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Multiobjective optimization of the particle aspect ratio for gravel pack in a methane-hydrate reservoir using pore scale simulation

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A B S T R A C T

In gas production from methane-hydrate (MH) reservoirs, consolidation induces invasion of the reservoir, and the gravel pack may be replaced by the invading sand. Therefore, the gravel pack of an MH reservoir must have a high shear strength and a higher permeability than the reservoir. In this study, we investigated the shear strength and permeability of different particles, with the gravel aspect ratio as the design variable. Particles with aspect ratios of 1, 1.5, 2, and 2.5 were packed under isotropic compression using discrete-element method (DEM) simulations. Particles with an aspect ratio of 1.5 exhibited the lowest void ratio. Shear strength was measured using triaxial compression DEM simulations, with the 2.5 aspect ratio particles exhibiting the highest value. Permeability was evaluated using pore scale computational fluid dynamics (CFD) simulation of the particle pack generated by the DEM. Particles with an aspect ratio of 2.5 exhibited the highest permeability. The performance of the four types of particles was compared using multiobjective optimization, with shear strength and permeability as the objective functions. Particles with an aspect ratio of 2.5 exhibited the highest performance against both objective functions.

1. Introduction

Depressurization is a promising method for producing natural gas from deep-water methane-hydrate (MH) bearing sediment. MH is concentrated in the pore space of unconsolidated sand layers under the sea floor. Because the state of MH depends on the pressure and temperature of the pore water, porous flow toward the wellbore owing to depressurization enables the retrieval of dissociated methane gas from the MH reservoir. The depressurization method was applied and validated in 2013 during an offshore production test in Japan. However, excessive sand production, which would impede gas production, was observed even though a sand control method using openhole gravel pack (OHGP) completion was adopted in the test. Sand production is often observed in gas or oil production from conventional reservoirs such as sandstone. The OHGP method is one of the most commonly used sand control methods (Matanovic et al., 2012).

The OHGP filters unwanted reservoir sand using an assembly of gravel particles. In conventional gas production, the OHGP requires higher permeability than the reservoir sand to avoid reducing the flow rate of gas and water. To meet this requirement, the gravels used often have a larger diameter than the reservoir sand. The gravels are usually packed into a gap between the screen pipe and the borehole (annulus) using a carrier fluid (Penberthy and Echols, 1993). The mixture of gravel and carrier fluid forms a slurry, and the slurry flow may induce borehole enlargement by hydraulic erosion. To avoid this, spherical (or rounded) gravels are often employed in conventional gas production.

Solid-state MH is dissolved by depressurization, which means that the MH reservoir becomes transformed into unconsolidated sand. According to the effective stress principle for granular media (Terzaghi et al., 1996), the effective stress increases as the pore water pressure decreases. The effective stress is an average soil skeleton stress, comprising the sum of forces in the soil particles. The increase in effective stress causes consolidation of the MH reservoir. Sandstone has cohesion strength, whereas an MH reservoir without solid-state hydrates lacks cohesion. Hence, the consolidation of the sandstone may be significantly smaller than that of the MH reservoir. The consolidation causes reservoir sand to

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invade, replacing the OHGP in the reservoir. Engineers may employ resin-coated gravels to prevent the displacement of OHGP completion. Cohesion from the resin enhances the shear strength of the OHGP. In this study, we investigated the enhancement of the shear strength of the OHGP by modifying the gravel shape. The goal of the study was to optimize the gravel shape and maximize the shear strength and permeability.

Previous studies have evaluated the shape of the gravel and the proppant that is often used in hydraulic fracturing. Angular gravels tend to form arches or bridges (Gulati and Maly, 1975) and may therefore exhibit higher mechanical resistance to replacement than rounded gravels when used in OHGP. However, sand arching is not generally required for absolute stoppage of reservoir sand (Robertson et al., 1989). Angular gravels also tend to induce borehole enlargement and plugging of the proppant. In current gravel packing theory, rounded gravel is therefore considered preferable. Based on these past studies, both the International Organization for Standardization (ISO) and the American Petroleum Institute (API) recommend the use of rounded or spherical particles.

The current design recommendations of ISO and API are focused on behavior during gravel filling. However, shear resistance to reservoir invasion, i.e., behavior after gravel filling, is another important objective function for the use of OHGP in MH reservoirs. In this study, we assumed that the gravels completely fill the annulus without inducing borehole enlargement, and evaluated the shear behavior and porous flow of the OHGP. The discrete-element method (DEM) (Cundall and Strack, 1979) was employed to simulate triaxial compression in order to evaluate the shear strength. Permeability was evaluated using computational fluid dynamics (CFD) simulation of the particle pack generated by the DEM, following previous studies (Katagiri et al., 2015; Sun et al., 2013). The Pareto principle was applied to address the multiobjective optimization (MOO) problem, with the simulated shear strength and permeability chosen as the objective functions.

2. Overview of OHGP design for sanding

2.1. Conventional reservoir

We use sandstone to represent a conventional reservoir. As noted above, because of its cohesion, sandstone undergoes little consolidation. During gas production, plastic deformation and de-cementation of the sandstone can appear at the surface of the borehole. As a result, the de-cemented fragments and soil particles flow toward the well. The sanding mechanism in sandstone has been confirmed in previous experimental (Cerasi et al., 2005; Heiland and Flor, 2006; Papamichos et al., 2001) and numerical studies (Climent et al., 2014; Cook et al., 2004; Zhou et al., 2010). Since there is little consolidation in sandstone reservoirs, there is little replacement of the OHGP.

The current design recommendations of ISO and API are set out in ISO-13503 and API-RP-58. Both standards focus on the packing efficiency and permeability of the OHGP. According to the Kozeny-Carman equation, the pressure drop due to porous flow depends on the diameter of the constituent particles (Carrier, 2003; Chapuis and Aubertin, 2003; Wyllie and Gregory, 1955). Previous studies have demonstrated the importance of gravel diameter in determining OHGP behavior, including permeability (Coberly and Wagner, 1938; Maly and Krueger, 1971; Penberthy Jr. and Cope, 1980; Schwartz, 1969). The diameter of the gravel selected is usually 5–6 times higher than that of the reservoir sand to ensure high permeability (Matanovic et al., 2012).

The hydraulic erosion of the reservoir is important when evaluating the packing efficiency of OHGP. The gravels are mixed with carrier fluid, forming a slurry, and are then packed by the flow of the slurry. The apparent viscosity of the slurry is higher than the dynamic viscosity of the carrier fluid. At the same flow velocity, the shear stress of the slurry is also higher than that of the carrier fluid. This elevated shear stress may produce larger amounts of eroded sand. Slurry with entrained angular particles can cause a higher shear stress than slurry with rounded particles. For this reason, rounded gravel is often employed in conventional gas production.

Current design recommendations use Krumbein's sphericity, S_k and roundness, R_k (Krumbein, 1941) to characterize the gravel shape, and recommend values of $S_k > 0.6$ and $R_k > 0.6$. The S_k and R_k values are usually represented by a Krumbein chart, in which the particle shape is classified on the basis of visual impression.

2.2. MH reservoir

The MH reservoir loses cohesion because the cementation of the solid-state hydrate is lost due to depressurization. Previous studies have confirmed a reduction in the shear strength of MH bearing sand following the loss of the solid-state hydrate (Masui et al., 2005; Miyazaki et al., 2011; Yoneda et al., 2015). An MH reservoir without solid-state hydrate forms a granular solid, and may then exhibit a larger consolidation deformation than that of sandstone. The plastic deformation and fragmentation of sandstone is concentrated at the surface of the borehole, whereas, in an MH reservoir, it tends to flow toward the wellbore. This causes the OHGP to be replaced by the invading sand. The sanding mechanism of an MH reservoir is therefore different from that of sandstone.

The OHGP for MH reservoir is subjected to confining stress due to the consolidation. The reservoir sand is prone to invade to the OHGP, which means that stress due to the invasion is transmitted to the OHGP. The stress tensor in continuum mechanics consists of normal and shear components. The normal and shear stress can cause compression (or dilation) and shear deformation, respectively. According to the past studies, particle crushing triggers compressive yielding of granular material (McDowell and Bolton, 1998; Nakata et al., 2001). On the other hand, shear yielding can appear without the particle crushing. Hence, the shear strength is smaller than compression strength of granular material.

As well as a high packing efficiency and permeability, the OHGP required for an MH reservoir must have high shear strength, because reservoir invasion induces shear stress. The OHGP used for an MH reservoir is therefore expected to have high shear strength, high packing efficiency, and high permeability. To increase the shear strength, resin-coated gravel is employed in conventional gas production from unconsolidated reservoirs. The gravel cements together as the resin melts under stream injection, and this provides cohesion. To date, no design recommendations exist for OHGP in MH reservoirs.

3. Simulation method

3.1. Outline of the DEM

The DEM is a simulation method developed for frictional particles such as sand and powder (Cundall and Strack, 1979). In this study, the contact between particles was modeled by the Voigt model, which comprises linear springs, dashpots for velocity damping, and a frictional slider (Fig. 1). The algorithm for conventional DEM is given in the cited references (O'Sullivan, 2011; Pöschel and Schwager, 2005).

A non-spherical particle shape was represented by a cluster of rigidly connected spheres in the three-dimensional DEM used in this study (Matsushima and Saomoto, 2002; Matsushima et al., 2009). Fig. 2 shows the four types of particles used, which comprised 1-, 2-, 3-, and 4-element clumps. The particle aspect