Physical rock properties relevant for deep drilling

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Geological-tectonic cross section for Switzerland
(from Labhart T. P.: Geologie der Schweiz, 1992)

Simplified cross section
In Switzerland, there are only 9 boreholes deeper than 3 km. According to my knowledge, none of them went into the crystalline basis.
What do we need to know to estimate the borehole stability

- **Rock stresses *in situ***
  - vertical overburden stresses \( \sigma_v \)
  - horizontal (tectonic) stresses \( \sigma_{H_{\text{max}}} \) and \( \sigma_{h_{\text{min}}} \)
  - Pore pressures \( p_0 \)

- **Rock failure strength**
  - Shear strength parameters such as
    - angle of internal friction and
    - cohesion

- **Pressure \( p_w \) inside the borehole**
  - from some kind of casing
  - mud pressure

As a function of rock temperature and the existing in situ stresses
The in situ stress field consists of natural earth stresses and pressures, generated by gravity, tectonics...

A reason for different horizontal stresses at a certain depth $z$ (= anisotropic stress state) is tectonic stresses.

Borehole stresses are generated by creation of an opening in a natural stress field.

As a result, a stress concentration is produced around the borehole, and so the in situ stresses are modified. This could lead to rock failure.
In situ stresses in the rock

- The vertical principal in situ stress $\sigma_v$ is usually assumed to be equivalent to the weight of the overburden, i.e.

$$\sigma_v = z \cdot \gamma$$

- Generally the ratio of the minimum horizontal stress $\sigma_{h\text{ min}}$ to the vertical stress $\sigma_v$ is within the limits of:

$$\frac{\sigma_{h\text{ min}}}{\sigma_v} = 0.3 \text{ to } 1.5$$

- and the ratio of the maximum horizontal stress $\sigma_{H\text{ max}}$ to the minimum horizontal $\sigma_{h\text{ min}}$ stress ranges from:

$$\frac{\sigma_{H\text{ max}}}{\sigma_{h\text{ min}}} = 1 \text{ to } 2$$

1 = isotropic stress field
Stresses around vertical boreholes in anisotropic stress field

Stress calculation approach for Linear Elastic rock behavior based on the “Kirsch” Equations

\[
\sigma_r = \frac{\sigma_H + \sigma_h}{2}\left(1 - \frac{R_w^2}{r^2}\right) + \frac{\sigma_H - \sigma_h}{2}\left(1 + 3\frac{R_w^4}{r^4} - 4\frac{R_w^2}{r^2}\right)\cos 2\theta + p_w \frac{R_w^2}{r^2}
\]

\[
\sigma_\theta = \frac{\sigma_H + \sigma_h}{2}\left(1 + \frac{R_w^2}{r^2}\right) - \frac{\sigma_H - \sigma_h}{2}\left(1 + 3\frac{R_w^4}{r^4}\right)\cos 2\theta - p_w \frac{R_w^2}{r^2}
\]

\[
\sigma_z = \sigma_v - 2\nu_{fr}(\sigma_H - \sigma_h)\frac{R_w^2}{r^2}\cos 2\theta
\]

At the wall of the borehole (r = R_w) the equations simplify to:

\[
\sigma_r = p_w
\]

\[
\sigma_\theta = \sigma_H + \sigma_h - 2(\sigma_H - \sigma_h)\cos 2\theta - p_w
\]

\[
\sigma_z = \sigma_v - 2\nu_{fr}(\sigma_H - \sigma_h)\cos 2\theta
\]

\(\theta\) is measured relative to the direction of the major horizontal stress \(\sigma_H\)
Stresses around vertical boreholes

Assume for an isotropic stress field
\[ \sigma_{\text{HMAX}} = \sigma_{\text{hmin}} = \sigma_h \]

It is assumed that the borehole wall is impermeable (i.e. casing or perfect mud cake), and that the pore pressure in the rock is zero.

- **Pressure inside borehole \( p_w = 0 \):**
  - \( \sigma_r \)
  - \( \sigma_\theta \)
  - \( \sigma \)

- **Pressure inside borehole \( p_w = 0.3\sigma \):**
  - \( \sigma_r \)
  - \( \sigma_\theta \)
  - \( \sigma \)

- **Pressure inside borehole \( p_w = 0.8\sigma \):**
  - \( \sigma_r \)
  - \( \sigma_\theta \)
  - \( \sigma \)

Radius \( r \)
Borehole failure criteria based on Mohr-Coulomb

Mohr-Coulomb failure criterion

$$\tau = S_0 + \sigma \cdot \tan \varphi$$

- $S_0 = \text{cohesion [kPa]}$
- $\varphi = \text{angle of internal friction [°]}$

Redefining

$$\beta = \frac{\pi}{4} + \frac{\varphi}{2}$$

$$C_0 = 2 \cdot S_0 \cdot \tan \beta$$

Reformulated Mohr-Coulomb failure criterion

$$\sigma_1 = C_0 + \sigma_3 \cdot \tan^2 \beta$$
Conditions for shear failure in vertical borehole for isotropic stress field and impermeable borehole wall

<table>
<thead>
<tr>
<th>$\sigma_1 \geq \sigma_2 \geq \sigma_3$</th>
<th>Borehole failure occurs if</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_\theta \geq \sigma_z \geq \sigma_r$</td>
<td>$p_w \leq p_f + \frac{2(\sigma_h - p_f) - C_0}{1 + \tan^2 \beta}$</td>
</tr>
<tr>
<td>$\sigma_z \geq \sigma_\theta \geq \sigma_r$</td>
<td>$p_w \leq p_f + \frac{\sigma_v - p_f - C_0}{\tan^2 \beta}$</td>
</tr>
<tr>
<td>$\sigma_z \geq \sigma_r \geq \sigma_\theta$</td>
<td>$p_w \geq p_f + 2(\sigma_h - p_f) - \frac{\sigma_v - p_f - C_0}{\tan^2 \beta}$</td>
</tr>
</tbody>
</table>

and hydraulic fracturing occurs at

\[
p_{w,\text{max}} = 2 \cdot \sigma_h - p_f + T_O
\]

where $T_O = $ tensile strength of the rock

The principal stresses at the borehole wall are

\[
\begin{align*}
\sigma_r &= p_w \\
\sigma_\theta &= 2\sigma_h - p_w \\
\sigma_z &= \sigma_v
\end{align*}
\]

In summary we can state

- $\sigma_\theta$ is the tangential stress, also called the hoop stress.
- $\sigma_\theta$ lies parallel (tangential) to the borehole wall.
- The magnitude of $\sigma_\theta$ is affected by:
  - In situ stresses
  - Stabilizing pressure inside the borehole
  - Temperature and rock behavior
- The most critical stress conditions are around a borehole:
  - High $\sigma_\theta$ values can lead to rock failure or yield
  - Lower $\sigma_\theta$ values usually imply stability
What information do we need to successfully lower a deep borehole and keep it open

- **First, we need stresses around the borehole**
  - In *in situ stresses* are vital
  - Temperature profile; thermally induced changes in stress affect both the tangential and the axial stress.
  - In some cases, rock properties are also needed

- **Then, we must compare the maximum shear stress with the rock strength**
  - We need to know the *rock strength for the in situ temperature, creep behavior for long term stability and deformation properties*

- *If stress exceeds strength, the rock will yield or “fail”*
What information do we need to successfully lower a deep borehole and keep it open

- The only possibility to stabilize a borehole from failing or yielding is by providing some kind of lateral support $p_w$ from within the borehole. This could be:
  - some casing
  - fluid pressure

- It is of greatest importance to estimate/calculate/control this stabilizing support during all phases of drilling. If a fluid pressure is used, care has to be exercised to be within the pressure band of possible minimum and maximum values
References

• ARGE Geothermie Espace Bern, «Grundlagenstudie Tiefengeothermie Espace Bern», 45 p; Juni 2010

• Fuchs F., «Conceptual Model for a geothermal enhanced district heating grid in Thun, CAS DEEGEOSYS University of Neuchâtel, 18 p; 2011 - 2012,


• Labhart, T., «Geologie der Schweiz», 1992

Thank you

Questions?