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Reservoir compaction and surface subsidence resulting from oil and gas production

*A review of theoretical and experimental research approaches**

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Abstract

Reservoir compaction and associated surface subsidence have been the subjects of theoretical and experimental research in Shell since the 1950's. Analytical models were developed for translating reservoir compaction to surface subsidence. The validity of these models was recently confirmed by field observations and finite element studies for the Groningen gas field in The Netherlands. Experimental methods for determining the compaction coefficient on core samples in the laboratory have been developed and refined and can now closely simulate reservoir conditions. Nevertheless, data from the Groningen field show that a discrepancy remains between the compaction coefficient measured on core material and the value derived from field observations. To resolve this discrepancy, which cannot be explained by existing compaction theories, a better understanding is required of the physical mechanisms of sandstone compaction and of the way they operate under laboratory and field conditions. Current experimental and theoretical research is aimed at the formulation of a constitutive compaction law. With such a law, predictive models that use experimentally determined rock parameters as input can be formulated for reservoir compaction.

Introduction

Reservoir compaction and associated surface subsidence have been the subjects of theoretical and experimental research in Shell since the 1950's. This article gives a comprehensive overview of the types of research carried out at the Koninklijke/Shell Exploratie and Produktie Laboratorium (KSEPL) to achieve the most reliable prediction of surface subsidence possible, in particular with regard to application in The Netherlands. In The Netherlands, studies have focused on the Groningen gas field. The theoretical models and experimental techniques, however, are also applicable to other fields.

The emphasis of the present paper is on the behaviour of sandstone reservoir rocks. Generally, reduction of reservoir pressure causes gradual compaction in this type of rock. Carbonates tend to behave similarly. In high-porosity carbonates the phenomenon 'pore collapse' has been observed when a certain drop in reservoir pressure is exceeded. Pore collapse may cause a sudden increase in compaction. Pore-collapse studies at KSEPL yield-

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* Based on a review paper originally presented at Symposium 'Bodemdaling in Nederland' (Surface subsidence in the Netherlands), Technical University Delft, 8 November 1990.

ed descriptive models (Van Ditzhuijzen & De Waal 1984, Smits et al. 1988) for this type of behaviour; the phenomenon is not discussed further in this paper.

The main subjects reviewed in this paper are:

- models for converting reservoir compaction into surface subsidence;
- the experimental method for determining the uniaxial compaction coefficient C_m (also termed compressibility) of the reservoir rock and the effect of various experimental factors on this coefficient;
- the theoretical approach to the compaction process.

A number of conclusions and recommendations for further research that the KSEPL studies have resulted in are given at the end of the paper.

Conversion of reservoir compaction into surface subsidence

The 'nucleus-of-strain' model

Compaction of a reservoir induces deformations in the rock layers surrounding that reservoir, both in the overburden and the underlying formations. During the early 1970's, KSEPL investigators developed models for describing the mechanical behaviour of these rock layers. Geertsma (1973) considered the homogeneous case, in which the reservoir was modelled as a horizontal disc of limited thickness. On the basis of the 'nucleus-of-strain' concept from thermoelastic theory, Geertsma and Van Opstal (1973) developed a numerical solution for the surface subsidence resulting from the compaction of such a disc-shaped reservoir. This model assumed linear stress-strain relations and uniform deformation properties throughout the entire reservoir, the overburden and the underlying formations. Van Opstal (1973) elaborated on this solution and added the 'rigid-basement' concept. In reality, the surrounding rock shows a rigidity that increases with depth and from a given depth, the underlying layers no longer react to the compacting reservoir. This condition is taken into account by assuming a non-deforming rock layer (the 'rigid basement') at a specific depth. With this model, a computer program (SUBCAL, Van Opstal 1973) was developed for predicting surface subsidence resulting from reservoir compaction caused by the production of oil or gas.

The model shows that, for extensive shallow reservoirs, the amount of subsidence at a particular location at the surface is equal to the compaction of the reservoir at that point. For extensive deeper reservoirs, such as the Groningen gas field, this also applies, specifically at the centre of the field. The smaller the extent of a deep reservoir, the smaller the ratio of subsidence to compaction for that reservoir.

The finite-element method

Another method for describing the behaviour of the sediments overlying a reservoir is the finite-element approach. Not only the elastic behaviour of a rock but also its plastic behaviour and the possibility of faulting are considered. The elastic and plastic deformation of the gas-bearing Slochteren Sandstone in the Groningen gas field and its overburden was studied using GEOFEP (geomechanical finite-element program), a two-dimensional finite-element code that has been developed at KSEPL to study geomechanical problems with linear elastic, poroelastic and/or elastoplastic behaviour (Thomas & Walters 1982, Thomas 1984).

The finite-element equations for linear elastic behaviour in GEOFEP are based on the principle of minimum potential energy. The set of linear equations can be solved directly. To describe elastoplastic behaviour, including fault formation, models have been used that consider changes in friction coefficient and reduction in cohesion. This necessitates iterative and/or incremental numerical techniques to solve the finite-element equations.

Surface subsidence above the Groningen gas field

To test the realibility of results achieved with the SUBCAL program based on the 'nucleus-of-strain' concept, the relation between reservoir depletion and surface subsidence was studied for the Groningen gas field, using the finite-element modelling program GEOFEP. Special attention was paid to the influence of mechanical heterogeneities (such as an overburden consisting of different layers, each of which has its specific material properties) on the relation between reservoir compaction and surface subsidence.

Finite-element modelling of surface subsidence has been performed along a number of cross-sections through the Groningen gas field (Fig. 1). The main conclusions are:

(a) The results of the GEOFEP study agree with the SUBCAL subsidence calculations. This implies that the mechanical behaviour of the overburden may be described in purely elastic terms. It was also found that the magnitude of the elastic parameters of the overburden layers has no significant impact on the calculated surface displacement.

(b) The subsidence profiles observed in the field cannot be explained solely by a drop in reservoir pressure in the gas-bearing part of the reservoir. This is shown in Figs 2 and 3, in which the measured subsidence profile along section A-A′ (Fig. 1) is compared with three modelled profiles A1 to A3. In model A1, only the pressure drop in the gas-bearing part of the reservoir is considered (see Fig. 3). In model A2, also a pressure drop in the water-bearing reservoir in a small graben east of the Ten Boer block (approximately 10 km east of the city of Groningen) has been simulated. In model A3 an additional pressure drop in the water-bearing part of the reservoir west of the actual gas-field was assumed. The observed subsidence corresponds best with model A3 (see Fig. 4). The numerical simulations thus indicate that compaction also takes place in the water-bearing Slochteren Sandstone outside the actual gas-field.

(c) For optimum simulation results, lateral changes in reservoir thickness should be taken into account.

KSEPL investigators have also used GEOFEP to study the risk of fault movements at the surface above the Groningen gas field. Differential compaction on either side of reservoir boundaries might cause or reactivate faults. This study (described in a public report of the Commission on Surface Subsidence, 1987), however, demonstrated that a differential vertical movement of 65 cm (the maximum predicted at the time) would not result in fault reactivation (elastoplastic behaviour). Only elastic deformation of the overburden was predicted. The minimum differential vertical movement needed to activate a fault that reaches the surface was calculated to be 12 m. The possibility of surface faulting can therefore be ruled out.

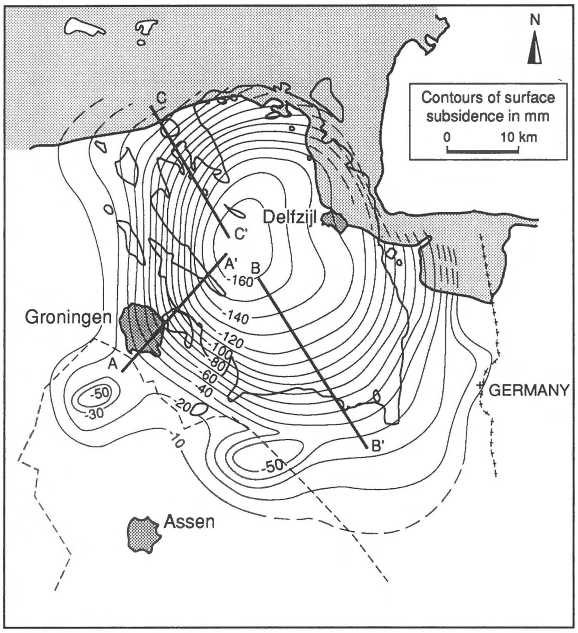
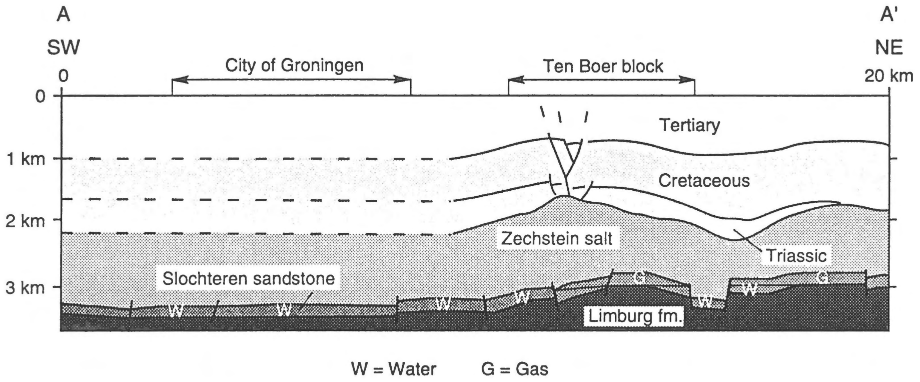


Fig. 1. Contour map of surface subsidence above the Groningen gas field (1964–1987). Contour interval: 10 mm. A-A′ etc.: cross-sections finite-element analysis. Outlines of Groningen gas field indicated.

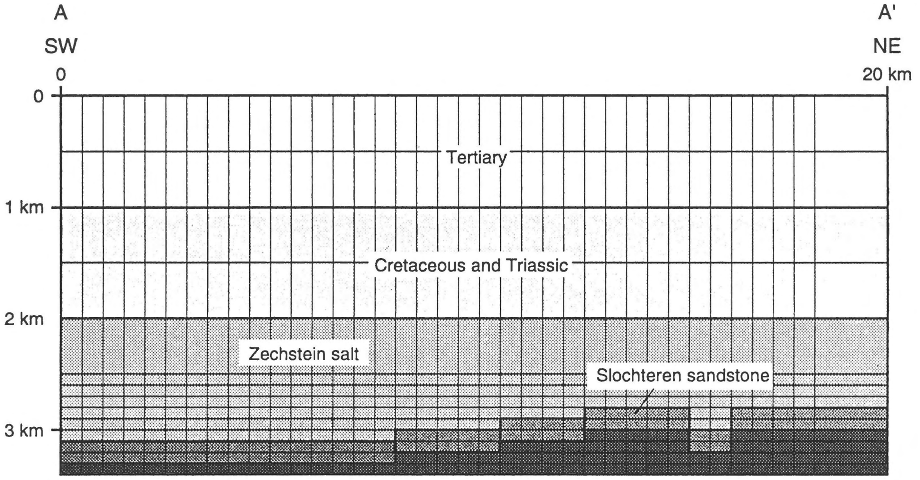
Laboratory experiments

Introduction

An important parameter in describing the compaction of a reservoir is the uniaxial compaction coefficient of the reservoir rock, C_m, which is expressed



(a) Geological cross-section



(b) Model for finite-element study

Fig. 2a, b. GEOFEP finite-element study for SW-NE section A-A′ through the city of Groningen (Fig. 1). (a) Geological cross-section. (b) Model for finite-element study.

in bar^{-1}*. This coefficient is defined as the relative reduction in length per unit of stress increase in an axial direction under a constant loading rate, with radial deformation being prevented.

$$C_m = \frac{1}{h_0} \frac{dh}{d\sigma_z} \qquad \dot{\sigma}_z = \text{const.}, \; dr = 0$$

C_m uniaxial compaction coefficient (bar^{-1})
h_0 initial axial length (m)
dh length reduction under axial stress increase $d\sigma_z$(m)
$d\sigma_z$ axial stress increase (bar)
dr radial deformation (m)
$\dot{\sigma}_z$ axial loading rate (bar/h)

The compaction of the reservoir is determined by this C_m, by the thickness of the reservoir H and by the drop in pressure in the reservoir Δp. In the simplest case:

$$\Delta H = C_m \cdot H \cdot \Delta p$$

H reservoir thickness (m)

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* Throughout this article the unit ‘bar’ is used for pressure and stress (1 bar = 10^5 Pa).

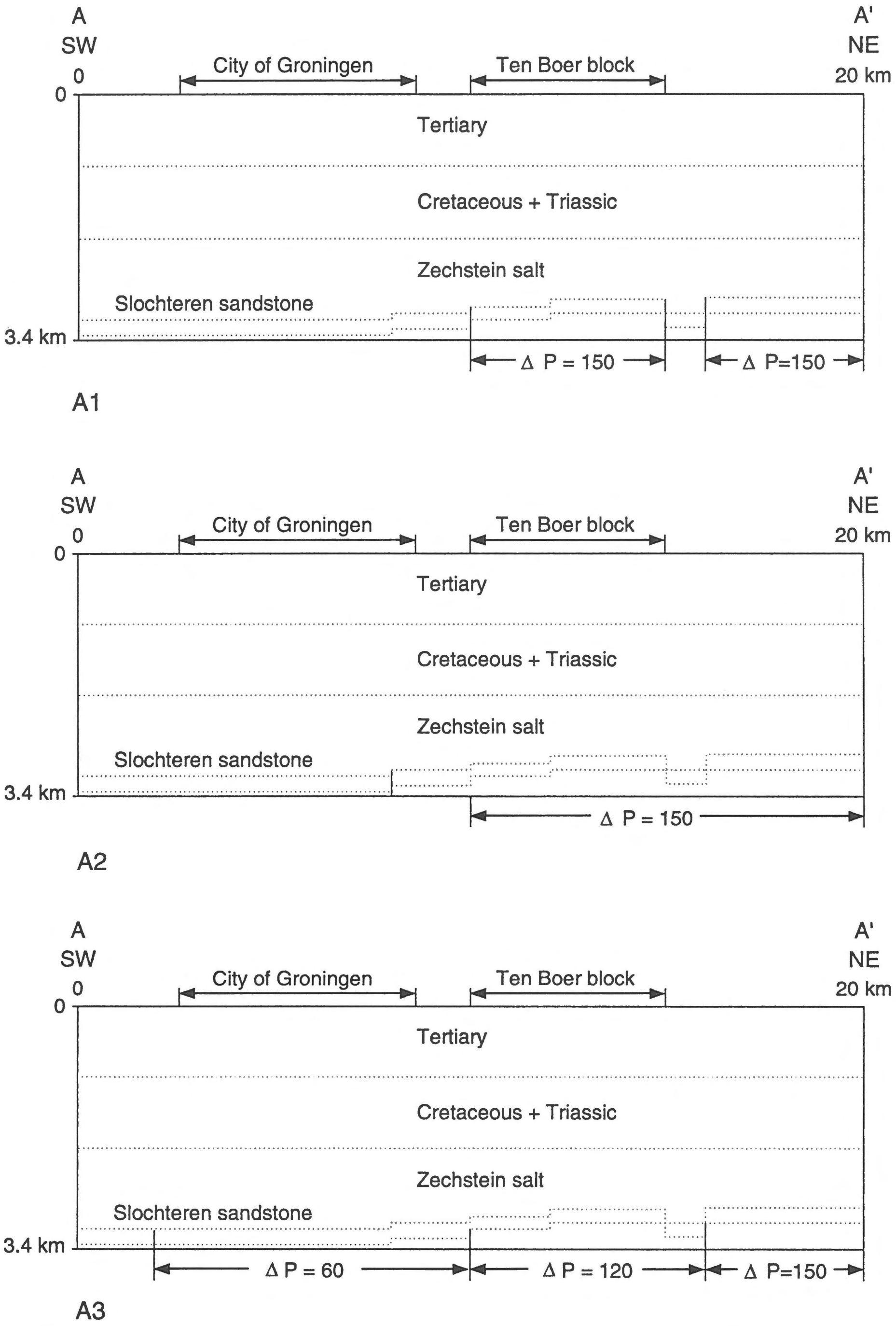
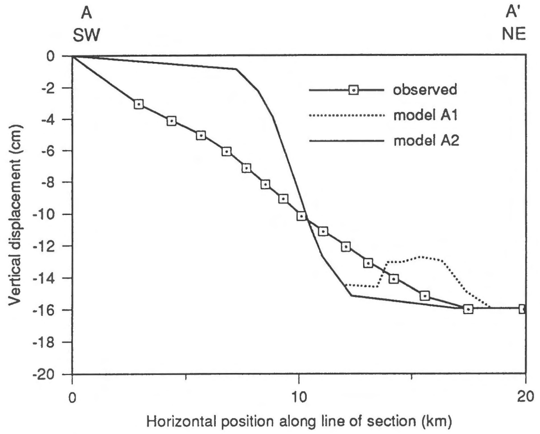


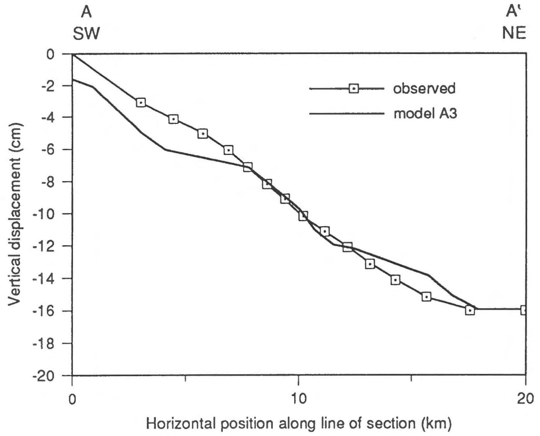
Fig. 3. GEOFEP finite-element study for SW-NE section A-A′. Pressure drop (ΔP in bar), in model A1 to A3.

ΔH reservoir thickness reduction due to reservoir pressure drop Δp(m)
Δp reservoir pressure drop (bar)

To determine C_m, rock samples drilled from cores from the formation can be subjected to experiments in the laboratory. This method is rapid, but it is not always possible to obtain a series of test



Results for models A1 and A2 compared with observations.
Subsidence profiles cannot be explained solely by a drop in reservoir pressure in the gas-bearing part of the reservoir. (Profiles for models A1 and A2 coincide in the left half of the section.)



Results for model A3 compared with observations.
Good correlation for gradual pressure drop across the western boundary of the gas-bearing part of the reservoir.

Fig. 4. GEOFEP finite-element study for SW-NE section A-A′. Calculated and observed subsidence profiles in models A1 to A3.

samples that is completely representative of the formation. Another drawback is that the experimental procedure (sample preparation, test equipment and experimental conditions) may affect the magnitude of C_m.

In-situ measuring techniques can also be used for determining C_m, for instance, monitoring the distance between weakly radioactive bullets that have been fired into the formation from an observation well (De Loos 1973). This technique supplies direct information on the behaviour of the reservoir, but the information becomes available only at an advanced stage in the production life of the field.

Equipment for determining the compaction coefficient

Figure 5 shows the triaxial measuring cell used for the determination of C_m. A cylindrical rock sample of 2.5 cm diameter and 3 cm length is enclosed in an impermeable jacket of elastomer and placed lengthwise between two pistons. These pistons can subject the sample to a uniformly increasing stress along its axis. Simultaneously, the radial expansion of the sample is monitored and a feedback mechanism automatically increases the oil pressure around the sample to prevent radial expansion. These deformation conditions correspond with those in a reservoir, in which only vertical compaction is possible while lateral deformation is prevented by the surrounding rock. The reduction in the length of the sample yields the uniaxial compaction coefficient of the rock (Fig. 6).

Determining the compaction coefficient

An important notion in the experimental determination of the compaction coefficient is the concept of effective stress. In the reservoir, the rock is subjected to a constant overburden pressure. This pressure is counteracted by the pore pressure; the difference between the two determines the vertical effective stress on the rock. During reservoir depletion, the pore pressure decreases while the pressure exerted by the overburden remains constant. This leads to an increase in effective stress on the reservoir rock and thus to compaction. This compaction is vertical; no horizontal deformation of the rock can occur.

The modern triaxial compaction equipment enables various techniques to simulate this process in the laboratory:

(a) Uniaxial deformation without prestressing

This is the conventional technique for determining

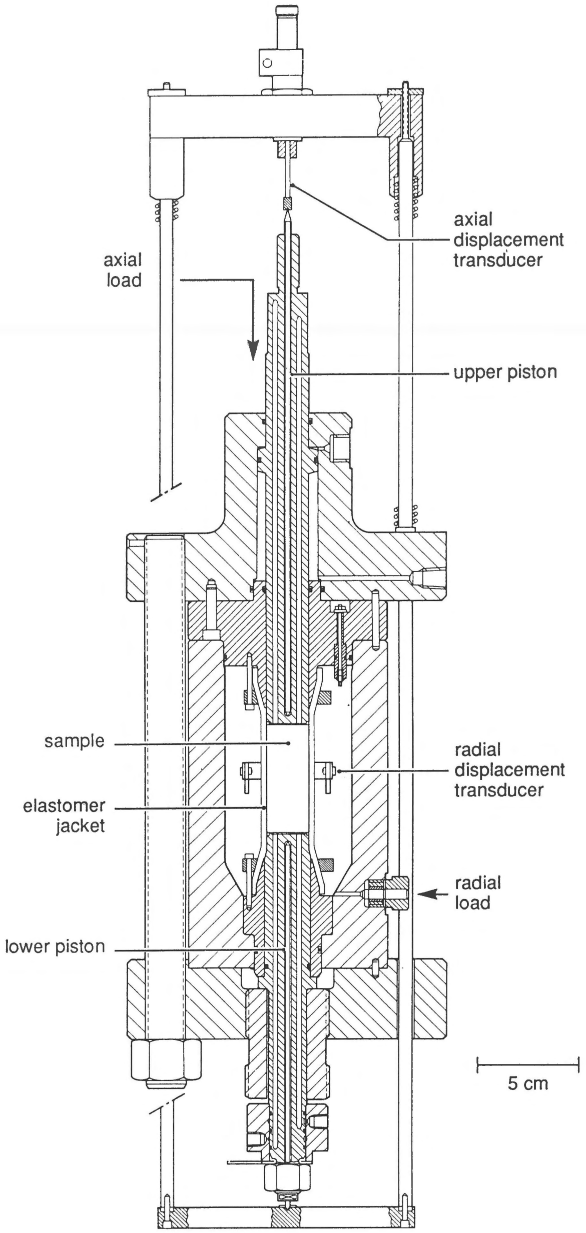


Fig. 5. Triaxial compaction equipment for determining the compaction coefficient.

C_m. In this test an increase in effective stress is simulated by increasing the axial stress on the sample uniformly, starting at atmospheric conditions. The radial stress is adjusted simultaneously, using the feed-back mechanism, to prevent radial deformation. The pore pressure is kept atmospheric during the experiment. The C_m is calculated from the length reduction of the sample over the effective stress range of interest.

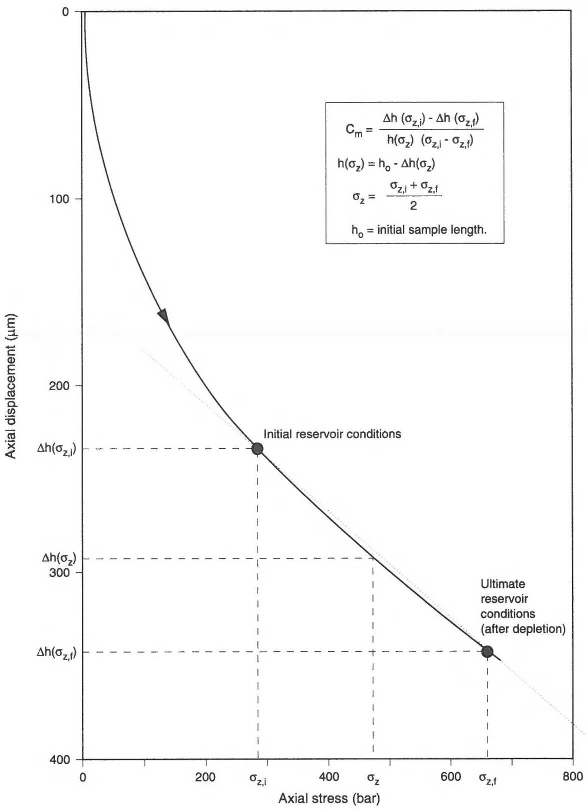


Fig. 6. Schematic determination of the uniaxial compaction coefficient from a laboratory test. Initial sample length approx. 3 cm. Axial stress and displacement ranges typical for a test on Slochteren Sandstone.

(b) Uniaxial deformation after prestressing

In this procedure the sample is brought into an in-situ stress state prior to the test. This is done by applying a radial stress and an axial stress in a ratio that corresponds with reservoir conditions (for the Groningen gas field a ratio of 1:2 has been assumed, based on borehole measurements). The resulting radial and axial strains can be measured accurately. Subsequently, the axial stress is increased further under uniaxial strain conditions (i.e., under variable radial stress), and the C_m is determined. This technique provides a better reproduction of actual field conditions than uniaxial deformation without prestressing.

(c) Uniaxial deformation by reducing the pore pressure

In the two previous techniques the pore pressure of the sample is kept at atmospheric pressure throughout the experiment. A drop in pore pressure in the reservoir is simulated by an increase in the axial load on he sample. As an initial assumption this is correct, but an important effect is not reproduced in this type of experiment. When the pore pressure in a reservoir drops, not only does the effective stress on the rock increase, causing compaction, but at the same time the hydrostatic pressure of the pore fluid around the rock grains decreases. This causes individual grains to expand slightly and counteract the compaction of the rock as a whole. This effect is particularly important when the rock's C_m is almost as low as the compressibility of its constituting grains.

In the present configuration of the triaxial equipment it is possible to apply a pore pressure in the sample equal to the initial pore pressure in the reservoir (approximately 350 bar). At the same time the axial and radial loads on the sample are raised to reservoir levels. From this simulation of initial stress conditions in the reservoir the axial effective stress on the sample is increased by reducing the pore pressure under constant axial load from the piston and maintaining uniaxial conditions. The C_m determined by this third technique will yield the closest approximation to the field value. This 'depletion' C_m is generally a few percent lower than the C_m measured under atmospheric pore pressure, as a result of the expansion of the rock grains with decreasing pore pressure.

The influence of experimental parameters on C_m

Since the 1970's, field observations in the Groningen gas field have shown that actual compaction was about half that expected on the basis of laboratory measurements of the compaction in a triaxial cell, using the conventional technique described above. At the time, a mean C_m of 1.45×10^{-5} bar^{-1} was found in conventional uniaxial compaction experiments starting from atmospheric conditions (test type (a)), whereas the mean C_m deduced from field observations by the Nederlandse Aardolie Maatschappij (NAM) is approximately 0.7×10^{-5} bar^{-1}. In an attempt to explain this discrepancy the impact of various experimental factors has been studied:

(1) the ratio of radial and axial stress during prestressing;
(2) the pore pressure;
(3) the temperature;
(4) innate rock properties, such as porosity, grain size and sorting and the presence of cement;
(5) permanent damage to the core resulting from its extraction from the reservoir and any damage to the sample as it is drilled from the core (e.g., microfractures and the disruption of the cemented contacts between grains).

(1) The ratio of radial and axial stress during prestressing affects the experimentally determined C_m. Increasing this ratio strengthens the sample: after prestressing at a ratio of 1:2, the C_m obtained on a number of samples from the Groningen reservoir was approximately 15% lower than the C_m measured on the same material in another uniaxial experiment without prestressing. This observation has led to the introduction of the second experimental procedure described above (type (b)), in which the sample is first brought to the prevailing initial stress conditions and subsequently further compacted uniaxially.

(2) The C_m of an individual grain can be calculated from compaction experiments under decreasing pore pressure (test type (c)). This enables a correction of the conventionally determined uniaxial C_m to be made for the impact of a reduction in pore pressure, such as occurs during reservoir depletion. This correction lowers the conventionally determined C_m, since the effect of an increase in the volumes of the rock grains as a result of the decreasing hydrostatic pressure is included. The experiments on a number of samples from the Groningen field show an average reduction of the C_m by approximately 6% as a result of this effect.

(3) A limited number of experiments was performed to determine the effect of temperature on compaction behaviour. These experiments, at tem-

peratures ranging from 20 to 100° C, have not shown any relationship between the compaction coefficient of sandstone and its temperature.

(4) Microstructural analysis of rock samples before and after a compaction experiment showed that the rock texture may affect C_m. At constant porosity, C_m decreases with a decrease in grain size, an increase in sorting and an increase in cementation.

(5) Extracting cores from a reservoir brings about major changes in the loading conditions of the rock and may cause permanent deformation, which may greatly affect the physical properties of the material. These effects are very hard to quantify, as all reservoir rock material is obtained via core extraction, and thus potentially is damaged. Some experiments were performed to see if additional core damage could be induced by simulating the coring process. A core sample was subjected to in-situ loading conditions, the axial load was gradually reduced and subsequently the radial load was reduced very rapidly. The C_m that was determined on the sample after this treatment, however, showed no measurable difference with the C_m measured conventionally on an adjacent sample from the same core. The artificial disturbance of the sample therefore apparently did not induce any additional damage to the rock. This of course does not exclude the possibility that the core had been disturbed so much already during the coring process that this attempt at artificially further disturbing the core no longer affected its C_m.

Loading rate effects

The loading rate to which a sample is subjected during an experiment was found to affect its C_m. The lower the loading rate, the higher the C_m (Fig. 7). The C_m of a consolidated sandstone, such as the Slochteren Sandstone in the Groningen reservoir, is, for instance, under typical laboratory loading rates of 100 bar per hour, approximately 5% lower than under loading rates of 0.3 bar per hour. Under field conditions, the loading rate is considerably lower than the lowest rates in the laboratory: in the Groningen gas field, for instance, the loading rate resulting from depletion is approximately 1 to 4 × 10^{-3} bar/hour. Extrapolation of the experimentally determined loading-rate effects to the low field rates would yield a field C_m that is a few per cent higher than the experimentally determined value. Quantification of this effect was attempted on the basis of laboratory experiments and investigation of field cases (De Waal 1986, De Waal & Smits 1988). This is further discussed in the next section.

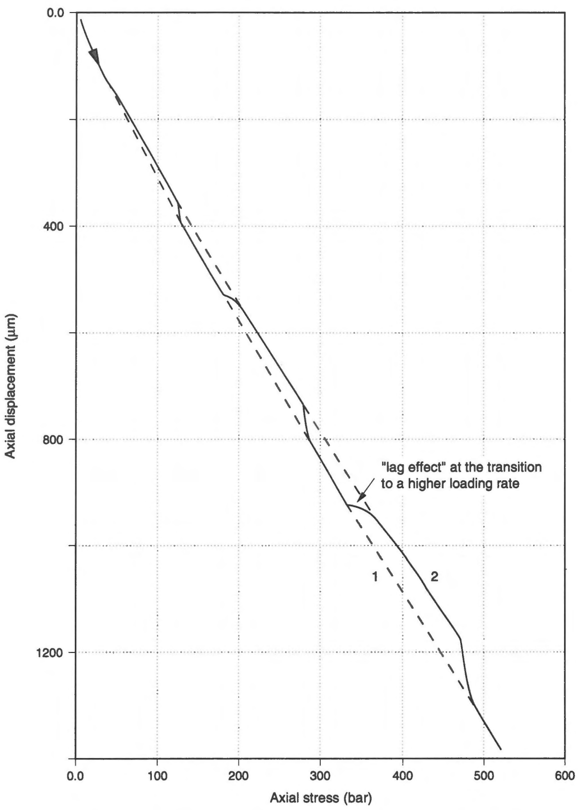


Fig. 7. Schematic compaction curves at high(2) and low(1) loading rates. Laboratory test on an unconsolidated sediment.

Theoretical considerations

Model used in earlier predictions

In the early 1980's an empirical model was developed at KSEPL for quantifying the effect of large variations in loading rate on the compaction behaviour of sandstones (the rate-type compaction model, RTCM: De Waal 1986; De Waal & Smits 1988). In the field, reservoir rocks are buried very slowly at a geological rate and the vertical effective stress increases gradually (for instance, of the order of 10^{-4} to 10^{-5} bar each year). Production of hydrocarbons from the reservoir may cause a much more rapid increase in the vertical effective stress, for instance of 10 to 20 bar per year. As described above, compaction experiments on consolidated sandstones show the effect of the loading rate on the uniaxial compaction coefficient C_m: the higher the loading rate, the lower the C_m. If this behaviour occurs at the much lower field loading rates as well, this would imply that the compaction coefficient determined in the laboratory is lower than that at a hydrocarbon-depletion loading rate, which in turn is lower than that at a geological loading rate. The RTCM describes the sensitivity of a rock to such differences in loading rate with a parameter 'b'. Moreover, an increase in loading rate from a (very low) geological value to a much higher value during depletion would result in a non-linear relation between axial effective stress and compaction, as indicated by laboratory observations (Fig. 7). Such a sudden increase in loading rate would be accompanied by a 'lag effect', in that, during the first few years of production, compaction and therefore surface subsidence would be relatively small. Only after some time would the compaction of the reservoir increase more rapidly and follow the C_m for the increased loading rate resulting from depletion. This interpretation was substantiated by published data on compaction and surface subsidence in a number of oil fields in Venezuela and the United States that had been producing for a long time (De Waal 1986; De Waal & Smits 1988, and references therein).

The RTCM could thus explain the difference between the experimental C_m and the C_m calculated from field observations in the Groningen field. The lower value of the field C_m would reflect the fact that the field was still in its infancy, in the 'lag phase' that belongs to the transition from a low (geological) to a high (depletion) loading rate.

Comparison with observations in the Groningen gas field

The Groningen gas field has been documented very thoroughly; many data have been gathered on surface subsidence, shallow compaction, reservoir pressure and in-situ compaction (Doornhof 1992). The field is unique in this sense; in few other cases is such a complete and reliable dataset available. This provides an excellent circumstance for a quantitative comparison between the predictions on the basis of a compaction model and field observations as made by NAM.

The latest field observations show that the amount of compaction in the Groningen gas field keeps increasing linearly with increasing vertical effective stress (Doornhof 1992). This deviates from the non-linear compaction behaviour predicted earlier on the basis of the RTCM with experimentally determined values of C_m and the loading rate sensitivity parameter b. The RTCM predicted that, after an initial small compaction, the compaction rate would increase until the compaction would proceed in accordance with the experimentally determined C_m. The field data indicate an in-situ C_m approximately half that determined in conventional compaction experiments.

It should be noted that the RTCM can still describe the observed field behaviour when, instead of taking the C_m and b values determined in the laboratory, the compaction coefficient as derived from field data is used and when a corresponding very low value for b is assumed. The latter assumption implies that the reservoir rock of the Groningen field is not sensitive to the loading rate.

Current theories

A critical review of the compaction model and of experimental procedures has not explained why, in the case of the Groningen gas field, the extrapolation of laboratory data to field conditions on the basis of the RTCM does not correspond to the compaction that was actually measured in-situ. This discrepancy might be due to sample disturbance during the coring process. Another possibility is that at the high loading rates of the laboratory experiments the compaction process is dominated by other physical mechanisms than at the (low) field loading rates. These issues are the subject of ongoing research.

In the meantime, caution should be exercised in using loading-rate effects observed in the laboratory as a basis for the prediction of compaction under field conditions. Compaction in the Groningen gas field was found to be essentially linearly dependent on the drop in reservoir pressure. When future compaction behaviour of the field is predicted, it seems warranted, therefore, to assume a linear relation between the vertical effective stress and the amount of vertical compaction.

Conclusions

Conversion of compaction into surface subsidence

The nucleus-of-strain model used for the conversion of reservoir compaction into surface subsidence has been confirmed by recent field observations and finite-element modelling studies for the Groningen gas field in the Netherlands. The possibility of fault movements extending to the surface as a result of differential compaction has been studied for this field and can be ruled out.

Determination of the compaction coefficient of a rock

A discrepancy was found between C_m values determined in the laboratory on Groningen reservoir rock and C_m values deduced from field data. A number of experimental factors were investigated as possible causes of this discrepancy, but these do not fully explain it. The coring process might cause permanent damage to the rock, making it weaker and resulting in higher C_m values being determined in the laboratory than actually exist under similar stress conditions in the reservoir.

Model for describing compaction

For the Groningen gas field, a linear compaction model provides a good description of the observed compaction behaviour. Until now, the amount of compaction follows almost immediately upon the increase in effective vertical stress that occurs as a result of gas depletion. Non-linear compaction in time, the 'lag effect' predicted in an earlier compaction model, has not been observed. Therefore it seems warranted to use the linear compaction model in future predictions.

A similar procedure is recommended for general use: initial compaction prediction for an oil or gas field may be based on experimentally determined C_m values and a linear compaction model. This will generally indicate an upper limit to the compaction ('worst case'); in reality compaction may turn out to be lower. Field data that become available during production may necessitate adjusting the prediction.

Current and future research

To achieve a better understanding of the compaction process, it is necessary to do fundamental research into mechanisms that cause compaction under increasing vertical effective stress as well as under constant vertical stress. In the past, this process was studied at a macroscopic scale; current research focuses on physical processes on a microscopic scale. Microstructural studies attempt to describe the actual compaction mechanisms and the effect of experimental parameters (pressure, temperature, etc.) on the compaction process. The possible damage ensuing from core extraction will be given special attention. The objective is to formulate a constitutive (i.e., physically founded) compaction law. Such a law can be used to design new prediction models that use rock parameters determined in the laboratory.

At the same time, it is necessary to gain a better understanding of the stress conditions prevailing in the reservoir and the surrounding formations before, during and after depletion. This can be achieved by measuring in-situ stresses in the field and by performing theoretical studies. These stress values should be a crucial parameter in future compaction models and the accompanying experimental techniques.

Acknowledgements

The research reviewed in this paper was conducted by many different workers from various disciplines – geology, rock mechanics and (petro)physics – over the course of several decades. Aside from the publications quoted in the References, this review also comprises unpublished work by J.F.C. van Kooten, W. Sassi, R.J.H. Loosveld and others.

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