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Numerical and experimental study of the stability of non-circular boreholes in high-permeability formations

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ABSTRACT

One innovative drilling concept explored in recent years is based on the use of a non-circular well cross section, in particular a well with grooves running along the well axis. The grooves are expected to improve wellbore hydraulics and hole cleaning. In the present study, borehole stability analysis has been carried out for a horizontal rifle well in a high-permeability formation. It has been found that tensile failure is likely to develop at several locations around the non-circular cross section, a failure mode that is not normally found in conventional (circular) wells. The numerical results obtained with a finite-element code have been qualitatively confirmed in a dedicated laboratory experiment performed on a block of concrete with a section of non-circular well. In the experiment, the unusual failure mode was clearly observed. Traditional breakouts were also observed in the same test, but had smaller size. Numerical simulations have been carried out for different drilling conditions, both onshore and offshore, and depths from 1000 m to 2000 m, normal or abnormal pore pressure. The borehole was always found to fail in tension unless a considerable overbalance was applied by the drilling fluid. Similar results were obtained with formations that had hydrostatic pore pressure, elevated pore pressure (overpressure) or reduced pore pressure (underpressure, depleted reservoirs). The results are of importance for practical application of non-circular wells.

1. Introduction

With steadily increasing depth of hydrocarbon reserves, novel technologies are needed that would make drilling safer, more cost-effective and more environmentally-friendly. Current challenges in drilling, in particular drilling of horizontal wells, include friction between the drill string and the borehole wall, as well as elevated annulus pressures required to circulate the drilling fluid and to transport cuttings out of the hole. Rifle well is an innovative drilling concept that was originally expected to significantly reduce the friction between the drill string and the borehole wall and to improve the circulation and cleaning of the hole [1]. The ongoing experiments seem to indicate that this might not be the case in a practical setting. This issue will be subject of a future publication.

At each point along the length of a rifle well, its cross section looks like a traditional circular cross section, in which several (in the current design: four) grooves have been made. This non-circular shape rotates around the well axis as it moves along the length of the well. Each groove thus follows a helix pattern along the well (Fig. 1). Due to the helix pattern, the contact area between the string and the wall is reduced. Moreover, the grooves create continuous flow pathways for the drilling fluid.

The "rifle profile" considered in this study is not the only conceivable non-circular profile. However, since the rifle profile is the main focus of the current research activities on non-circular wells, this profile was chosen for our borehole stability analysis.

In oil industry, drilling is carried out with the drilling fluid ("drilling mud") that is pumped down the well through a central channel in the drill pipe. The fluid returns to the surface via the

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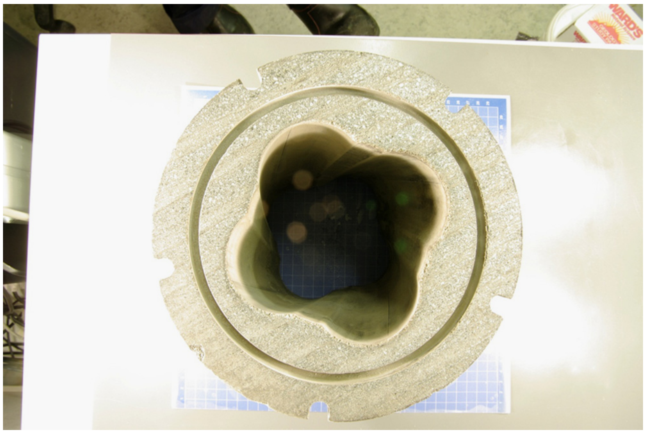

Fig. 1. Non-circular hole in a concrete block used in the laboratory tests.

annulus between the drill string and the borehole wall, and it transports drill cuttings to the surface. Apart from cleaning the hole from the drill cuttings, another important function of the drilling fluid is to provide sufficient support on the borehole wall to keep the hole stable. If the mud weight is too low, the borehole may collapse. This typically happens by development of so-called breakouts (dog ear shaped failure zones) along the borehole [2–4]. If the mud weight is too high, the fluid may escape into the porous or fractured formation surrounding the borehole, resulting in mudlosses, or it may even generate new fractures in the formation [3,5]. Keeping the mud weight within the range delimited by the two types of borehole instability, i.e. breakouts and mudlosses/fracturing, the so-called "mudweight window", is one of the prerequisites for successful drilling operations.

If the drilling fluid pressure in the borehole is equal to the formation of fluid pressure, i.e. the pore pressure, the drilling is said to be in balance. If the borehole pressure is higher than the pore pressure, the drilling is said to be overbalanced. If the borehole pressure is below the pore pressure, the drilling is said to be underbalance. Traditionally, drilling has been carried out in overbalance. However, underbalance drilling is known to have certain advantages, in particular an improved rate of penetration, but more importantly reducing the risk of fracturing weak formations. Therefore, in the last decades, underbalance drilling has often been successfully employed in oil industry.

Borehole stability is one of the issues that need to be clarified before non-circular well technology can be taken out of the laboratory and into the field. Due to the geometry, it is expected that stress concentrations may arise around the non-circular profile that otherwise would not be there had the cross section had a conventional circular shape. Even though stress distributions and failure modes around concave non-circular tunnels and perforations have been studied before (e.g. [6,7]), the non-circular boundary of the rifle well has some parts that are convex. This leads to a new failure mode, as we shall see below, and thus requires a dedicated study.

2. Finite-element borehole stability analysis

Finite-element analyses of tensile failure around the non-circular profile are carried out for different depths and overbalance conditions. Shear failure, i.e. breakouts, is not considered in this study, since it is covered in depth in classical treatments of borehole or tunnel stability (e.g. [3,8]). It should be noted however that shear failure is expected to be exacerbated with non-circular profile as compared with circular wells since the grooves are stress concentrators that can facilitate shear failure. Since this mechanism is no different with non-circular wells than with circular wells, it is not considered in this paper (we will however see examples of shear failure, i.e. breakouts, in the experiment presented in Section 3).

High-permeability rocks, e.g. reservoir sandstones, are considered in this analysis. Permeability of reservoir sandstones can be on the order of hundreds of milliDarcy. Therefore, a filter cake can easily be deposited on the borehole wall soon after the borehole has been drilled. The filter cake then provides a hydraulic insulation of the porous media from the borehole pressure. The latter thus does not propagate into the formation, after the cake is set. Initial transients of the pore pressure in the near-well area are assumed to equilibrate quickly because of the high permeability. Therefore, the pore pressure distribution in the formation can be assumed to be the same as it was before drilling, i.e. uniform formation pore pressure. The borehole stability analysis can therefore be performed as a steady-state analysis in terms of both stress and hydraulic regime, with the borehole pressure equal to or different from the formation pore pressure. Stability of non-circular wells in low-permeability rocks, e.g. shales, is not covered in this study and should be subject of a separate analysis.

In porous media, the applied stresses are carried partly by the matrix, i.e. mineral grains, and partly by the saturating fluid(s). The part of the total normal stress transferred through the matrix is called effective stress. The part transferred through the pore fluids is called pore pressure, or formation fluid pressure. The effective stresses control stress–strain response of the material, and its strength. The total stress is controlled by the applied stress boundary conditions and thus enters the equilibrium equations of solid mechanics. In soil mechanics (e.g. [9]), it is usually assumed that normal total stress is simply a sum of the effective normal stress and the pore pressure (Terzaghi's principle). In competent rocks, on the other hand, the total stress is equal to a sum of the effective stress and a product of pore pressure with a dimensionless coefficient often called Biot effective stress coefficient α.

2.1. Simulation setup

Finite-element simulations were carried out with the commercial code ABAQUS. Poroelastic material model ("Biot poroelasticity") was used in the simulations. Since only steady-state was considered, the poroelastic parameters were of no consequence for stress distributions obtained in these simulations, except for the Biot effective stress coefficient, α. The latter was set equal to 0.92 in all simulations, which is within the range typically reported for sandstones (e.g. [10,11]).

Simulations were steady-state one-step simulations. The model geometry is shown in Fig. 2. The two orientations of the in situ far-field stresses shown in Fig. 2 represent different orientations of the non-circular profile with respect to the anisotropic in situ stress field studied herein. Since the non-circular cross section has rotational symmetry characterized by dihedral group D_4, it was sufficient to consider rotations by angles from 0° to 45°. We chose to run simulations with two extreme values of the rotation angle, i.e. 0° and 45° (Fig. 2).

The model analyzed with the finite-element method was a square block with the non-circular hole placed in the center. Assuming a horizontal non-circular well, the vertical in situ stress was applied at the top edge of the model. The horizontal stress perpendicular to the well was applied at the right-hand edge of the model. Rollers, i.e. zero normal displacements, were applied at the bottom edge and at the left-hand edge. The non-circular hole could be orientated so that the grooves were aligned with the in situ principal stresses ("rotation 0°", solid arrows in Fig. 2), or so that the protrusions were aligned with the in situ principal stresses ("rotation 45°", dashed arrows in Fig. 2).