Consolidation of water saturated shales at great depth under drained conditions


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ABSTRACT: The principles of critical state mechanics appear to apply for shales. The isotropic consolidation behavior of four shales have been investigated experimentally at effective pressures of 1 to 65 MPa to evaluate some critical state parameters as a function of mineralogy and porosity. Sample volume change as a function of effective pressure was measured to determine the normal consolidation (NCL) and over consolidation (OCL) lines. The slopes of the NCL and OCL (λ and κ) are distinct for the four shales. The slopes of the NCL correlate strongly with porosity and with the sum of porosity and swelling clay content, i.e. the water sources. The slopes of the OCL correlate with non-swelling minerals (clays and non-clays), i.e. the elastic components. The results suggest that careful mineralogical and porosity characterizations may be used to estimate both isotropic consolidation and deformation parameters of shales.

RESUME: Les principes de la mécanique à l'état critique sont applicables également aux schistes. Dans un appareil triaxial on a étudié le comportement de consolidation isotrope de quatre schistes à des pressions effectives de 1 à 65 MPa, afin d'étudier leur caractéristiques en fonction de leur minéralogie et de leur porosité. Le changement de volume de l'échantillon en fonction de la pression effective a permis de déterminer les courbes de consolidation normale (NCL) et de sur-consolidation (OCL). Les pentes des courbes NCL et OCL (λ et κ) sont distinctes pour les quatre schistes. Le pente de la courbe NCL est en forte corrélation avec la porosité, ainsi qu'avec la somme de la porosité et du contenu en argile gonflante, la principale provenance d'eau. La courbe OCL est en corrélation avec la teneur en minéraux argileux non-gonflants et minéraux non-argileux qui représentent les composants élastiques. Il en résulte qu'une caractérisation soigneuse de la minéralogie et de la porosité des schistes permet de connaître leur comportement de consolidation isotrope et de déformation.


I. INTRODUCTION

Shales make up over 75% of sedimentary rocks near the Earth's surface. They are often encountered when excavating foundations and tunnels and are important liners for hazardous waste repositories. Shales are also the most common caprock for oil and gas reservoirs. Clays have been proposed as a possible host medium for the geological disposal of radioactive waste (e.g. Chapman, 1984). Failure of shale formations in repositories, tunnels and wells can increase drilling costs dramatically (e.g. Steiger and Leung, 1988). The prediction of wellbore stability in shale is one of the most important needs in the petroleum industry. Quantitative determination of physical properties of shales are necessary to constrain models of compaction and deformation of these important sedimentary rocks. Isotropic consolidation data are used in models that predict drainage in low permeability shales (e.g. Savage and Braddock, 1991) and models that make risk analyses of ground water movement near hazardous wastes.

Using clay compression experiments that related porosity to burial, Skempton (1970) demonstrated that the relation between void ratio and log overpressure is essentially linear for any clay. Moreover, at a given overburden pressure the porosity (void ratio) depends on the amount and type of clay minerals. Genetically the difference between shale and clay is the degree of lithification by diagenesis, which is mostly a pore size reduction, reorientation of particles and cementation. Although there is a macroscopic difference between a clay which behaves plastically and a shale which is brittle, consolidation of shales can be described using the principles of critical state soil mechanics developed for ideal clays (Johnston and Novello, 1985; Steiger and Leung, 1991).

The primary objective of this paper is to describe the consolidation behavior of four shales in terms of critical state mechanics. These rocks cover a wide spectrum of typical shale mineralogies and porosities, parameters easily determined from drill cuttings and rock density. This paper is part of a larger study on the mechanical and microstructural response of shales during consolidation and deformation under triaxial compression (Olgaard et al., 1993, 1994; Dell'Angelo et al., 1993).

1.2 Critical state parameters

The principles of critical state mechanics state that the behavior of a soil during isotropic consolidation (e.g. Wood, 1990) is a function of the specific volume (υ = 1-ΔV/Vo, where ΔV and Vo are the volume change and initial volume of the specimen, respectively) and the effective isotropic pressure (p' = confining pressure (Pc) - pore-fluid pressure (Pf)). During consolidation, υ of a soil decreases with increasing p' along a specific path (Figure 1). For an ideal clay, during initial, or virgin, isotropic compression the volume of an unconsolidated sediment decreases along a normal consolidation line (NCL) give by

υ = N - λlnp'

The maximum effective pressure reached along the NCL is p' max. Upon unloading, the volume change reverses, also along a straight-line path, but at a shallower slope. Unloading paths and reloading paths, the over consolidation lines (OCL), are given by...
\[ u = K - \lambda \ln \sigma' \]  
\[ p'_{\text{max}} = A - \kappa \ln \sigma' \]

and \( \lambda > \kappa \). If a specimen is reloaded to a effective pressure that exceeds the previous maximum (\( p' > p'_{\text{max}} \)), then the reloading path follows the OCL up to \( p'_{\text{max}} \) then continue along the NCL (Figure 1). The NCL describes the total deformation of a specimen (permanent and reversible) while the OCL describes only the reversible component.

Applying a differential load causes compaction initially, but will eventually induce dilation or compaction depending on the previous isotropic loading path. The neutral line superimposed onto the \( u \) vs. \( \ln p' \) plane is the critical state line (CSL) given by

\[ u = \Gamma - \lambda \ln \sigma' \]

i.e., the CSL is parallel to the NCL (Figure 1). The CSL is important for predicting high strain, non-isotropic compression behavior because deformations are considered at critical state when the CSL is reached where specific volume, differential stress (\( \Delta \sigma \)) and mean stress (\( \sigma' + \kappa \sigma / 3 \)) are independent of strain.

These critical state parameters can also help to understand non-isotropic deformations; for example, \( \lambda \) is the slope of the CSL in the \( u \) vs. \( \ln p' \) plane. Also, the parameter, \( \Lambda (= 1 - \kappa / \lambda) \), is a function of the undrained effective stress path and relates the undrained critical shear stress to the isotropic pressure (\( p' \)) at the initiation of non-isotropic loading and the over consolidation ratio (\( p'_{\text{max}} / p' \)) (e.g. Wood, 1990, section 7.2).

II. ANALYSES OF MINERALOGY AND POROSITY

II.1 Shale samples and material properties analyzed

Four shales with contrasting mineralologies and porosities: Pierre shale, Red mudstone, Black shale and Montigel bentonite, were characterized using X-ray diffraction, infrared spectroscopy, specific surface area analysis (BET), mercury injection porosimetry, and \( \Delta H_2O \) adsorption (Table 1). The black shale is the same material as the brown shale described in Urai and Wong (1994).

II.2 Distinguishing characteristics

Two shales have low swelling clay fractions and relatively low porosities. Pierre shale is a well-known "generic" shale often used in experiments. The mineralogy and porosity of the Pierre shale used here is intermediate for shales in general (Hoshino, 1972). However, a wide range of compositions are reported elsewhere. For example, Nichols et al. (1985) report a composition of 50 to 100% clay minerals, 60-100% of which is smectite and porosities as high as 35% from a single location. Red mudstone has a similar amount of non-clays to Pierre but almost no swelling clays. It has the lowest porosity of all shales analyzed.

Two shales have high swelling clay contents and high porosities. Black shale has approximately equal amounts of swelling clays and non-swelling clays, the highest porosity and the highest organic fraction. The organics are significant because, like the swelling clays, they can adsorb water. Montigel bentonite has the highest swelling clay content and similar amounts of non-clays and non-swelling clay minerals. It has a porosity only slightly higher than that of Pierre shale.

Table 1: Mineralogy and porosity

<table>
<thead>
<tr>
<th>Sample</th>
<th>Non-clays (wt%)</th>
<th>Non-swelling clays (wt%)</th>
<th>Swelling clays (wt%)</th>
<th>Total clay</th>
<th>Porosity (vol%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pierre</td>
<td>40</td>
<td>41</td>
<td>74</td>
<td>26</td>
<td>13</td>
</tr>
<tr>
<td>Red</td>
<td>45</td>
<td>30</td>
<td>15</td>
<td>36</td>
<td>41</td>
</tr>
<tr>
<td>Black</td>
<td>74</td>
<td>15</td>
<td>15</td>
<td>74</td>
<td>30</td>
</tr>
<tr>
<td>Montigel</td>
<td>81</td>
<td>74</td>
<td>19</td>
<td>74</td>
<td>13</td>
</tr>
<tr>
<td>Red</td>
<td>2.5</td>
<td>2.0</td>
<td>1.5</td>
<td>3.0</td>
<td>1.3</td>
</tr>
<tr>
<td>Pierre</td>
<td>10</td>
<td>9.0</td>
<td>7.4</td>
<td>16.4</td>
<td>4.0</td>
</tr>
<tr>
<td>Montigel</td>
<td>5</td>
<td>4.1</td>
<td>7.4</td>
<td>16.5</td>
<td>4.0</td>
</tr>
<tr>
<td>Black</td>
<td>7</td>
<td>6.0</td>
<td>7.4</td>
<td>20</td>
<td>4.0</td>
</tr>
</tbody>
</table>

III. EXPERIMENTAL METHODS

III.1 Apparatus

The consolidation experiments were performed in a pressure vessel with independent confining pressure and pore-fluid pressure control. The volume of fluid expelled from the specimen (\( \Delta V \)) was measured using a calibrated volumometer which also served as the pore pressure pump. The volume change in the pump that was necessary to maintain pore-fluid pressure (\( P_f \)) constant is a direct measure of the volume of water expelled from the specimen (\( \Delta V \)). Therefore, the volume change of the specimen equals -\( \Delta V \). Tap water was used as both the confining medium and the pore medium because it is closer to being in chemical equilibrium with the shales than other readily available waters such as distilled or de-ionized.

III.2 Specimen preparation and sample assembly

Red and Pierre specimens were stored in tap water prior to testing. Black and Montigel were stored nominally dry under a humidity of ~60%. For Red, Pierre and Montigel, cylindrical samples (12 mm diameter x 25 mm length) were cored with a diamond drill from relatively homogeneous blocks of shales. Red and Pierre were cored using tap water as a lubricant while Montigel was cored nominally dry. Cylinders of Black shale were prepared by machining nominally dry rectangular blocks on a lathe.

In all cases, the cylinder axis was perpendicular to bedding. Since Red mudstone and Pierre shale were always stored in water, they were considered saturated at the beginning of the experiment. Water was always expelled (\( \Delta V > 0 \)) from Red, Pierre and Montigel during the first pressure increment (Figure 2). However, since the Black shale has a relatively large porosity, a high swelling clay content, and was prepared and stored nominally dry, the specimen absorbed a substantial amount of water, up to 10% of the sample volume, during the first pressure increment. The cylindrical specimens were jacketed in heat-shrink tubing (polyolefine) between two end spacers. The pore-fluid pressure was regulated through holes in one end spacer. To enhance drainage and thus shorten consolidation times, a porous paper was wrapped around the specimen on the inside of the jacket. In
this way, water could drained radially, parallel to bedding until
the jacket wall and then out along the paper to the drained end.
The \( \Delta V \) data shown in Figures 3 and 5 have been corrected for
the paper wrap.

III.3 Experimental procedures

Pore pressure was held constant and the effective pressure was
changed by changing the confining pressure. At the beginning of
an experiment, \( P_c = P_p \) was maintained by opening a valve
between the confining pressure and pore pressure systems and
pumping up both \( P_c \) and \( P_p \) until the prescribed \( P_p \) was reached.

Then the valve was closed and \( P_c \) was increased to the first
increment. Pore pressures were maintained automatically at 10
\pm 0.1 MPa for all experiments (\( \Delta V \pm 0.35 \text{ mm}^3 \) at \( P_p = 10 \text{ MPa} \)).

Confining pressure (\( P_c \)) was varied from 11 MPa to 75 MPa.
The uncertainties in the measurements were: \( \Delta V \pm 1 \text{ mm}^3 \) (main
source of error was room temperature fluctuations), \( P_p \) and \( P_c \)
\pm 0.1 MPa.

Enough time was allowed for \( \Delta V \) to reach a constant value for
at least 8 hours before the confining pressure was changed. The
initial \( \Delta V \) at \( P_c = 1 \text{ MPa} \) (y-intercept in Figure 3) was very
difficult to control and varied by over 100 mm\(^3\) for a given shale.
The uncertainty arose because of initial variations in the amount
of water in the sample assembly at atmospheric pressure.
However, the NCL and OCL-slopes (\( \lambda \) and \( \kappa \), respectively) were
reproducible between experiments (Figures 3 and 5; Table 2).

Table 2: NCL and OCL consolidation data

<table>
<thead>
<tr>
<th>Specimen</th>
<th>( \lambda )</th>
<th>( \kappa )</th>
<th>( \frac{1-\kappa}{\lambda} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pierre</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P-31</td>
<td>0.0160</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P-35</td>
<td>0.0250</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P-36</td>
<td>0.0250</td>
<td>0.0106</td>
<td>0.576</td>
</tr>
<tr>
<td>P-37</td>
<td>0.0190</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P-38</td>
<td>0.0180</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P-40</td>
<td>0.0193</td>
<td>0.0099</td>
<td>0.487</td>
</tr>
<tr>
<td>P-41</td>
<td>0.0300</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P-42</td>
<td>0.0182</td>
<td>0.0130</td>
<td>0.286</td>
</tr>
</tbody>
</table>
<pre><code>                                               | 0.0142       | 0.220            |
</code></pre>
<p>| Montigel |              |              |                  |
| M-3      | 0.0493       | 0.0166       | 0.663            |
| M-4      | 0.0490       |              |                  |
| Red      |              | 0.0090       |                  |
|          |              |              |                  |</p>

Figure 2. Example of the volume change during NCL loading, unloading
(OCL1) and reloading (OCL2) as a function of time for Pierre shale (P-42).
Data are not corrected for the effect of the porous paper wrap.

A typical consolidation experiment lasted from a few days to a
few months depending on the material and the number of
pressure increments. Red mudstone tended to equilibrate the fastest and
Black shale the slowest. For the longest experiment, B-8, the
consolidation part lasted 98 days and produced an NCL, an
unloading OCL(1), and a reloading OCL(2) (Table 2).

IV. RESULTS AND DISCUSSION

IV.1 Normal consolidation lines (NCL)

The NCL for Pierre, Red and Montigel are quite linear (e.g.
Figure 3a), as expected from critical state mechanics (e.g. Wood,
1990) and the variation of \( \lambda \) for each shale is relatively small
(Table 2). For Black shale, \( \lambda \) are non-linear, increasing from
near zero between \( p' = 1 \text{ and } 2 \text{ MPa} \) to 0.8 at \( p' > 10 \text{ MPa} \) (Figure
3b). This non-linearity suggests that either: 1) \( \Delta V \) did not
equilibrate to the initial \( p' \) increment (1 MPa) (Black shale was
initially under saturated with respect to water) or 2) that the \( p'_{\text{max}} \)
experienced by Black in its natural state is within the range of
experimental conditions. Independent of the cause of the non-
linearity of the initial consolidation, \( \lambda \) for Black shale should be
equal to or greater than the maximum value measured because all
other isotropic loading paths, such as unloading and reloading
(OCL), should give shallower slopes.
The $\lambda$ for all four shales increase with both porosity (Figure 4) and swelling clay fraction. A correlation between $\lambda$ and porosity and swelling clay fraction may be expected because these are the two sources of water in shales. There appears to be a linear correlation between $\lambda$ and porosity, the primary water source (Figure 4). If the storage capacities of both the pores and the swelling clay minerals are functions of effective pressure, there should be a relationship between the sum of these two water sources and $\lambda$. Comparing Black to Montigel suggests that porosity accounts for a larger portion of the water than the swelling clays. To estimate the relative contributions of porosity and swelling clay minerals, we made a least squares fit to the equation:

$$\lambda = \lambda_0 + m(\phi + n\chi)$$  \hspace{1cm} (4)

where $\phi$ is the porosity and $\chi$ is the swelling clay volume fraction. The variable $n$ is chosen to minimize the root mean square. A third possible source for water is the organic component. Like the swelling minerals, organic material adsorbs H$_2$O. The organic component is especially significant for Black shale. Assuming the swelling clay and organic fractions contribute equally ($\chi = \phi$), the best fit to (4) is with $n = 0.3$ (Figure 5). The results suggest that the normal consolidation behavior of shales correlates with the total water content and that water expelled from the pores makes a larger contribution to the measured volume change than water expelled from the swelling clays and organic material. Therefore, measurements of porosity and, to a lesser extend, swelling clay and organic fractions may both be necessary to predict the consolidation behavior of natural shales.

IV.2 Over consolidation lines (OCL)

The unloading OCL are relatively linear for Pierre shale, Red mudstone and Montigel bentonite (Figure 6) and $\kappa$ is always less than $\lambda$ (Table 2), as predicted from critical state theory. As with the NCL, the OCL for Black shale are non-linear and decrease with $p'$. In the two cases where reloading OCL were determined, the reloading curves mimic the initial unloading curves until near $p'_{\text{max}}$ where the slope increases towards the NCL. For comparisons among the shales, we chose only the unloading OCL, and for Black shale only the unloading OCL for $p' \geq 10$ MPa.

According to critical state theory (Wood, 1990), the OCL is reversible and, therefore, should correlate with the elastic parameters of the shales. The good correlation between $\kappa$ and total non-swelling minerals (Figure 7) suggests that these components are elastic and may control the reversible consolidation of these shales. The correlations between $\kappa$ and initial porosity and swelling clay content are quite poor suggesting that the OCL does not depend on water content.
suggesting that this shale may record its natural p’\text{max}. The non-clays). Vol% as in Figure 4.

Figure 7. The slopes of the OCL (κ) vs. total non-swelling minerals (clays and non-clays). Vol% as in Figure 4.

IV.3 The parameter \( A \)

Values of the parameter \( A \), important for determining undrained behavior in clays (e.g., Wood, 1990), are shown in Table 2. Although the range of values for Pierre shale is quite large, in general, \( A \) is higher for the low swelling clay shales, Pierre shale and Red mudstone than for the high swelling clay shales. This relation is expected since Pierre and Red contain high percentages of non-clay and non-swelling clay minerals which are presumably more elastic than the swelling clays and porosity.

IV.4 Maximum previous effective pressure

As an illustration of how the experimentally determined critical state parameters can be used to estimate properties of shales in their natural states, we attempt to estimate \( p’\text{max} \). The maximum effective pressure \( (p’\text{max}) \) that a shale experienced in its natural state can sometimes be recognized in laboratory data by an apparent increase in \( \lambda \) (e.g., McKown and Ladd, 1982). For \( p’ < p’\text{max} \) the shale is over consolidated. Therefore, laboratory consolidations should initially follow the shallower OCL until \( p’\text{max} \) is reached (Figure 1) and then increase to the true NCL. For the depth of samples from one drill core of Pierre shale, McKown and Ladd (1982) estimated a maximum \( p’\text{max} \) of approximately 8 MPa, based on geologic information from the well site. However, laboratory tests on these samples gave an apparent \( p’\text{max} \) of up to 22 MPa for this location. The large over estimation of \( p’\text{max} \) was attributed to calcite cementation. From our experiments on Pierre shale, no break in slope is recognized for \( p’ \leq 40 \) MPa (Figure 3a). Since there is a clear difference between \( \lambda \) and \( \kappa \) for all \( p’ \) tested, our starting material does not appear to be over consolidated. Therefore, either \( p’\text{max} \) was much less than 5 MPa or our Pierre shale relaxed from its natural state and no longer records its previous \( p’\text{max} \). The reason for this apparent memory loss is uncertain but may be related to time-dependent inelastic processes such as adsorption of H\text{2}O by swelling clay minerals or to dissolution of cement during storage in tap water. Red mudstone and Montigel bentonite also lack a break in \( \lambda \).

Only Black shale shows an apparent non-linear \( \lambda \) (Figure 3b) suggesting that this shale may record its natural \( p’\text{max} \). The shapes of all of the NCL for Black shale are remarkably similar over the complete \( p’ \) range suggesting that the non-linearity is not simply an experimental effect. For \( p’ < 10 \) MPa the apparent NCL is approximately parallel to a reloading (OCL) line but for \( p’ > 10 \) MPa, consolidation follows the NCL (compare Figures 3b and 4). Therefore, a \( p’\text{max} \) of approximately 10 MPa is suggested.

VI. SUMMARY AND CONCLUSIONS

Analytical characterizations:
The four shales can be divided into two groups: low swelling clay shales (\( < 20\% \)), Pierre shale and Red mudstone, and high swelling clay shales (\( \geq 30\% \)). Black shale and Montigel bentonite. The former group has lower porosities and higher non-clay contents than the latter.

Isostatic consolidation and critical state behavior:
1) The NCL for three of the four shales are linear, the exception being Black shale. The NCL for all four are irreversible and \( \kappa \) correlates with porosity and, to a lesser extent, swelling clay content.
2) The OCL are linear, also with the exception of Black shale. For all four \( \kappa < \lambda \) and the OCL are reversible, suggesting that the OCL depend on the elastic components. \( \kappa \) correlates best with the non-swelling mineral content.
3) The parameter \( A \) is lower for the shales with the higher elastic components, Pierre shale and Red mudstone.
4) The maximum effective pressure \( p’\text{max} \) experienced by a shale in its natural state can sometimes be recognized by a non-linear NCL. The experimental data suggest that \( p’\text{max} \) was approximately 10 MPa for Black shale. For the other three shales, the NCL are linear and therefore do not record the original \( p’\text{max} \).

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REFERENCES


