Effects of loading rate and saturating fluid on chalk mechanical behavior

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Motivation

Many oil and gas fields in the North Sea are found in very porous over-pressured chalk formations which compact significantly during the lifetime of the field

→ contributes significantly to the recovery mechanism, in some areas of the Valhall field up to 50-60 %

→ sea bed settlement (ref Valhall and Ekofisk)

→ Implications for foundation, and well casing failure

Reservoir compaction: 1) result of changes in effective stresses, 2) water weakening of the chalk during massive seawater injection.

Chalk mechanical behavior is susceptible to changes in several parameters: Pore fluid composition, porosity, strain/load rate

Chalk exhibit pronounced creep deformations under constant load at high stresses or near the strain rate dependent elastic-plastic limit
Background for current tests

### In situ conditions

<table>
<thead>
<tr>
<th>Stress / Pore pressure</th>
<th>(MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total vertical stress $\sigma_V$</td>
<td>22.5</td>
</tr>
<tr>
<td>Initial total horizontal stress $\sigma_H$</td>
<td>18.0</td>
</tr>
<tr>
<td>Initial octahedral stress $\sigma_{oct}$</td>
<td>19.5</td>
</tr>
<tr>
<td>Initial Reservoir Pressure $P_o$</td>
<td>13.5</td>
</tr>
<tr>
<td>Initial Effective vertical stress $\sigma'_{V}$</td>
<td>9.0</td>
</tr>
<tr>
<td>Initial Effective horizontal stress $\sigma'_{H}$</td>
<td>4.5</td>
</tr>
<tr>
<td>Initial Effective octahedral stress $\sigma'_{oct}$</td>
<td>6.0</td>
</tr>
</tbody>
</table>

### Pore fluid

<table>
<thead>
<tr>
<th>Salt</th>
<th>Concentration (g/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaCl</td>
<td>58</td>
</tr>
<tr>
<td>KCl</td>
<td>-</td>
</tr>
<tr>
<td>CaCl$_2$, 6 H$_2$O</td>
<td>55.6</td>
</tr>
<tr>
<td>MgCl$_2$, 6 H$_2$O</td>
<td>8.5</td>
</tr>
</tbody>
</table>

Gas and brine (~30%) saturated

### Conducted tests

- Uniaxial strain, depletion (CAUST)
  - vertically drilled plugs

- Isotropic, drained
  - horizontally drilled plugs

### Conducted tests

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Porosity (%)</th>
<th>Fluid type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1131.45</td>
<td>39.9</td>
<td>brine</td>
</tr>
<tr>
<td>1133.55</td>
<td>34.6</td>
<td>brine</td>
</tr>
<tr>
<td>1309.56</td>
<td>30.6</td>
<td>dry</td>
</tr>
<tr>
<td>1309.56</td>
<td>31</td>
<td>brine</td>
</tr>
<tr>
<td>1309.56</td>
<td>31</td>
<td>brine</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Porosity (%)</th>
<th>Fluid type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1128.55</td>
<td>36.85</td>
<td>30% brine</td>
</tr>
<tr>
<td>1131.00</td>
<td>30.6</td>
<td>brine</td>
</tr>
<tr>
<td>1132.90</td>
<td>37.83</td>
<td>30% brine</td>
</tr>
<tr>
<td>1134.10</td>
<td>36.3</td>
<td>brine</td>
</tr>
<tr>
<td>1134.20</td>
<td>36.2</td>
<td>brine</td>
</tr>
<tr>
<td>1134.20</td>
<td>33.8</td>
<td>brine</td>
</tr>
</tbody>
</table>
Experimental approach

0% brine saturation  →  directly built into triax for test
100% brine saturated  →  built directly into triax and saturated in the cell
30% brine saturation  →  saturated in vacuum chamber w/diluted solution, evaporation to target weight/saturation level,

Homogeneous fluid distribution along the core axis verified with X-ray CT
Results – fluid and porosity effects

Pore fluid composition has a pronounced effect on the behavior of chalk:
- Alters stiffness, elastic-plastic transition (pore collapse), creep rate.
Water weakening effect upon flooding:
- Instantaneous permanent deformation and increase of creep rate
- Radical increase up to 15% water saturation in initially oil saturated chalk
- Not as well documented for water flooding in initially gas saturated samples
Results – fluid and porosity effects
Results – fluid and porosity effects

Before Pc

$C_{pe} = 1 / (K n)$

Trend line $K = 83596e^{-11.3n}$

After Pc

$C_{bp} = \frac{d\varepsilon_y}{dp} = \frac{\lambda}{(1 + e_0)p}$

Trend line $\lambda = 0.032e^{4.1n}$

(after JCR database and Hickman 2004)
Results – fluid and porosity effects

Failure envelope largely depend on saturating fluid and porosity.
Results – rate sensitivity

... but also on load rate!
Results – rate sensitivity (load phase)

\[ Et = \frac{\Delta \sigma^\text{\textacute{oct}}}{\Delta \varepsilon^\text{\textacute{oct}}} \]

\[ \sigma^\text{\textacute{mean}} = \sigma^\text{\textacute{oct}} \]
Results – rate sensitivity (0.01MPa/h)

36.2%  $E_t=0.50$

30.6%  $E_t=0.97$

33.8%  $E_t=0.81$

Porosity $\uparrow$ = $E_t$ $\downarrow$
Results – rate sensitivity (0.10MPa/h)

- $36.2\%$  $E_t=0.28$
- $30.6\%$  $E_t=0.58$
- $33.8\%$  $E_t=0.74$

Strain hardening


graphs showing the relationship between effective vertical stress ($\sigma_v'$) and volumetric strain ($\varepsilon_{oct}$) with corresponding regression equations and $R^2$ values.
Results – rate sensitivity (1.0MPa/h)

36.2% \( E_t = 0.26 \)

30.6% \( E_t = 0.59 \)

33.8% \( E_t = 0.75 \)

36.9% \( E_t = 0.50 \)

Strain hardening
Results – rate sensitivity (10.0MPa/h)

36.2%

30.6%

33.8%

Load rate $\uparrow$ = $E_t \downarrow$

36.9%  $E_t$=0.17

37.8%  $E_t$=0.19
## Results – rate sensitivity (load phase)

<table>
<thead>
<tr>
<th>Test type</th>
<th>Fluid type</th>
<th>Porosity (%)</th>
<th>Mean stress (MPa)</th>
<th>Mean stress rate (MPa/h)</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$p_1$</td>
<td>$p_2$</td>
<td>$\dot{p}_1$</td>
</tr>
<tr>
<td>Isotropic</td>
<td>brine</td>
<td>36.2</td>
<td>14.1</td>
<td>16.1</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>20.61</td>
<td>24.18</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>34.6</td>
<td>43.7</td>
<td>0.01</td>
</tr>
<tr>
<td>Isotropic</td>
<td>brine</td>
<td>30.6</td>
<td>31.1</td>
<td>41.77</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>50.64</td>
<td>57.27</td>
<td>0.1</td>
</tr>
<tr>
<td>Isotropic</td>
<td>brine</td>
<td>33.8</td>
<td>22</td>
<td>28</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>42</td>
<td>45.77</td>
<td>0.1</td>
</tr>
<tr>
<td>Isotropic</td>
<td>30% brine</td>
<td>36.9</td>
<td>23.5</td>
<td>25.9</td>
<td>1</td>
</tr>
<tr>
<td>Isotropic</td>
<td>30% brine</td>
<td>37.83</td>
<td>21.37</td>
<td>23.66</td>
<td>1</td>
</tr>
</tbody>
</table>

Visco-plastic rate dependent compaction model (de Waal)

$$
\dot{p} = \frac{\dot{\varepsilon}_v}{c_{b,o}} + b \frac{\dot{\varepsilon}_v}{\varepsilon_v}
\quad \Rightarrow \quad \frac{p_2}{p_1} = \left(\frac{\dot{\varepsilon}_{v2}}{\dot{\varepsilon}_{v1}}\right)^b
$$

$$
b = \frac{\ln\left(\frac{p_2}{p_1}\right)}{\ln\left(\frac{\dot{p}_2}{\dot{p}_1}\right)}
$$
Results – rate sensitivity (creep phase)

\[ \dot{\varepsilon}_v^t = b c_{b,0} p \ln \left[ 1 + \frac{\dot{\varepsilon}_{vo} t}{b c_{b,0} p} \right] \]

\[ C_c = b c_{b,0} p, \quad \tau = b c_{b,0} p / \dot{\varepsilon}_{vo} \]

\[ \dot{\varepsilon}_v^t = \frac{C_c}{t + \tau} \]

\[ \sigma'_{\text{mean}} = 32.0 \text{ MPa} \]

\[ \sigma'_{\text{mean}} = 50.3 \text{ MPa} \]

<table>
<thead>
<tr>
<th>Mean Stress ( p ) (MPa)</th>
<th>Slope inverse strain rate vs time ( 1/C_c )</th>
<th>Offset ( \tau / C_c )</th>
<th>( \dot{\varepsilon}_{vo} ) (mS)</th>
<th>( c_{b,0} ) (/MPa)</th>
<th>( b )</th>
</tr>
</thead>
<tbody>
<tr>
<td>31.86</td>
<td>0.1986</td>
<td>1.3701</td>
<td>0.7299</td>
<td>0.0024</td>
<td>0.0651</td>
</tr>
<tr>
<td>50.22</td>
<td>0.1496</td>
<td>0.7708</td>
<td>1.2973</td>
<td>0.0049</td>
<td>0.0271</td>
</tr>
</tbody>
</table>
Results – rate sensitivity (creep phase)

$\text{Volumetric strain (mS)}$

$\text{Time, } t^* \text{ (hours)}$

$b = 0.651$

$b = 0.271$

0.045 (dry) to 0.108 (fully water-saturated)

$b = 0.17 e^{-3.1n} \rightarrow 0.054-0.065$

Priol (2006), Lixhe outcrop chalk

Kristiansen & Plischke (2010), Valhall field
Relating laboratory data to field

At $\varepsilon_r = 10\%$

<table>
<thead>
<tr>
<th>lab</th>
<th>in situ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Berthierville : 3.0 - 3.9 m</td>
<td>O</td>
</tr>
<tr>
<td>Berthierville : 3.9 - 4.8 m</td>
<td>△</td>
</tr>
<tr>
<td>Saint-Alban : 3.1 - 4.9 m</td>
<td>□</td>
</tr>
<tr>
<td>Väsbys : 4.3 - 7.3 m</td>
<td>◊</td>
</tr>
</tbody>
</table>

At $\varepsilon_r = 10\%$

$$\left(\frac{\sigma_{\text{field}}}{\sigma_{\text{yield}}}\right)^b = \left(\frac{\dot{\varepsilon}_{\text{field}}}{\dot{\varepsilon}_{\text{lab}}}\right)$$

Trend lines for field depletion rates

Porosities not compatible with in situ stress state
Modelling field deformation

Initialize stresses, pressure, porosity dependent parameters

Main loop repeated n times, \( \Delta u = u_{\text{f}}/n \)

Update stresses and pore pressure

\[
\begin{align*}
\sigma' &= \sigma'_{\text{f}} + \Delta u \\
\sigma'_{\text{h}} &= \sigma'_{\text{h}} + \Delta K' \Delta u \\
p &= (\sigma'_{\text{f}} + 2\sigma'_{\text{h}})/2 \\
p_{\text{sep}} &= p + \frac{q^2}{M^2 + p}
\end{align*}
\]

Pore collapse?

\( P_{\text{eqp}} \geq P_{\text{c}, \text{field}} \)

Yes \( \rightarrow \) Plastic compressibility

\( C_b = \frac{\lambda}{(1 + e_0)p_{\text{sep}}} \)

No \( \rightarrow \) Elastic compressibility

\( C_b = \frac{1}{K} \)

Calculate increments of volumetric strain and void ratio

\[
\begin{align*}
d\varepsilon_{\text{vol}} &= C_{\nu} d p_{\text{sep}} \\
de &= (1 + e_0) d\varepsilon_{\text{vol}}
\end{align*}
\]

Update variables

\[
\begin{align*}
\varepsilon_{\text{vol}} &= \varepsilon_{\text{vol}} + d\varepsilon_{\text{vol}} \\
e &= e - de \\
n &= \frac{e}{1 + e}
\end{align*}
\]

Calculate equivalent compressibility

\[
C_{\text{eqv}} = \frac{\varepsilon_{\text{vol}}}{(u_0 - u)}
\]
Summary

Demonstrated porosity, rate and saturating fluid effects on mechanical behavior:

Chalk exhibit rate dependent stiffness: 0.01 MPa/h > 0.10 MPa/h > 1.00 MPa/h > 10.00 MPa/h

Only subtle difference between mech. response at 30% brine saturation as vs 100% saturation (\(P_c\) and \(E_t\) slightly higher, \(b\) slightly lower)

The elastic and plastic compression properties of the chalk have been compared to available data from open literature: fit within the general scatter observed for chalk and proposed porosity-dependent correlations.

Laboratory experiments have been analyzed within the frame work proposed by de Waal (1986) to characterize the time and rate dependent behavior: agreement with other chalk data from the open literature.

A simple model is developed, and based on the defined material correlations it estimates the volumetric strain due to depletion.