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A strain energy criterion based on grain dislodgment at borehole wall in poorly cemented sands

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ABSTRACT

The breakage of bonding between sand particles at a borehole wall usually precedes the borehole failure and it can be considered as a sign that the onset of the borehole collapse is imminent in granular formations. Detecting the particle detachment point and introducing an appropriate failure criterion will play a key role in borehole stability analysis. To investigate the influence of different factors on the initiation of particle debonding at the borehole wall, a series of new laboratory tests was designed and performed on synthetic poorly cemented sand specimens. The tests were devised to allow visual observation of the onset of dislodgment of particles from the borehole wall under various stress paths, for two different borehole sizes and various cement contents. In order to simulate the conducted laboratory tests on TWHC a series of numerical modelling has been conducted by discrete element method to estimate the stresses and strains at the borehole wall. The total strain energy up to the point of the observed particle debonding was calculated for each stress path and a failure criterion based on the total strain energy was introduced. The results showed that the particle detachment point at the borehole wall was reached both before and after the peak strength of the TWHC specimens depending on the stress path and cement content. Also, it was concluded that the stress path has a significant effect on the onset of the particle detachment. The introduced criterion based on absorbed strain energy will help to design more effective support systems for boreholes.

1. Introduction

Shallow depth boreholes with diameters ranging from 100 to 600 mm and at depths of 30–400 m are often drilled for exploration purposes or direct geothermal applications. In vertical loop systems for direct-use of geothermal energy, boreholes are usually no deeper than 150 m.[1] When a borehole is drilled through an unconsolidated formation such as poorly cemented granular formations, it may collapse within a short period of time after drilling is completed depending on the magnitude and direction of in situ stresses and pore pressures. If the strength of the cementation between the sand particles is not high enough to withstand the excessive stress concentration at the borehole wall the latter may cause grain debonding and this may lead to the borehole failure. If a borehole instability develops, the breakouts that were already formed on the borehole wall due to falling out of dislocated grains may cause drilling issues such as stuck-pipe, pack-off and tight holes. Depending on the magnitude of the induced stress around the borehole, the particle dislocation process may diminish after the formation of a stable arch. However, in some cases, especially in deeper boreholes and for reverse faulting stress regimes where $\sigma_{H\,max} > \sigma_{hmin} > \sigma_v$, the arching effect cannot halt the process of particle dislocation and the borehole will collapse completely.[2] Bratli and Risnes[3] identified the driving forces (e.g. in situ stresses and pore pressures), formation resisting forces (e.g. friction, cementation and arching effect) and operational approach (e.g. air core drilling and sonic drilling methods) as the main factors affecting the particle debonding at the borehole wall which causes instabilities. Wang and Papamichos[4] studied the sand production by three different sanding models and showed that the results from the shear failure criterion provide the most conservative prediction and the effective plastic strain model can provide the closest results to the experimental investigations. Hashemi et al.[5] numerically simulated the borehole failure in granular materials and showed that the main reason for borehole failure in such formations is the dislocation of particles. Cerasi et al.[6] investigated the sand production in gas reservoirs by laboratory testing and showed that the sand production onset is delayed in gas reservoirs

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relative to oil or brine flow through the same rocks. Drying of many sandstones is accompanied with an increase in its strength which may be responsible for the observed sand onset delay.

Number of researchers have utilised the thick-walled hollow cylinder (TWHC) specimens for studying the stability of man-made underground openings such as tunnels, boreholes and oil and gas wells. Alsayed[7,8] performed a series of TWHC tests on rocks to study the effect of anisotropic stress conditions on the behaviour of hard rocks. Perie and Goodman[9] investigated the macroscopic failure mechanisms of synthetic rocks made of gypsum cement by conducting TWHC tests. Ewy and Cook[10,11] carried out a valuable experimental study on the behaviour of Indiana limestone and consolidated Berea sandstone in the form of TWHC. Younessi and Rasouli[12] conducted laboratory tests on cubic synthetic sandstone specimens and studied the micromechanical properties of the borehole breakouts. However, in the previous studies, the borehole status was not monitored during the tests and the particle dislodgment point at the borehole wall which can be observed prior or after the peak stress was not studied. In most of the suggested failure criteria for this granular material, maximum stress and the corresponding strain was considered as the failure point, however, the results of this study showed that this point on the stress-strain diagram may not represent the borehole failure. In this study, the TWHC laboratory tests were designed and conducted on poorly cemented sand specimens under controlled conditions. Status of the borehole wall was visually monitored by real-time camera recording to determine the point of the first particle detachment which leads to dislodgment of the particle from the borehole wall. Since the used material showed non-linear behaviour on the stress-strain graph, numerical modelling analysis was conducted in discrete element method (DEM) using PFC3D software to approximate the stresses and strains at the borehole wall. The numerical models were calibrated based on the results from laboratory tests. The total potential and dissipative strain energy per unit volume that is absorbed by the material, U, was derived for different stress paths and cementation strengths and a new borehole sanding criterion was introduced. In fact, U indicates the strain energy density of material before it breaks and it refers to the ability of the material to absorb energy without failure. The results of this study give a more realistic insight into the actual failure behaviour of poorly cemented sandy formations, and they will help to design an enhanced support system to avoid borehole collapse.

1.1. *Induced stresses around a drilled borehole*

The in situ stress state can be defined in terms of the principal stresses, σ_V, $\sigma_{H\,max}$, and σ_{hmin}. Fairhurst[13] showed that the maximum vertical stress can be calculated as the weight of the overlying layers at a certain depth and the minimum horizontal stress is estimated by in-field tests such as hydraulic fracturing and leak off tests.[14] Nevertheless, measuring the maximum horizontal stress ($\sigma_{H\,max}$) is not straightforward and it can be estimated based on specific assumptions and considerations.[15–17] The tangential, radial and axial stresses around a borehole as a function of the far-field stress may be calculated by different equations, such as Kirsch equations which hold for isotropic linear elastic materials. In literature,[18,19] there are different closed form solutions for calculating stress and strain in a TWHC by the theory of elasticity. In this paper, stress-strain curves were used to calculate the total strain energy density. Although the “engineering” stress values can be easily obtained from the test results, in this study the “true” stresses were considered for deriving the precise strain energy values. In this approach, the actual diameter of the specimen at each step of the test was considered for calculating the stress.

1.2. *Basic concepts of thermodynamics on potential and dissipative energies*

According to Li,[20] macroscopic failure criteria can be classified into four different types, 1-stress or strain failure criterion; 2-energy based failure criterion; 3-damage failure criterion; and 4-empirical failure criterion. Also, the macroscopic deformation in materials can be categorized into elastic and inelastic deformations which correspond to different mechanisms at the microscopic level. In fact, the elastic deformation is a collective property of atomic displacements from their original positions.[21] However, increasing the external forces may cause atoms cross the established energy threshold and jump into a new equilibrium mode of free energy which will result in the bonding breakage and in establishing a new configuration of bonds.

In general, a failure criterion based on potential (elastic) strain energy density can be described as[20]:

$$U_s^e = U_{sc}^e(\phi, \dot{\phi}, T) \tag{1}$$

where U_s^e is the elastic strain energy density defined on a given control volume. U_{sc}^e is the critical value, ϕ and $\dot{\phi}$ are the mechanical dissipative energy density and dissipation rate respectively, and T is the material temperature. Due to various assumptions used for deriving the specified strain energy density, different failure criteria have been proposed for evaluating the material strength parameters. According to Freudenthal[22] if the specified elastic strain energy for a certain group of particles in a material exceeds the critical value, the failure occurs in that collection of material particles.

The plastic strain energy density failure criterion has been suggested and implemented for predicting the failure behaviour of ductile materials by a number of researchers.[23,24] According to Lee,[25] the material failure may take place due to excessive plastic dissipation with small material damage from void development or due to large material damage by void coalescence mechanism. In case of a drilled borehole, instability initiates during the process of re-bonding (in microscopic level) or macroscopic inelastic deformations which cannot be shown on the stress-strain graphs. According to Truesdell and Noll[26] the dissipative energy density can be expressed in a general form as:

$$\phi = U^p + U^d - U^v \tag{2}$$

where U^p is the plastic strain energy density, U^d is the damage dissipation density and U^v is the stored energy density of cold work. As suggested by Lemaitre and Chaboche et al.,[27] U^v accounts only for 5–10% of the plastic strain energy density and is negligible. ϕ measures material's life expectancy before macroscopic failure and it is an index to explain the strength of bonding at macroscopic scale in a thermodynamic framework. The non-brittle failure of a material is a progressive process and is accompanied by the reduction in the material strength and increase in the dissipation. Large inelastic deformations are the result of the ductile failure of a material. It has been shown that the plastic flow of a material and the material damage are two different physical processes.[27] If the material failure is controlled by the damage dissipation and the microscopic mechanism of failure is the coalescence of the adjacent porosities then the continuum damage failure criteria can be applied. Otherwise, the failure of the control volume is mainly controlled by the elastic and plastic strain energy densities. The application of the total dissipated energy for defining a failure criterion was also explained by Benallal et al.[28] Collins and Kelly [29] assessed some well-known existing critical-state models for geomaterials and indicated their shortcomings. They showed in any failure criterion that irreversible plastic deformations would happen without generating any dissipation,