Prediction of Optimal Perforation Orientation and Maximum Sand-Free Drawdown using a Finite Element Approach

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Results of a study for prediction of sand production in a 5000 m deep gas field on-shore Germany are presented. First a geomechanical model comprising stress magnitudes (all three principal stresses), stress orientations, and rock strength is developed for the field using information from wellbore logging and leak-off tests. Minifrac tests carried out at different reservoir depletions allow to constrain a stress path value which is used to extrapolate the changes in stress magnitudes to future expected depletions.

Rock mechanical triaxial tests of the Permian age reservoir sandstone allow to characterize the mechanical behavior and to derive a material model for use in finite element simulations. Simulations for arbitrary oriented boreholes and perforation orientations are carried out in order to quantify the maximum sand-free drawdown for each scenario. This is done for the initial reservoir pressure as well as for several depletion stages. The failure criterion that predicts the onset of sand production from the amount of plastic strain calculated in the finite element models is calibrated against sand production experience from a production test.

As a result of this study, optimally stable wellbore and perforation orientations are provided and maximum sand-free drawdowns are predicted that allow the operator to optimize the field development and production.

State of Stress

Detailed analysis of logging data, drilling experience, and analysis of wellbore failures such as breakouts and drilling induced tensile fractures are used to derive stress magnitudes and stress orientations for the reservoir section. While the overburden is characterized by a normal faulting stress regime, it is found that a strike-slip stress regime prevails in the reservoir. The North-South stress orientation is well documented by drilling induced fractures observed in electrical image logs and by analysis of breakouts from multi-arm caliper logs in several wells in the field. Stress magnitudes, initial reservoir pressure, and stress orientation for the reservoir are listed in Table 1. Determination of the least principal stress, S_{hmin}, by means of minifrac tests at different levels of reservoir pressure are used to derive the ratio between pore pressure change and change in horizontal stress magnitude. This so-called stress path value is used to extrapolate the changes in horizontal stress magnitudes to future expected depletions.

	SG	MPa
S_v	2.33	111.4
S_H	2.5	119.6
S_h	1.79	85.6
Pp	1.4	67.0
S_H azimuth	North - South	

Table 1: State of stress at initial reservoir conditions

Material Models for the Finite Element Analysis

In order to realistically model sand production in the reservoir formation, mechanical descriptions of the sandstones are derived that incorporate the most important physical properties of the reservoir rock. To achieve this, the reservoir rock is treated as an elasto-plastic material. In addition, this material is considered to be porous with the pore space fully saturated by a single phase fluid. Analysis of triaxial laboratory tests shows that the mechanical behavior of the tested rocks can adequately be described by a Mohr-Coulomb material model that includes strain hardening.

Stress-Strain curves for triaxial tests at different confining pressures (Figure 1) are fitted by an elasto-plastic material model with an elastic part, followed by a strain hardening part, and finally a perfectly plastic part.

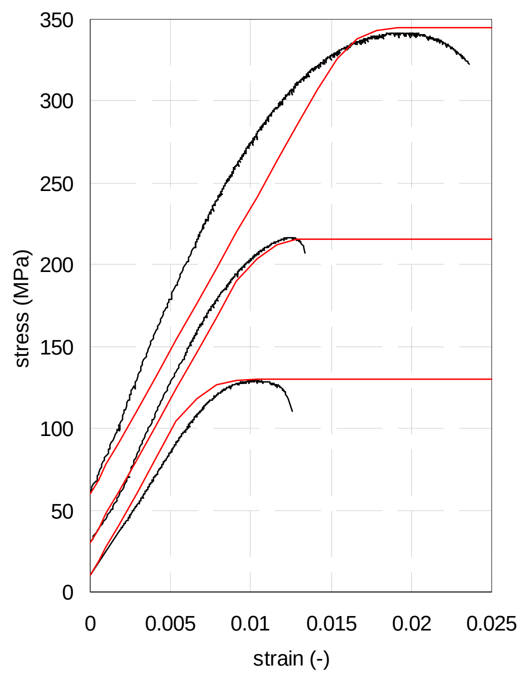

Figure 1. Axial stress versus axial strain for a material model (smooth lines) and triaxial test data (rough lines) for the reservoir rock.

Calibration of Failure Criterion

As a failure criterion a critical value of total plastic strain is used. This value is calibrated to field experience collected during a production test carried out in well W-1. No further calibration to thick wall cylinder tests is carried out as such tests were not available. Because substantial sand production is not experienced during the production test in well W-1 even at high drawdown, the calibration is conservative as it assumes that the highest drawdown applied during the production test is the onset of sand production. For the calibration, finite element simulations are carried out using the stress model described above combined with the information provided for the perforated interval and the material model displayed in Figure 1. The goal of these simulations is to calculate a value of total plastic strain that relates to the maximum drawdown conditions during the production test. It is found that the maximum sand-free drawdown of 383 bars observed in well W-1 corresponds to a total plastic strain of 8 mstrain. Thus, we use 8 mstrain as the critical value of total plastic strain in the reservoir sands.

Prediction of Sand Production

Using the stress information and the material models derived from rock mechanical laboratory tests, a large number of finite element simulations for various combinations of well and perforation orientations are carried out. Figure

2 summarizes results for wells drilled with an inclination of 30º and perforated to the sides of the well. The hole azimuth varies from 95º, through 105º, 115º, 125º, to 135º. The diagram allows identification of the maximum possible sand-free drawdown for each of these wells at any given reservoir pressure for a reservoir formation characterized by the material model that is used for these simulations.

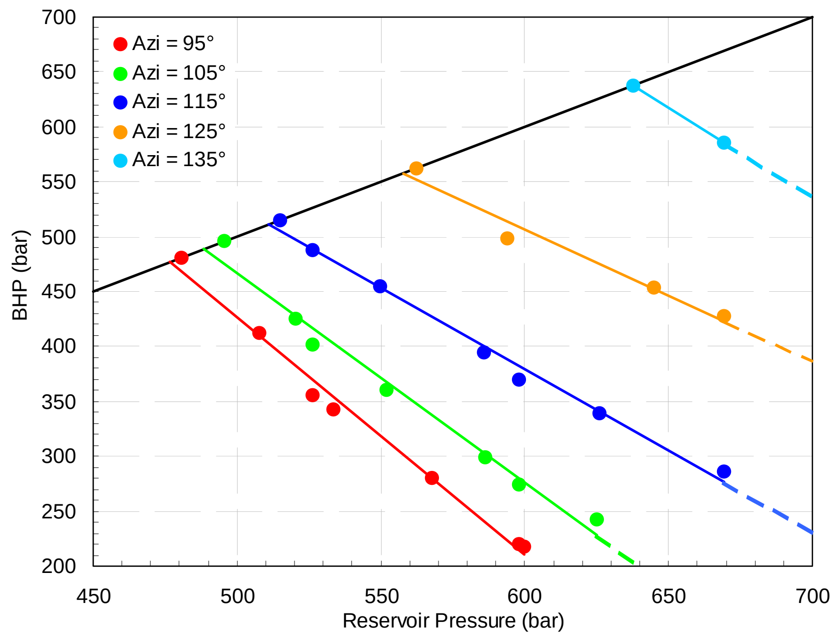

Figure 2. Bottom hole pressure (BHP) vs. reservoir pressure calculated for a well inclination of 30° and horizontal perforations. The solid black line is the BHP=Reservoir pressure line. A producing well will always plot below this line. The colored lines correspond to different wellbore azimuths. A well is stable during production when the corresponding BHP and reservoir data plot between the black and colored line. The difference between the black and colored line in the BHP direction at a given reservoir pressure is the maximum sand free drawdown for that reservoir pressure. For example, a well with an azimuth of 115° (blue line) at a reservoir pressure of 550 bars can produce sand-free with a BHP of 454 bars (96 bar drawdown).

An important goal of the study is to identify the optimal combination of drilling direction and perforation orientation to avoid sand production during production and to quantify the maximum sand-free drawdowns for each of these combinations. This task is carried out for a range of depletion scenarios. For example, Figures 3 & 4 display results for horizontal wells drilled along the direction of the least horizontal principal stress, S_{hmin} (Fig. 3), and along the major horizontal principal stress, S_{Hmax} (Fig. 4). Both figures display results for horizontal perforations, vertical perforations, and perforations inclined at angles of 15º, 30º, and 45º with respect to the horizontal direction. The horizontal red line marks the critical value for the onset of sand production that is determined from the production test.

The well drilled along the S_{hmin} direction (Fig. 3) is unstable for any perforation orientation even at very small drawdowns (for all scenarios, total plastic strains are calculated significantly above the critical total plastic strain). The well drilled along the S_{Hmax} direction, however (Fig. 4), can be produced sand-free to very high drawdown values from either vertical perforations or perforations inclined up to 30º with respect to the vertical direction.

Simulations for different depletion scenarios (Fig. 5) indicate that wells drilled along the S_{Hmax} direction and perforated in up-down directions will be stable even for large reservoir depletions.

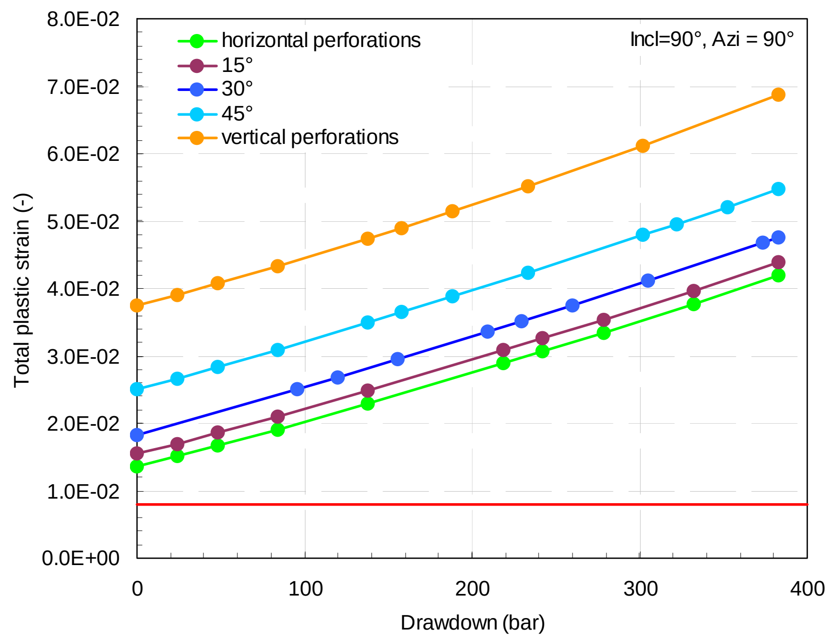

Figure 3. Total plastic strain vs. drawdown for a horizontal wellbore parallel to S_{hmin}. The different curves correspond to different perforation directions. The red horizontal line is the critical total plastic strain limit at which sand production is predicted.

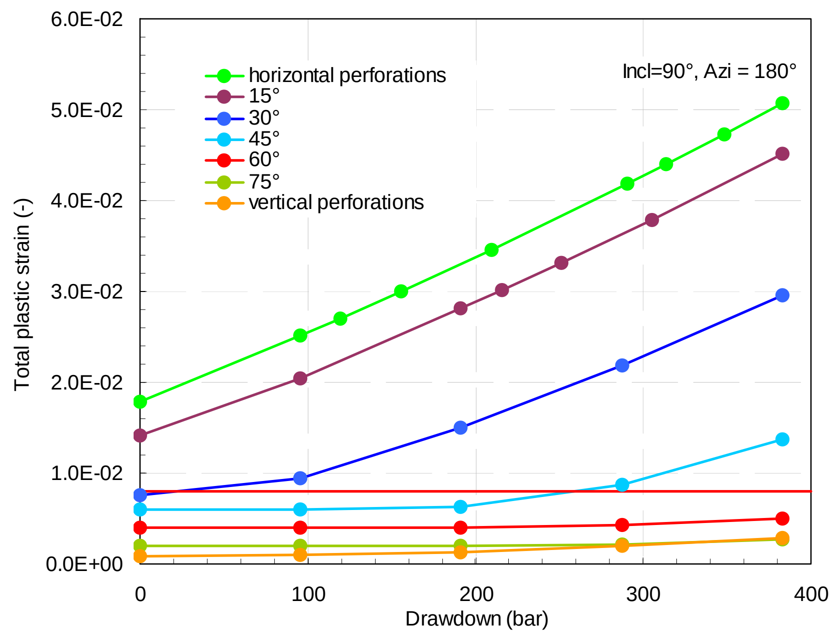

Figure 4. Total plastic strain vs. drawdown for a horizontal wellbore parallel to S_{Hmax}. The different curves correspond to different perforation directions. The red horizontal line is the critical total plastic strain limit at which sand production is predicted.

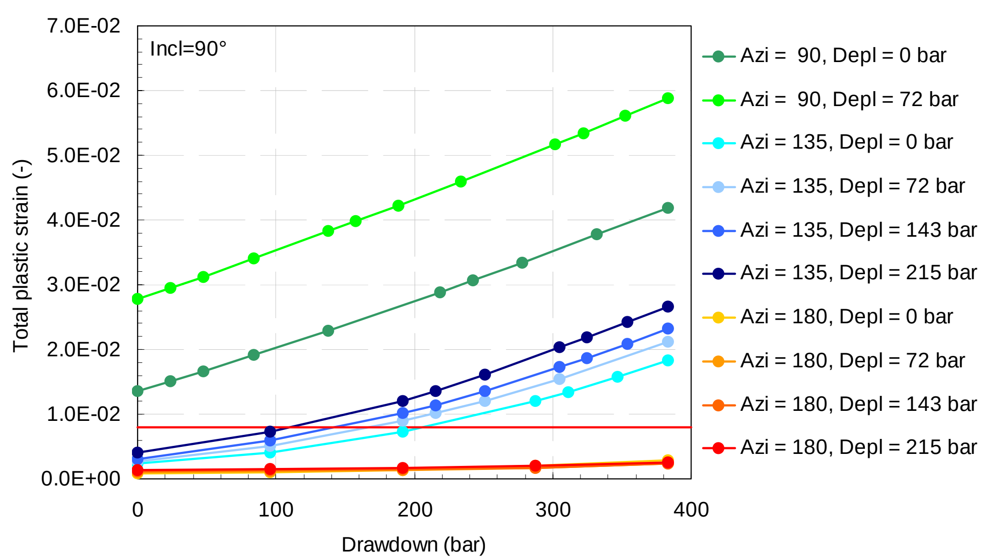

Figure 5. Total plastic strain vs. drawdown for horizontal wells perforated in the most favorable direction. For each direction, a set of depletions is plotted. The red horizontal line is the critical total plastic strain limit at which sand production is predicted.