxial stress and fluid flow conditions and is verified by the finite element software ABAQUS (Younessi et al., 2013). Studies suggest that there is a critical drawdown pressure difference to induce sand production in the sand producing area around the borehole (Song et al., 2022). The failure prediction under true triaxial stress state is more accurate than Drucker-Prager (Al-Ajmi and Zimmerman, 2005; Al-Ajmi and Zimmerman, 2006) and has a stronger correlation with the experimental results. However, the numerical model does not consider the plastic strain law, and the sample is in an ideal state after yielding, which deviates from the actual value.

2.1.2 Equivalent plastic strain analysis

Since the 1990s, some scholars have introduced the equivalent plastic strain to analyze the sand production conditions and sand production, thereby improving the accuracy of sand production prediction, Figure 1B. (Morita et al., 1989; Bai et al., 2012). Volonte et al. established a reliable workflow through finite element modeling to estimate the actual sanding conditions (Volonté et al., 2010). As shown in Figure 1A, the rock failure around the perforation is evaluated by analyzing the distribution of equivalent plastic strain, and the Cosserat continua is introduced to simulate the slit type of failure around the borehole, so as to achieve the purpose of sand production prediction (Muller et al., 2011; Saski et al., 2021). Gui et al. (2016) further improved the accuracy of this method by combining core experiment and field experiment.

2.1.3 Thick wall cylinder calculation

Santana and Likrama proposed a workflow for optimal matching between laboratory tests and finite element model simulation results (Santana and Likrama, 2016). In this method, the finite element model under the same test is developed by testing the experimental curve of thick-walled cylinder (TWC) to calibrate the strength and plasticity of the material. When the numerical test values match the experimental results, the failure threshold is determined according to the critical equivalent plastic strain to simulate the failure near the wellbore during production (Deng et al., 2019).

2.1.4 Prediction of sand production

Prediction of sand production is by considering the erosion process of coupling finite element method, by simulating the fluid flow phenomenon, to observe the sand erosion process, and then to predict the amount of sand in the wellbore (Servant et al., 2006). This method can reproduce the process of an erosion front, and the proposed finite element numerical model does not depend on specific erosion pattern, which is reproducible. The amount of sand is mainly affected by the degree of erosion and finite element time step and mesh refinement (Liu, 2012; Pak and Pak, 2020).

2.2 Finite difference method

Based on erosion criterion (Vardoulakis et al., 1996) (Papamichos et al., 2001), Detournay et al. (2006) proposed a sand production prediction to study the onset and rate of sand production by using the finite difference model. Rahmati et al. (2012) extended Detournay's mechanical-erosion model with strain hardening/softening Mohr-Coulomb yield surface and fracture energy regularization technique (Nouri et al., 2009), which reduced the mesh dependence of strain results to a certain extent, and introduced erosion coefficient K to improve the accuracy of sand production prediction, as shown in Figure 1B. Shahsavari et al. (2021) further reduced the negative impact of mesh size on sand production prediction by combining hollow cylinder sand production experiment and finite difference program on the basis of predecessors.

2.3 Discrete element method

The discrete element method includes three aspects: Coupled Lattice-Boltzmann and Method Discrete Element Method (LBM-

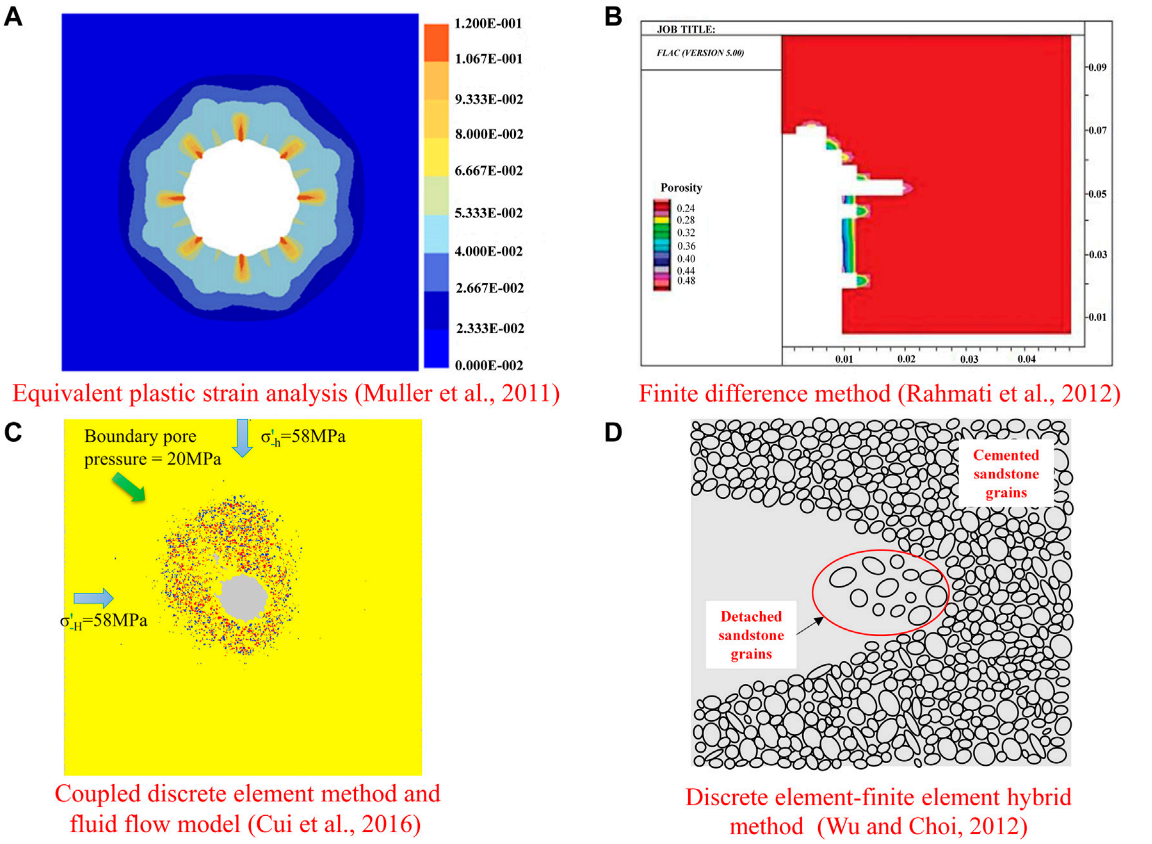

FIGURE 1
Numerical simulation methods for sand production prediction of unconsolidated sandstone. **(A)** corresponds to the numerical simulation results of equivalent plastic strain analysis, **(B)** corresponds to the numerical simulation results of finite difference method, **(C)** corresponds to the coupled discrete element method and fluid flow model, and **(D)** corresponds to the discrete element-finite element hybrid method.

DEM), Coupled Computational Fluid Dynamic and Discrete Element Method (CFD-DEM), Coupled Discrete Element Method and Fluid Flow Model (DEM-FFM) (Wang et al., 2016; Rakhimzhanova et al., 2021; Zhang et al., 2022).

2.3.1 Coupled Lattice-Boltzmann and method-discrete element method

LBM code in LBM-DEM coupling method simulates fluid flow in each time step, and DEM is used to determine the particle position. Through the two-dimensional numerical simulation of fluid flow in deformable particulate media comprising of movable circular particles, the sand production phenomenon in weakly cemented sandstone reservoirs can be simulated. Also, can be used to study the basic mechanism of sand production on an experimental scale (Ghassemi and Pak, 2015; Han and Cundall, 2017) and analyze the permeability before and after sand production and the evolution process of the complex force chain network inside the model (Xia et al., 2022). On the basis of predecessors, Honari et al. simulated different stages of sand production by integrating Immersion Moving Boundary (IMB) method, including scale effect, extension of failure zone under incremental stress, and stress change during particle erosion (Honari and Hosseininia, 2021). The study believed that the smaller the pore diameter and the greater the stress value, the easier the sand production.

2.3.2 Coupled computational fluid dynamic and discrete element method

The coupling CFD-DEM model is used to study the sand production time, sand production amount and particle migration in the perforation damage zone of weakly cemented sand body under different fluid flow condition (Song et al., 2020; Khamitov et al., 2021). Then, the sand production of different fluid types is coupled (Khamitov et al., 2022). It is found that the stripped sand particles are mostly clustered or blocky, and the strength of sand body and fluid velocity are the key factors to determine whether to produce sand. Under the influence of fluid flow, the compacted core will release particles to the perforation location, and then produce transient sand retention. Ismail et al. extended the CFD-

DEM coupling model to the study of screen sand consolidation and analyzed the influence of key parameters such as fluid velocity and particle size ratio on sand retention effect. The research results show that the method can better predict the sand production observed in the experiment (Ismail et al., 2021; Ismail et al., 2022).

2.3.3 Coupled discrete element method and fluid flow model

The DEM-FFM coupling model uses the particle flow code (PFC) developed by ITACSA to calculate by the discrete element method. The particles in the software are rigid and can overlap. The time steps calculated by the discrete element method correspond to the boundary conditions in PFC3D. The influence of boundary stress and fluid pressure on the spalling and sand production of sandstone particles is simulated by updating the variations of permeability and porosity change (Cui et al., 2016), as shown in Figure 1C. The research shows that the high boundary stress and seepage force plays a major role in the sand production process, and lead to the redistribution of stress, which makes the plastic area near the wellbore asymmetrically distributed and aggravates the sand production behavior. After that, Zhao et al. (2020) built a discrete element model based on the PFC3D platform and made a quantitative analysis of sand production.

2.4 Discrete element-finite element hybrid method

Wu and Choi based on the hybrid discrete element-finite model (DE-FE), use the strength of cementing materials, the degree of cementation between particles, and the property of pore fluid to evaluate the formation of pore types, the evolution of sand production volume and sand production rate, and whether the sand production is continuous (Wu and Choi, 2012). When the cementation between particles is destroyed, particles will separate from sandstone and flow out from the tip of the cavity through the fluid, as shown in Figure 1D. If the degree of cementation is poor, the toughness and permeability are high enough, the drag force of pore fluid is enough to cause bond failure, and the detached sandstone particles gather toward the borehole center, resulting in continuous sanding (Zhou et al., 2011).

3 Analysis and discussion

1) Finite element method and finite difference method are based on continuum mechanics. The strength and elastic properties of the numerical model can be obtained by laboratory tests, which is suitable for large-scale sand production prediction, but cannot capture local sand production phenomena.
2) The discrete element method can capture the motion, interaction and micro-failure mechanism of a single sand particle in the dynamic process, but it cannot be used for large-scale calculation and the calibration of model parameters is difficult. The calibration of parameters is not unique, and the micro properties cannot be determined by laboratory specimens.
3) The discrete element-finite element hybrid method can use the continuum theory to simulate the small deformation away from the wellbore, and the sand production behavior near the wellbore can be analyzed by using the discontinuous characteristics of discrete element. This method increases the accuracy of sand production prediction, but there are few related studies, most of which are still based on finite element method or discrete element method.
4) Discrete software PFC can simulate the discontinuous characteristics of rock and reproduce the separation phenomenon of single sand particle from rock matrix. The establishment of numerical model and parameter calibration are relatively simple, and the calculation amount is small, which has high sand production prediction accuracy (Cui et al., 2016; Zhao et al., 2020) (Rahmati et al., 2013) (Shirinabadi et al., 2016).

4 Conclusion

1) Accurate prediction of loose sandstone sand production has always been the focus of domestic and foreign scholars. From the perspective of numerical simulation, this paper summarizes the current research progress of numerical simulation methods, and analyzes the advantages and disadvantages of various methods, in order to provide research direction for future sand production prediction.
2) The finite element method may consider developing special numerical elements to characterize the effect of perforation geometry on sand production during perforation. The finite difference method uses the fracture energy regularization technique to extend the mechanical-erosion criterion and reduce the dependence of the fluid on the grid. In the future, the sand deposition after compression can be considered to further improve the prediction accuracy of sand production. The discrete element method can correlate the microscopic parameters of rock with macroscopic properties and realize the calibration of microscopic parameters of 3D DEM models. Due to the poor applicability of fluid flow at the perforation tip in the current 3D discrete element perforation test simulation, the reliability of the fluid simulation results at the perforation tip can be improved

by introducing the discrete element-finite element hybrid method, considering the cementation state between particles, and providing reference for sand production prediction.

3) Although the discrete software PFC has high precision in sand prediction, there are still some calculation errors. In the future, based on the interface provided by the discrete software PFC, combined with the C++ language, a discrete contact model suitable for unconsolidated sandstone is established to further improve the accuracy of sand production prediction.

Author contributions

HS: mainly responsible for research literature and writing manuscript. GJ: mainly responsible for framework adjustment and thesis guidance. ZL and DH: mainly responsible for literature research.

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Conflict of interest

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