Compaction assessment of a depleting shallow chalk reservoir

DeWijk compaction and subsidence study

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Summary

The DeWijk gas field had been producing for 30 years since early 60-ies when was shut in in 1991. By then the reservoir pressure was drawn down from the initial 61 bar to 51 bar at which it remains today.

The client is planning to resume production, and has an ongoing evaluation considering production rates and total pressure drawdown with respect to possible reservoir compaction and surface subsidence issues, and ultimately considering action on pressure support. Two production scenarios are suggesting pressure reduction down to A) 31 bar, and B) 37 bar.

This study is divided into two phases:
1. Chalk behavior and compaction study to investigate possible elasto-plastic behavior of the DeWijk chalk.
2. Study of overburden near well stresses on casing – a 2D axi-symmetrical numerical model

In task 1 the elastic and plastic compression properties of the chalk have been compared to available data from open literature, in particular public data compiled throughout the Joint Chalk Research Program, as well as conferring with reports on Harlingen and Lixhe chalk data. The results from provided experimental compaction data (from client) fit within the general scatter observed for these chalk studies. Existing correlations have been justified and proposed to define the porosity-dependent elastic and plastic compression parameters (i.e. bulk stiffness and compression coefficient lambda) for DeWijk.

A simple compaction model (Matlab) is used, based on the defined material correlations, to calculate the volumetric strain due to a decrease of reservoir pressure, assuming that the volume consists of homogeneous porosity and that depletion occurs under constant effective horizontal to vertical stresses. Only monotonous reservoir pressure decrease is considered (i.e. it excludes period after production stopped). In addition plastic hardening is not taken into account.

The output from the conceptual model can be used directly to calculate surface settlements (subsidence) due to reservoir compaction during pressure reduction.

The output gives a qualitative description of chalk behavior for different porosities in the 24-38% range (relevant porosities from logs) during pressure reduction.

Production up to 1991 display very little strain and does not indicate plastic behavior, i.e. by pore collapse, using the best fit correlation functions. Although, applying the lower bound pore collapse vs porosity trend line seems to induce plastic failure and increased strains from 35.8% porosity and higher. This is however not backed up by field observations.

Using best fit correlation function of pore collapse yield pressure vs porosity the model suggests a certain likelihood of pore collapse for porosities between 36% and 37.6%, below ~32 bars and 37 bars reservoir pressure, during production according to scenario A) protocol. For depletion scenario B large induced strains by pore collapse are not expected, but the most porous chalk reported (37.6%), represent the threshold porosity for plastic yield. Thus, production scenario B) may be pushing towards the very limit in terms of plastic yield.

In the worst case situation and as a conservative consideration; by applying the lower bound pore collapse correlation function, the minimum porosity for pore collapse to occur is 29.9% and 31.6%, for production scenario A) and B) respectively.
Note that low porosity chalk may very well support pockets of high porosity by bridging effects, thereby limiting local compaction. However if high porosity chalk exists in stratified layers, collapse may occur, inducing significantly larger strains.

Elements/porosities where pore collapse is encountered are likely to produce relatively significant time dependent (creep) strains after shut-in. Being rate dependent by nature, the creep strain contribution can be limited by pressure mitigation during and/or after end production.
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1 Introduction

This study is initiated by Shell Netherlands through Nederlandse Aardolie Maatchappij (NAM) under PO 4511910456. The main scope is to provide an overview of possible chalk behavior and induced near well effects on casing and surface subsidence as result of gas production of the DeWijk field.

The DeWijk gas field had been producing for 35 years since early 1956 when was shut in in 1991. By then the reservoir pressure was drawn down from the initial 60.5 bar to 50 bar, today remaining at 53.3 bar.

The client is planning to resume production, and has an ongoing evaluation considering production rates and total pressure drawdown with respect to possible reservoir compaction and surface subsidence scenarios, and ultimately considering action on pressure support.

The goal is to further deplete the reservoir starting in 2016 and ending in 2030. Under production the targeted down-hole pressure is 25 bars (local). The far field pressure reduction is down to 31 bar or 37 bar given two likely production scenarios for western and eastern segment.

The change in reservoir pressure increases the effective stress in the reservoir and the nearby rock formation. As a response to the increased stresses the rock formation subjected to an elevated stress may deform by compaction.

Chalk displays a particular susceptibility to deformation, more complex than many other rock materials. The behaviour is strongly dependent on several factors; such as the chalk porosity, pore fluid composition and degree of saturation, as well as loading rate (i.e. depletion/production rate). From a mechanical point of view the implications of these parameters become particularly apparent when applying load or stress beyond the virgin consolidation.

Compaction due to increased loading is described as elastic up to a certain stress limit which is determined by porosity, pore fluid and production rate. Beyond this limit the stress-strain behaviour is characterized by pore collapse, a plastic behaviour inducing significantly larger strain than in the elastic domain.

This study addresses plausible chalk behaviour of the DeWijk chalk under the conditions specified by the client under Task 1. The main elements of the study are:

- Summary of available DeWijk experimental data
- Comparison against published data and available correlations from open literature: Synthesis plots of compaction lines, compressibility before and after pore collapse, yield stress at pore collapse as a function of porosity.
- Provide suitable mechanical parameter values for chalk under laboratory loading rate conditions and extrapolation to field loading rate conditions
- Analysis of DeWijk chalk using available rate dependent model
Task 2: 2.5D axi-symmetrical model, to be supplied January-February 2014.

1.1 Conceptual model for chalk behaviour

The compressibility of chalk under uniaxial strain loading conditions is stress dependent and increases dramatically as loading is pursed into pore collapse. Furthermore since chalk is a rate sensitive geomaterial, the yield stress at pore collapse and chalk compressibility are rate dependent. Hence, the onset of pore collapse under field loading conditions must be inferred together with the compressibility before and after pore collapse to calculate the bulk volume change. A constant effective stress ratio (representative of uniaxial strain boundary conditions) is assumed.

In the following, the rate sensitivity of chalk is interpreted using the rate type compaction model (RTCM) proposed by de Waal (1986). The model was originally developed for the time-dependent compaction of sandstones in order to extrapolate laboratory tests, which are loaded at relatively fast rates, to field depletion rates. The model was later adapted by Andersen et al. (1992) to model the compaction of Valhall chalk at field depletion loading rates.

De Waal’s model is basically formulated as a 1D-model. In order to extend the 1D-model to general state of stress, the stress invariants \( \sigma' = \sigma''_c \) and \( q \) are adopted. The extension to general state of stress is required because laboratory experiments encompass both isotropic and uniaxial strain loading conditions. Further the state of stress vary from point to point within the reservoir, so that pore collapse will be encountered at different stress levels with respect to the pore collapse yield surface.

A new stress measure named \( p'_{eq} \) is defined as:

\[
p'_{eq} = p' + \frac{q^2}{M^2 p}
\]

The parameter \( M \) represents the slope of the so-called “critical state line” in the modified Cam-Clay model. A similar approach is adopted by Vermeer & Neher (1999) to extend the well-known 1-D logarithmic creep law for secondary compression during oedometer-type strain conditions to general 3-D state of stress and strain.

Assuming that the ratio \( K'_0 \) between horizontal and vertical (principal) effective stresses \( \sigma'_h \) and \( \sigma'_v \) is constant, \( p'_{eq} \) can be expressed as (Vermeer & Naher, 1999):

\[
p'_{eq} = \sigma'_v \left[ \frac{1 + 2K'_0}{3} + \frac{3(1 - K'_0)^2}{M^2 (1 + 2K'_0)} \right]
\]
1.2 Rate-type model by de Waal

De Waal’s model follows the formulation of rate-type models (e.g. Kolymbas, 1978 and 1984, Gudehus and Kolymbas, 1979). Only the main equations and assumptions are recalled here. For a detailed description, the reader is referred to de Waal (1986).

From the general form given by Kolymbas, de Waal considered the special case of uniaxial (vertical) virgin compaction under constant ratio of lateral (confining) to vertical stresses. Further, the threshold strain rate under which rate effects disappear, which was originally present in Kolymbas’s formulation, is not considered by de Waal, who assumes the same rate dependency equally valid from very low strain rates to engineering rates. Hence, under these assumptions, the RTCM can be formulated as:

\[
\sigma_z = \frac{\dot{\varepsilon}_z}{c_{m,o}} + b\sigma_z \frac{\dot{\varepsilon}_z}{\dot{\varepsilon}_z},
\]

where \( c_{m,o} \) is the uniaxial compressibility along the virgin compaction curve (i.e. plastic) and \( b \) is a friction factor. Dots denote time differentiation.

The previous equation is re-formulated in the isotropic loading case (the effective prime is omitted) as:

\[
p = \frac{\dot{\varepsilon}_v}{c_{b,o}} + b p \frac{\dot{\varepsilon}_v}{\dot{\varepsilon}_v},
\]

where \( c_{b,o} \) is the bulk compressibility along the virgin compaction curve and \( b \) the same friction factor as above. \( \varepsilon_v \) is the volumetric strain.

The uniaxial compressibility can be related to the bulk compressibility by (Pauget et al., 2002):

\[
C_m = C_b \left[ \frac{1 + 2\Delta K'_0}{3} \right]
\]

where \( \Delta K'_0 \) is the ratio between effective horizontal and vertical stresses along a stress path (i.e. the value can be different from the initial stress ratio). Note that in the elastic phase, this ratio can be related to Poisson’s ratio as \( \Delta K'_0 = \nu'/1 - \nu' \).

The \( b \)-parameter can be inferred using the methodology given by De Waal, modified for isotropic loading conditions, as applied in the recent experiments. According to Eqs (3) and (4), the rate sensitivity \( b \)-parameter of the chalk should be the same, irrespective of loading conditions, as long as the correct compressibility (\( c_{m,o} \) or \( c_{b,o} \)) is taken into account.
The distance between two constant loading rate virgin compaction curves is determined along the integration path with constant strain. Since $d \varepsilon_v = 0$ between two stress points $p_1$ and $p_2$ for two compaction curves, the ratio of the stresses and the strain rates for the curves is given from Eq. (4) as:

$$\frac{p_2}{p_1} = \left( \frac{\dot{\varepsilon}_{v2}}{\dot{\varepsilon}_{v1}} \right)^b \quad (6)$$

Assuming that the compressibility does not change much with the change of rate, the value of $b$ is inferred directly from:

$$b = \frac{\ln \left( \frac{p_2}{p_1} \right)}{\ln \left( \frac{\dot{\varepsilon}_{v2}}{\dot{\varepsilon}_{v1}} \right)} \quad (7)$$

1.3 Elastic-plastic transition

The elastic-plastic transition (or onset of pore collapse) is usually interpreted for the tests for the phases performed at standard laboratory loading rates (i.e. 1 MPa/hour). It is based on the intersection of the initial fast loading elastic curve and the final plastic fast loading curve.

In order to unify both uniaxial and isotropic compaction experiments into a single pore collapse trend line (e.g. porosity versus mean effective stress $p'$), the equivalent mean stress $p_{eq}$ defined in Eq. (1) is used.

The critical state parameter $M$ is not measured specifically but typically reported values are between 1-1.5. $M = 1.0$ has been used in model.

Data synthesis of isotropic equivalent stresses at pore collapse is plotted versus porosity for water and oil saturated samples, revealing a trend lines depending on saturating fluid (Figure 1). The dataset from the Joint Chalk Research consortium is confidential, but experimental trend lines for the data have been published in Hickman (2004).

Data from Harlingen and Lixhe studies concur with trend lines (NGI 2010, 2011a, 2011b). It is found that experiment perform in dry state (gas saturated) fits within the trend for oil saturated chalk, whereas the fully and partially brine saturated experiments agree reasonably well with the trend line for water saturated chalk, in particular when considering the amount of intrinsic scatter in combination with the limited set of measurements on these cores.
Based on all JCR data, Hickman (2004) proposes the following best fit trend line for the brine saturated samples ($R^2 = 0.69$):

$$p_c = 346.5 \ e^{-7.7n}$$ (8)

and ($R^2 = 0.66$):

$$p_c = 364.4 \ e^{-7.0n}$$ (9)

for oil and gas saturated samples.

The data scatter for the brine saturated case is confined by a lower and an upper boundary defining the bandwidth of this parameter:

$$p_c^{\text{low}} = 250 \ e^{-7.7n}$$
$$p_c^{\text{avg}} = 346.5 \ e^{-7.7n}$$
$$p_c^{\text{up}} = 450 \ e^{-7.7n}$$ (10)

The lower bound $p_c^{\text{low}} = 250 \ e^{-7.7n}$ represents lower pre-consolidation stress, and serves as a conservative estimate of the onset of pore collapse.

Figure 1: Oil-saturated and water-saturated experiments from JCR database (data from Hickman, 2004). Upper and lower bound trend lines appear in blue and red.
1.4 Rate dependency from changes of loading rate

The load rate parameter $b$ is used in order to translate between stress points and strain rates between different stress curves at different loading as given in Eq. (6) and (7). Thus one can extrapolate between lab scale and field scale loading. One can thus relate pore collapse $P_c$ at lab rates to a $P_c$ at field rate through the exponent $b$, which can act as an input parameter to modeling creep behavior as well since expressing time dependency implicitly. The compaction and subsidence modeling proves highly sensitive to the $b$-parameter, in terms of onset of pore collapse and accumulated strain.

Numerous models have been proposed in the literature to characterize the time-dependent behavior of soils, e.g. Liingaard et al. (2004) for a recent overview. In fact, theories based on the concept of constant $Ca/C_c$ (e.g. Mesri & Godlewski, 1977) or the strain rate approach developed for clays (e.g. Leroueil et al., 1985) lead to a similar relation, with the equality (Liingaard et al., 2004; Andreassen & Fabricius, 2010):

$$b = \frac{1}{m'} = \frac{C_a}{C_c}$$

Hence the results from constant rate of strain (CRS) oedometer tests performed by Priol (2005) on outcrop high porosity chalk (Lixhe, Belgium) under controlled suction, interpreted in terms of $C_c$ and $Ca$, can be used for comparison (Figure 2). Experiments were carried out for fully oil or water saturated, dry, or partially saturated conditions under constant suction. A 200 kPa suction is nearly equivalent to 30% water saturation shows the rate sensitivity of the yield stress under uniaxial strain loading conditions for different strain rates. The value of $1/m'$, equivalent to the $b$-parameter, varies between 0.045 (dry) to 0.108 (fully water-saturated).

![Figure 2: Yield stress versus strain rate from CRS oedometer tests on Lixhe chalk (from Priol, 2005).](image-url)
However the logarithmic creep, as given by Eq. (10), predicts infinite strain for infinite time, which is not physically admissible. Hence the value of the b-parameter must decrease at very large times. This is supported by the back-analysis of field creep measurements in clay by Leroueil (2006), showing a decrease at very small strain rates from constant \( C_{\alpha}/C_{c} = 0.04 \) (Figure 3). Long term oedometer laboratory tests performed at NGI on clay show a deviation from the logarithmic creep law at very large creep times (\( \approx 1 \) year) (NGI, 1969).

![Normalized stress-strain rate relations at a strain of 10% (from Leroueil, 2006)](image)

**Figure 3: Normalized stress-strain rate relations at a strain of 10% (from Leroueil, 2006)**

Kristiansen & Plischke (2010) gives a correlation of b with porosity used for geomechanical modelling of Tor and Hod reservoir formations at the Valhall field. The authors argue that even if no reliable experimental data was available at the time to quantify the porosity dependency, the use of a rate dependent model seems to give a better match of subsidence prognosis to observed GPS data. They proposed that b increases with decreasing porosity \( n \) (in fraction):

\[
b = 0.17e^{-3.1n}
\]  

Although the authors do not provide any background to justify the porosity dependency in the expression above, the expression gives values of b around 0.054-0.065 for the porosities of the tested samples, in accordance with the interpreted experimental values (NGI 2011b, NGI 2013).

A background to the porosity dependency proposed above can be found by looking at parameter dependency through other constitutive models developed for chalk. Hickman (2004) shows that, using the joint chalk model (based on Bjerrum’s creep law) under controlled strain rate, the yield stress scales accordingly to:

\[
\begin{pmatrix}
p_2 \\
p_1
\end{pmatrix}
= \begin{pmatrix}
\varepsilon_{a2} \\
\varepsilon_{v1}
\end{pmatrix}^\psi \begin{pmatrix}
\varepsilon \\
\varepsilon_{v}
\end{pmatrix}
\]  

(13)
A direct comparison between Eq. (13) and (6) shows that \( b = \psi / \Gamma \) (it can indeed be shown by comparing the expression of the creep volumetric strain for large times). This expression is similar to Eq. (6), except that the elastic rebound is taken into account.

Hence \( b \) can be directly inferred from the parameters \( \psi \) and \( \Gamma \) which are available from the JCR database. \( \Gamma \) is a plastic hardening parameter, which, following the Cam-clay model, is equal to \( \Gamma = \lambda - \kappa \), where \( \kappa \) and \( \lambda \) are, respectively, the slopes of the swelling (or elastic) and virgin consolidation (or elasto-plastic) portions of the compaction curve in the \( e \) vs. \( \ln(p) \) diagram. The compression coefficient \( \lambda \) is strongly related to porosity. Hickman (2004) gives the following relationship based on the JCR database:

\[
\lambda = 0.052 e^{3.467n}
\]

where \( n \) is the porosity in fraction.

As first approximation, the swelling coefficient can be taken as \( \kappa \approx \frac{\lambda}{10} \). The creep parameter shows much scatter without any correlation to porosity. Hickman (2004) reports values between 0.0014 - 0.0052 for water saturated Tyra chalk, but values 2-10 times higher for Valhall chalk (0.0145). Using \( \psi = 0.009 \) together with Eq. 13 and \( b = \psi / \Gamma \) gives \( b \)-values along the trend line proposed by Kristiansen & Plishke (2010).

The porosity dependent \( b \) parameter relation proposed by Kristiansen & Plishke (2010) is adopted in the model.

1.5 Extrapolation to field loading rates

The exponential trend line defined by Eq. (8) and (9) represents the pore collapse under laboratory load rates (e.g. 1 MPa/h). The trend line can be extrapolated to field loading conditions by using a constant field loading rate, a given \( b \)-value, and the procedure defined by de Waal (1986). The trend line under field conditions is then given by:

\[
\left( \frac{p_{c,\text{field}}}{p_{c,\text{lab}}} \right) = \left( \frac{\sigma_{\text{field}}}{\sigma_{\text{lab}}} \right)^b
\]

where \( p_{c,\text{field}} \) is the pore collapse under isotropic stress conditions for field loading rates, \( p_{c,\text{lab}} \) is the same exponential trend line as given in Eq.(9), and \( b \) is the porosity dependent rate parameter. Principle of changing yield cap under varied rate loading is given in Figure 4: lower rate closes the yield envelope, hence an earlier pore collapse onset.

Note that for high porosity and very low rates pore collapse can be predicted under in situ conditions prior to production due to log-linear regression applying a not admissible state (ref. discussion in previous section with reference to work by
Leroueil (2006). Note however that bridging in situ could potentially preserve isolated pockets of higher porosity.

Figure 4: Transition from elastic to plastic regime by onset of pore collapse shows direct load rate dependency for typical laboratory load rates as indicated for the contours (PASACHALK, 2004).

1.6 Compressibility during isotropic compression

1.6.1 Compressibility before pore collapse

Table 1: Compressibility and calculated bulk modulus of DeWijk chalk.

<table>
<thead>
<tr>
<th>Nr</th>
<th>Formation</th>
<th>MD</th>
<th>(\sigma_V) MPa</th>
<th>(\sigma_H) MPa</th>
<th>(\sigma_V') MPa</th>
<th>(\sigma_H') MPa</th>
<th>(n) %</th>
<th>(C_m) Mpa(^{-1})</th>
<th>(C_{bc}) Mpa(^{-1})</th>
<th>(K) Mpa</th>
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<tbody>
<tr>
<td>Silt</td>
<td>5*</td>
<td>NLFFT</td>
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<td>10.9</td>
<td>7.8</td>
<td>4.8</td>
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<td>7.8</td>
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<td>7.20E-04</td>
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</tr>
</tbody>
</table>

*The core in WYK-31 was taken in 1988 with a reservoir pressure of probably undepleted 60.5 bar as the chalk core interval is below the GWC in the water leg.

*Cores from the chalk in WYK-25 were taken in 1985 when the reservoir pressure was 53.3 bar.
Oedometer data are received from the client providing a relation between uniaxial compressibility $C_m$ and porosity (Table 1). In order to compare with literature data the bulk modulus $K$ is calculated via the bulk compressibility $C_{bc}$ as

$$C_{bc} = C_m \left[ \frac{1+2\Delta K'}{3} \right]^{-1}.$$  

During elastic deformation under uniaxial strain conditions, the ratio is related to the Poisson’s ratio $\nu$ of the chalk by $\Delta K' = \frac{\nu}{1-\nu}$. Typical values for Poisson’s ratio for chalk are within 0.2-0.25 given a ratio $\Delta K'$ between 0.25 and 0.33. Uniaxial strain experiments may be subjected to uncertainty in terms of representative Poisson’s ratio.

Chalk elasticity appears to be linear rather than stress-dependent (Hickman, 2004). Before pore collapse, the bulk compressibility is therefore computed as $C_{bc,e} = 1/K$ where $K$ is the tangent elastic bulk modulus. Likewise the pore compressibility reads $C_{p,e} = 1/(K \phi)$. The bulk modulus for DeWijk chalk is compiled in Table 1 and plotted in Figure 5 against the Joint Chalk Research database for water and brine saturated chalk (Hickman, 2004). The trend lines defined by Hickman reads $K_{brine} = 83596e^{-11.3n}$ for fully or partially brine saturated chalk and $K_{oil} = 86000e^{-9.4n}$ for oil saturated. Here $n$ represents the porosity in fraction, and the $K$ the bulk modulus is given in MPa.

NGI chalk studies are in agreement with trend lines (NGI 2010, 2011a, 2011b). However, from the few available data we see the DeWijk chalk is presumably softer than the chalks from JCR and NGI studies and better described by

$$K_{DeWijk} = 23885e^{-11.3n}$$  

Based on the fact that our only available data fits lower than the elastic bulk modulus of saturated chalk from the JCR database, it is fair to assume a somewhat softer behavior also for the yield threshold $P_c$ and compressibility in the plastic regime $C_{bp}$ as well.
Figure 5: Bulk modulus for DeWijk chalk (filled square) plotted together with water-saturated experiments (open circle) from JCR database (data from Hickman, 2004). Black line represents the trend line \( K_{\text{jcr}} = 83596e^{-11.3n} \) of the JCR data, the red line \( K_{\text{DeWijk}} = 23885e^{-11.3n} \) defines the trend of the DeWijk chalk.

1.6.2 Compressibility after pore collapse

The compressibility of chalk after pore collapse is stress dependent. Compressibility values and trend lines are provided by Havmøller and Foged (1996), but cover a wide range of stress level.

The compressibility after pore collapse is usually defined by the compression coefficient as defined in soil mechanics.

On the virgin consolidation line, the volumetric strain is written as:

\[
de_{\text{rel}} = \frac{de}{1+e_0} = \frac{\lambda}{1+e_0} \frac{dp}{p}
\]  

(18)

where \( \lambda \) is the compression coefficient. Hence the compressibility of the chalk along the virgin consolidation line is written as:
Compression coefficients for the plastic regime is not available for DeWijk chalk. JCR compression data is given in Figure 6, which other NGI chalk studies are in agreement with.

\[ C_{lp} = \frac{d\varepsilon_{vol}}{dp} = \frac{\lambda}{(1 + e_0)p} \]  \hspace{1cm} (19)

Figure 6: Compression coefficient from isotropic compression tests (Joint Chalk Research data after Hickman, 2004). Filled black symbols (oil-saturated) and empty triangles (water-saturated). A softer more compliant material trend line (red) is assumed for this study.

Based on the available uniaxial compressibility data indicating a softer material for the DeWijk chalk than the JCR correlation, a compressibility in the outskirts of the water saturated (more compliant) is assumed (Figure 6):

\[ \lambda = 0.08 e^{3n} \]  \hspace{1cm} (20)

where \( n \) is the porosity in fraction.

2 Time dependent deformation and creep effects

During its lifetime of production a chalk reservoir can experience elastic, plastic and time dependent deformation depending on the production and load parameters, i.e. load rates and degrees of pressure remediation, with respect to the in situ conditions. The total induced volumetric strain \( \Delta\varepsilon_{tot} \) can thus be separated into
occurred elastic $\Delta \varepsilon_{el}$, plastic $\Delta \varepsilon_{pl}$ (after pore collapse) and time dependent $\Delta \varepsilon_{creep}$ contribution:

$$\Delta \varepsilon_{tot} = \Delta \varepsilon_{el} + \Delta \varepsilon_{pl} + \Delta \varepsilon_{creep}$$  \hspace{1cm} (21)

Several models describing the time dependent deformation with a shared origin in soil mechanics has been proposed (NGI, 1969, Kolymbas, 1978, Borja and Kavanzanjian, 1985 and de Waal, 1986).

Time dependent deformation is considered present from the beginning of production and will in the case of modeling rate effects with RTCM model be accounted for implicitly by the application the rate exponent $b$ introduced for extrapolation between scenarios of different loading rate, i.e. laboratory to field. The time dependent deformation is sensitive to ageing and mechanical loading history.

In case of no applied pressure changes time dependent strain will still occur, autonomously and as a direct result of the preceding loading, i.e. by depletion, and is typically referred to as "creep" deformation.

Following the outlines of de Waal’s formalism (de Waal, 1986), creep deformation occurring at zero load rate ($d\sigma/dt = 0$) is given as

$$\varepsilon_t = C_c \ln \left[ 1 + \frac{t}{\tau} \right]$$  \hspace{1cm} (22)

in which $1/C_c$ and $\tau/C_c$ relates to the inverse strain rate

$$\dot{\varepsilon}_t = \frac{C_c}{t + \tau}$$  \hspace{1cm} (23)

as the slope ($1/C_c$) and the offset ($\tau/C_c$) respectively. $C_c = b_{c,b,o} p$ and $\tau = b_{c,b,o} p / \dot{\varepsilon}_o$, where $b$ is the rate sensitivity parameter, and the parameters representative of the instant of creep onset $t = 0$ is the volumetric strain rate $\dot{\varepsilon}_o$, the bulk compressibility $c_{b,o}$, and the mean effective stress level $p$.

The creep strain contribution can be numerically calculated by discrete integration over a time $t$ which leads to

$$\Delta \varepsilon_t = \int_{0}^{t} \frac{C_c}{t + \tau} \, dt$$  \hspace{1cm} (24)

The integration is carried out by discretization of $t$ into $N$ number of elements (number of iterations) for which Eq. (24) is solved. The onset of creep is defined at
\( t = 0 \) with a set of parameters \( p, b(n), c_{b,0}, \) and \( \dot{\varepsilon}_o \) inherited from the very end of the depletion phase (given \( c_c = b_c b_{b,0} p \) and \( r = b_c b_{b,0} p / \dot{\varepsilon}_o \)). Integration of Eq. (24) over a given \( N \) iterations (time steps \( \Delta t = t / N \)) leads to a volumetric strain contribution

\[
\Delta \varepsilon_{\text{creep}} = C_c \ln \left[ 1 + \frac{\Delta t}{r} \right],
\]

which accumulates over the creep period and adds to the previously occurred elastic and plastic strain.

Given the logarithmic function of \( \Delta \varepsilon_{\text{creep}} \) the resulting strain is affected by number of integration steps (i.e. step size). The necessary number of time steps \( N \) must be considered since finer subdivision of \( t \) leads to the integration converging towards a stable solution. Increasing the number of time steps will necessarily increase computation time.

3 Field application

3.1 In situ reservoir stresses and pore pressure conditions

The initial stress state in the reservoir is characterized by the total vertical stress (maximum principal stress), which equals the weight of the overburden, and the minimum horizontal stress which is inferred from fracture tests. The overburden gradient is approximately 1.95 bar/10m, whereas the minimum horizontal stress has a gradient around 1.4 bar/10 based on a lower bound fit to the LOT data, given in Figure 7 as provided by the client. The horizontal stress anisotropy is unknown.

For the reservoir depth the initial conditions are summarized in Table 2.
Figure 7: Vertical and horizontal total stresses. (a) The overburden gradient is approximately 1.95 bar/10m, whereas (b) the minimum horizontal stress has a gradient around 1.4 bar/10 based on a lower bound fit to the LOT data.

Table 2: Initial stress conditions for DeWijk.

<table>
<thead>
<tr>
<th>Stress / Pore pressure</th>
<th>Value (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total vertical stress $\sigma_V$</td>
<td>10.8</td>
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<tr>
<td>Initial total horizontal stress $\sigma_H$</td>
<td>7.7</td>
</tr>
<tr>
<td>Initial octahedral stress $\sigma_{oct} = (\sigma_V + 2\sigma_H)/3$</td>
<td>8.7</td>
</tr>
<tr>
<td>Initial total stress ratio $K = \sigma_V / \sigma_H$</td>
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</tr>
<tr>
<td>Initial reservoir pressure $u_o$</td>
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<tr>
<td>Initial effective vertical stress $\sigma'_V$</td>
<td>4.7</td>
</tr>
<tr>
<td>Initial effective horizontal stress $\sigma'_{H}$</td>
<td>1.6</td>
</tr>
<tr>
<td>Initial effective octahedral stress $\sigma'_{oct}$</td>
<td>2.6</td>
</tr>
<tr>
<td>Initial effective stress ratio $K' = \sigma'_{H} / \sigma'_V$</td>
<td>0.34</td>
</tr>
</tbody>
</table>

3.2 Core porosities

The available tested porosities from DeWijk field is given in Figure 8; ranging from 24.1% to 37.6%. The average and median is 32.0% and 32.6%.
3.3 Pressure depletion during production

DeWijk Tuffite and Chalk reservoir pressure history and forecast (two scenarios) is given in Table 3, Table 4, and Table 5. The FBHP may be increased for example for the high permeability scenarios, to 43 bar instead of 37 bar. 43 bar target version of scenario B) is the scenario C) option (for eastern pool).

Table 3: Pressure depletion history in DeWijk.

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<thead>
<tr>
<th>Year</th>
<th>Pressure history</th>
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<tr>
<td>1956</td>
<td>Initial pressure: 60.5 bar @480 m TVD</td>
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<tr>
<td>1991</td>
<td>Depletion to 50 bar</td>
</tr>
<tr>
<td>2015</td>
<td>Pressure equalization to 51.5 bar (average and equalized reservoir pressure)</td>
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Table 4: Scenario A) Depletion of the DeWijk Ph2 shallow wells (western pool).

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<th>Year</th>
<th>FBHP producer</th>
<th>Drawdown (bar)</th>
<th>Avg. pressure producing area (bar)</th>
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</thead>
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<td>Start-up</td>
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<td></td>
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<tr>
<td>1/2017</td>
<td>25</td>
<td>10</td>
<td>35</td>
</tr>
<tr>
<td>1/2018</td>
<td>25</td>
<td>8</td>
<td>33</td>
</tr>
<tr>
<td>-2030</td>
<td>25</td>
<td>6</td>
<td>31</td>
</tr>
</tbody>
</table>

Table 5: Scenario B) Depletion of higher permeability ranges (eastern pool).

<table>
<thead>
<tr>
<th>Year</th>
<th>FBHP producer</th>
<th>Drawdown (bar)</th>
<th>Avg. pressure producing area</th>
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</table>
3.4 Volumetric strain changes under constant stress path

In the following, we consider only the period with monotonous pressure reduction over time. In addition it is assumed that the stress path in the reservoir is constant during depletion and characterized by a constant ratio $\Delta K' = \frac{\Delta \sigma_h}{\Delta \sigma_v}$ between effective horizontal and vertical stresses. This ratio differs in the elastic and plastic regime. During elastic deformation under uniaxial strain conditions, the ratio is related to the Poisson’s ratio $\nu$ of the chalk by $\Delta K' = \frac{\nu}{1-\nu}$. Typical values for Poisson’s ratio for chalk are within 0.2-0.25 given a ratio $K'$ between 0.25 and 0.33. Along the virgin consolidation line (plastic regime) this ratio is between 0.4-0.6 as shown from laboratory experiments on chalk.

The total volumetric strain due to a pressure reduction $\Delta u$ is calculated according to the procedure shown in Figure 9. An equivalent secant compressibility $C_{eqv}$ is calculated from the predicted volumetric strain and the accumulated pressure reduction.

The procedure defined in the flow diagram in Figure 9 has been implemented into a Matlab script to predict the accumulated volumetric strain changes for a chalk of given porosity subjected to pressure reduction under field loading rate conditions and constant effective stress ratio, covering the production history and forecast.

Note that since very few rock mechanical data were available for the DeWijk field, therefore known correlations from the literature is borrowed. The choice is based on the assumption that the DeWijk as a shallow chalk formation behaves rather soft as the provided compressibility and calculated bulk modulus indicates (Table 1). Table 6 gives an overview of the parameters and relations used in the model.

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
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<tr>
<td>Total pressure reduction $\Delta u$</td>
<td>10MPa (1956-1991), 40 MPa (2016-2030)</td>
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<tr>
<td>Field depletion rate</td>
<td>0.29 MPa/year, 2.86MPa/year</td>
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</tbody>
</table>

Table 6: Input parameters used to predict chalk compaction behaviour during pressure reduction.
Rate dependent parameter $b$

$\Delta K'$, elastic Effective stress ratio $\Delta K'$, plastic

Critical state line, $M$

Bulk modulus (elastic) $K$

Compressibility (plastic) $\lambda$

Preconsolidation stress $P_c$

\begin{align*}
    b &= 0.17 e^{-3.1n} \\
    \Delta K' &= 0.25 \\
    \Delta K' &= 0.6 \\
    M &= 1 \\
    K_{\text{prime}} &= 23885 e^{-11.3n} \\
    \lambda &= 0.08 e^{3n} \\
    P_c,\text{medium} &= 346.5 \ e^{-7.7n} \text{ or } P_c,\text{lower} = 250 \ e^{-7.7n}
\end{align*}

Figure 9: Procedure for calculating volumetric strain changes during pressure reduction.

The results are illustrated in Figure 10 to Figure 12 for the input parameters given in Table 6. Porosity considered are in the 24-38% range covering porosities provided by the client (Table 1). The reference (average) trend lines for material parameters are used (Table 6).
The history up to 1991 (10.5 bar depletion) is showing minimal amounts of elastic strain and porosity change and no induced pore collapse (Figure 10 a, b, and c). The elastic-plastic yield point as given in Figure 1 and fitted through \( p_c = 346.5 \ e^{-7.7n} \) is used. This is a sensitive parameter in terms of not only the onset of pore collapse but also total strain. Thus we apply also the lower bound correlation (conservative) as a means of sensitivity in our modelling since the chalk presumably behaves rather compliant:

\[
\begin{align*}
p^{\text{up}}_c &= 450 \ e^{-7.7n} \\
p^{\text{avg}}_c &= 346.5 \ e^{-7.7n} \\
p^{\text{low}}_c &= 250 \ e^{-7.7n}
\end{align*}
\]

(26)

Figure 10: a) Porosity change, b) volumetric strain, and c) equivalent compressibility during pressure reduction in the period 1956-1991 (10.5 bar pressure reduction from initial 60.6 bar). Porosities represented are 24% (lowest reported), 32.0% (average reported porosity), 32.6% (median reported porosity), 36% and 37.6% (highest reported porosity). Figure d) shows equivalent compressibility when applying lowest bound correlation in Eq. (26).
For the period up to 1991 the model suggest the possibility of plastic behaviour for porosities larger than approximately 35.8% when applying the lower bound (Figure 10 d). This is not reported from field observations.

Figure 11 represents the expected behavior for depletion scenario A. According to average trend lines pore collapse may be occurring in for reservoir pressures below ~37 bars for 37.6% porosity chalk (maximum expected porosity) down to ~32 bars for 36% porosity.

Applying the average values Figure 12 does not indicate pore collapse is not expected to occur for porosities lower than 36%.

Figure 11: a) Porosity change, b) volumetric strain, and c) equivalent compressibility during pressure reduction in the period 1956-2030, pressure history plus "forecast" scenario A) in Table 4; pressure reduction from initial 60.6 bar down to 31 bar. Porosities represented are 24% (lowest reported), 32.0% (average reported porosity), 32.6% (median reported porosity), 35% and 37.6% (highest reported porosity). Figure d) shows equivalent compressibility for the range of pore collapse yield points in Eq. (26) for 37.6% porosity.
Figure 12: (a) Porosity change, (b) volumetric strain, and (c) equivalent compressibility during pressure reduction in the period 1956-2030, pressure history plus "forecast" scenario B) in Table 5; pressure reduction from initial 60.6 bar down to 37 bar. Porosities represented are 24% (lowest reported), 32.0% (average reported porosity), 32.6% (median reported porosity), 35% and 37.6% (highest reported porosity). Figure (d) shows equivalent compressibility for range of pore collapse yield points given in Eq. (26).

The uncertainty in the plastic yield threshold is indicated in Figure 12 (d) for 37.6% chalk. The lower bound suggests that pore collapse may occur for the highest expected porosity already at 55 bars reservoir pressure, slightly below today's level. The upper bound eliminates the possibility of pore collapse.

Figure 12 represents depletion scenario B. Pore collapse is not likely to be significant but may occur for the highest reported porosity of 37.6% at best fit conditions. The resulting induced strain is however not expected to be significant.

In case of applying the lower pore collapse pressure correlation boundary $p_c = 250 e^{-7.7n}$ as deduced from Figure 1 instead of the average $p_c = 346.5 e^{-7.7n}$, the plastic yield will occur at lower pressure and for rock belonging to lower porosity classes – valid for both cases. For production of the western pool depleting down to 31 bar (scenario A) the chalk is then indicated to yield at 29.9%, whereas pore
collapse may occur for porosities of 31.6% and higher for the 37 bar target pressure in the eastern pool (scenario B). This represents the conservative minimum porosities for which pore collapse can be expected to occur, respective of the two production scenarios. An indication of the expected strains for average, median and end-member porosities in these two cases are shown in Figure 13.

**Figure 13:** Volumetric strain during pressure reduction in the period 1956-2030, pressure history plus "forecast" for a) scenario A, and b) scenario B) in Table 5. Porosities represented are 24% (lowest reported), 32.0% (average reported porosity), 32.6% (median reported porosity), and 37.6% (highest reported porosity), as well as minimum porosity for which pore collapse occur using the lower bound pore collapse correlation function in Eq. (26); 29.9% and 31.6%.

**Figure 14:** Volumetric creep strain contribution over 25 years, a) scenario A), and b) scenario B) in Table 5. Porosities represented are 24% (lowest reported), 32.0% (average reported porosity), 32.6% (median reported porosity), and 38% (highest reported porosity), as well as minimum porosity for which pore collapse occur using the lower bound pore collapse correlation function in Eq. (26); 29.9% and 31.6%.
Figure 14 shows 25 years of creep contribution after production according to lower bound case as in Figure 13. Continued deformation is considerable for rock porosities that experience pore collapse.

An overview of total volumetric strain after production for all reported core porosities (Figure 8) given a lower bound pore collapse threshold is given in Figure 15 a). Figure 15 b) shows the strains from production and 25 years added creep strain.

By assuming a perfectly layered reservoir structure, where each of the 27 porosities in Figure 8 are evenly distributed in distinct horizontal layers over the reservoir thickness, we have a simplified porosity model for calculating compaction. Scenario A produces in a 6m thick zone giving a 0.22 m layer thickness, and scenario B produces a 15 m thick zone giving individual layer thickness of 0.56 m. By considering the vertical strain contribution for each layer and multiply by the layer thickness we get a rough estimate of the compaction as given in Table 7 and Table 8. Here, the vertical strain in for the constrained $K_0$ case applicable to field depletion can be calculated from the volumetric strain using the following relation:

$$
\varepsilon_{\text{vertical}} = \frac{1}{3} \frac{(1+\nu)}{(1-\nu)} \varepsilon_{\text{vol}}
$$

(27)

A typical Poissons ratio $\nu = 0.21$ gives $\varepsilon_{\text{vertical}} \approx 0.51 \cdot \varepsilon_{\text{vol}}$.

Note that the layered model is a suggesting a weak reservoir sphere given that it does not allow for any support from neighbouring low porosity zones, i.e. no arching effects, as is likely in an amorphous and more likely porosity distribution. Adding that a lower bound porosity threshold represent a very compliant rock, this should be considered a very conservative estimate.

*Figure 15: Accumulated strain from a) production up to 2030, b) production phase and 25 years creep addition after shut-in.*
Table 7: Estimated vertical compaction for various production cases, optimal fit correlation function.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Vertical compaction (cm) for best fit creep correlation and assuming a conservative layering of Chalk porosity (no support)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scenario A</strong> (western pool, Chalk depletion thickness=6m, res. pressure=31 bar)</td>
<td>Depletion 1956-2030</td>
</tr>
<tr>
<td><strong>Scenario B</strong> (eastern pool, Chalk depletion thickness=15m, res. pressure=37 bar)</td>
<td>Depletion 1956-2030</td>
</tr>
<tr>
<td><strong>Scenario C</strong> (eastern pool, Chalk depletion thickness=15m, res. pressure=43 bar)</td>
<td>Depletion 1956-2030</td>
</tr>
<tr>
<td>Depletion 1956-2030</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Table 8: Estimated vertical compaction for various production cases, conservative correlation function

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Vertical compaction (cm) for a conservative lowest fit creep correlation and assuming a conservative layering of Chalk porosity</th>
</tr>
</thead>
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<tr>
<td><strong>Scenario A</strong> (western pool, Chalk depletion thickness=6m, res. pressure=31 bar)</td>
<td>Depletion 1956-2030</td>
</tr>
<tr>
<td><strong>Scenario B</strong> (eastern pool, Chalk depletion thickness=15m, res. pressure=37 bar)</td>
<td>Depletion 1956-2030</td>
</tr>
<tr>
<td><strong>Scenario C</strong> (eastern pool, Chalk depletion thickness=15m, res. pressure=43 bar)</td>
<td>Depletion 1956-2030</td>
</tr>
<tr>
<td>Depletion 1956-2030</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Considering solely the elastic component of the accumulated strain, i.e. never allowing plastic yield to occur by setting pore collapse pressure $P_c$ infinitely large, the strains are very limited as seen from Table 9. Comparing the cases between Table 7 through Table 9 clearly shows the impact and sensitivity of pore collapse. The latter may serve as an optimistic case, or as an analogy for the full effect of supported confined pockets of collapsing zones taking place.

Table 9: Estimated elastic contribution only to the total vertical compaction for various production cases, i.e. considering

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Vertical compaction (cm) for an elastic compaction of Chalk (no plastic contribution)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scenario A</strong> (western pool, Chalk depletion thickness=6m, res. pressure=31 bar)</td>
<td>Depletion 1956-2030</td>
</tr>
<tr>
<td><strong>Scenario B</strong> (eastern pool, Chalk depletion thickness=15m, res. pressure=37 bar)</td>
<td>Depletion 1956-2030</td>
</tr>
<tr>
<td><strong>Scenario C</strong> (eastern pool, Chalk depletion thickness=15m, res. pressure=43 bar)</td>
<td>Depletion 1956-2030</td>
</tr>
<tr>
<td>Depletion 1956-2030</td>
<td>2.3</td>
</tr>
</tbody>
</table>
4 Conclusions

The elastic and plastic compression properties of the chalk have been compared to available data from open literature, in particular public data compiled throughout the Joint Chalk Research Program. The results of the experiments fit within the general scatter observed for chalk. Correlations have been proposed to define the porosity-dependent elastic and plastic compression parameters (i.e. bulk stiffness and compression coefficient lambda).

A simple Matlab model based on the defined material correlations is utilized to calculate the accumulated volumetric strain due to a decrease of reservoir pressure during production history (1956-1991) and two second phase production scenarios (2016-2030), assuming that the volume consists of homogeneous porosity and that depletion occurs under constant effective horizontal to vertical stresses. The model cannot replace more advanced constitutive models for describing the time-dependent behavior of chalk under general boundary conditions. In particular, the time-dependency is not explicitly modeled, but implicitly taken into account through scaling of pore collapse pressure proposed by de Waal (1986). Only monotonous reservoir pressure decrease is considered (i.e. it excludes period after production stopped). In addition plastic hardening is not taken into account. The output from the conceptual model can be used directly to calculate surface settlements (subsidence) due to reservoir compaction during pressure reduction.

The output gives a qualitative description of chalk behavior for different porosities in the 24-38% range (relevant porosities from logs) during pressure reduction.

Production up to 1991 display very little strain and does not indicate plastic behavior, i.e. by pore collapse, using the best fit correlation functions. Although, applying the lower bound pore collapse vs porosity trend line seems to induce plastic failure and increased strains from 35.8% porosity and higher. This is however not backed up by field observations.

Using best fit correlation function of pore collapse yield pressure vs porosity the model suggests a certain likelihood of pore collapse for porosities between 36% and 37.6%, below ~32 bars and 37 bars reservoir pressure, during production according to scenario A) protocol. For depletion scenario B large induced strains by pore collapse are not expected, but the most porous chalk reported (37.6%), represent the threshold porosity for plastic yield. Thus, production scenario B) may be pushing towards the very limit in terms of plastic yield.

In the worst case situation and as a conservative consideration; by applying the lower bound pore collapse correlation function, the minimum porosity for pore collapse to occur is 29.9% and 31.6%, for production scenario A) and B) respectively.
Note that low porosity chalk may very well support pockets of high porosity by bridging effects, thereby limiting local compaction. However if high porosity chalk exists in stratified layers, collapse may occur, inducing significantly larger strains.

Elements/porosities where pore collapse is encountered are likely to produce relatively significant time dependent (creep) strains after shut-in. Being rate dependent by nature, the creep strain contribution can be limited by pressure mitigation during and/or after end production.
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Shell Netherlands and Nederlandse Aardolie Maatchappij (NAM)

### Emneord/Keywords
Dewijk, chalk, compaction

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