



The Discontinuum Approach to Compaction and Subsidence Modelling as Applied to Ekofisk

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ABSTRACT

The Ekofisk Centre in the North Sea has undergone unexpected seabed subsidence involving 150 km² of underlying rock and sediments over an area of 50 km². NGI was engaged by the Norwegian Petroleum Directorate to perform independent studies of the factors involved in the subsidence, and of the implications of the compaction. NGI's studies included laboratory tests of the jointed reservoir chalk, numerical continuum modelling using the CONSAX code and discontinuum modelling using UDEC. In the final studies performed a special joint subroutine was incorporated in UDEC so that the effects of compaction on joint apertures and conductivity could be investigated. The studies showed that the steeply dipping conjugate joints in the 300 m thick reservoir were probably undergoing shear during the approximately one-dimensional compaction. Joint shear and dilation were admissible in this uniaxial strain environment, due to shrinkage and pore collapse of the matrix between the joints caused by the 20 MPa drawdown in pore pressure. The 3 km of overburden shale was also modelled as a discontinuum and demonstrated the possibility of shear along bedding planes and sub-vertical jointing. Discontinuum models showed larger ratios of subsidence to compaction than continuum models due to such shear mechanisms.

1. INTRODUCTION

Those working on the Ekofisk problem are frequently asked the question; why was it not foreseen? A 20 MPa (or more) reduction in pore pressure in a reservoir of large area (50 km²) at no more than 3 km depth must have been expected to cause compaction and surface subsidence?

The questions are well grounded. The answer is at least partly based on an insufficient understanding of a complex material such as chalk at that time.

More importantly, there was no precedent for subsidence occurring from such a deeply buried reservoir.

Figure 1 illustrates another possible reason for the failure to foresee the magnitude of potential problems. The strongly non-linear void ratio - effective stress behaviour leads to large strains in highly porous chalk (i.e. $n = 40\%$) for a pore pressure reduction large enough to cause yield [1]. The deformability of the higher porosity chalks could also have been underestimated due to poor sample recovery.

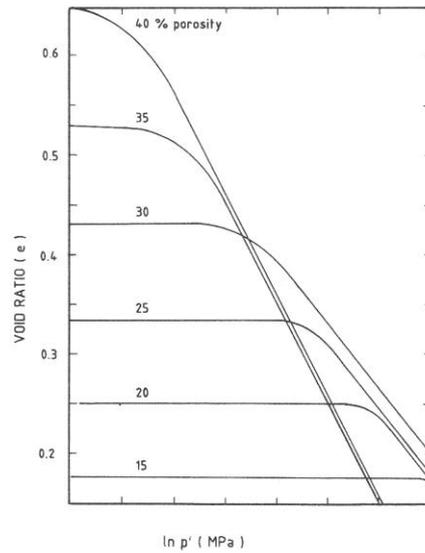


Figure 1. Non-linear stress strain behaviour under uniaxial strain conditions, emphasises the role of chalk porosity on the pore collapse phenomenon.

Figure 2 shows comparative photographs of the Ekofisk oil storage tank that were taken in 1973 and 1986. The submerged rows of wave baffle holes (2 m spacing) were the first clue to a subsidence problem. The tank itself had settled only 30 cm relative to the sea bed despite major winter storms. When checked, some 13 years after tank installation, NGI's vibrating wire pressure transducers confirmed the increased water depth.

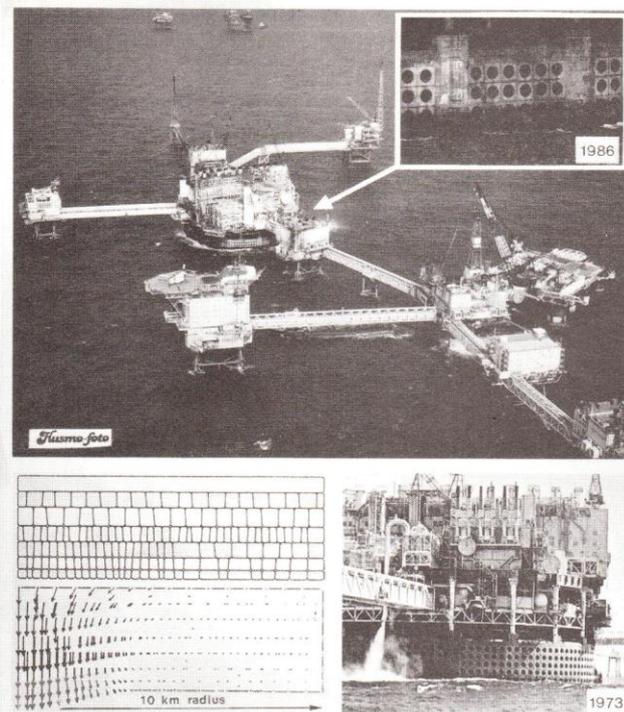


Figure 2. Sea bed subsidence at the Ekofisk centre is evident from the submerged wave baffle holes (2 m centre to centre). Left inset shows one of our UDEC models.

2. CONTINUUM ANALYSES OF COMPACTION AND SUBSIDENCE

Detailed axi-symmetric analyses of the compaction process were performed using various cross-sectional models of the reservoir supplied by Phillips Petroleum Co. Ltd. One of these is illustrated in Figure 3. The distribution of porosities implies various radius-dependent degrees of non-linearity (pore collapse). In addition to this complication, the pore pressure-time histories were radius-dependent and varied in drawdown rate from year to year. Furthermore, the pressure-time histories were different in the upper and lower parts of the reservoir (separated by the low porosity "tight zone"). The complex porosity distribution of the reservoir was used to enable the low porosity strata to "protect" any underlying high porosity strata through arching. Models employing discretised porosity bands do not allow this arching protection, and result in

unrealistically large magnitudes of compaction. Concerning future behaviour (up to the year 2010) an anticipated injection scenario was simulated.

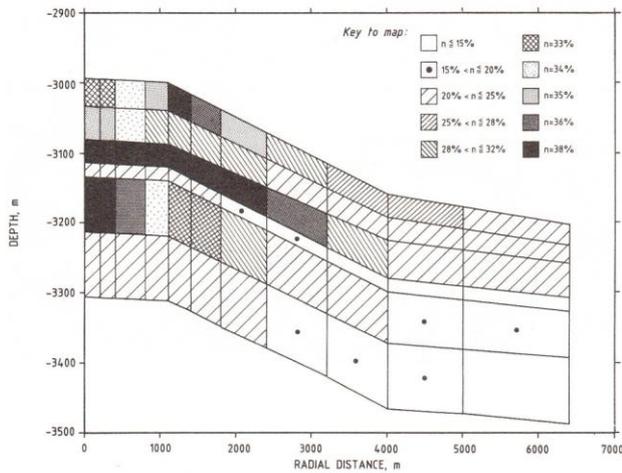


Figure 3 Example of porosity distribution used in one of the CONSAX compaction models

The continuum modelling of the compaction process was performed using the non-linear finite element consolidation program CONSAX [2], with a Cam-clay type material model formulation. The resulting compaction profiles were used as displacement boundary conditions for the base of the overburden during subsequent linear-elastic axi-symmetric finite element models of the subsidence. Model radii of 20 km were used. In general these compaction and subsidence models indicated ratios of subsidence to compaction in the range 0.52 to 0.65. Typical examples (for the year 1985) would be:

Maximum compaction 3.2 m
Maximum subsidence 1.9 m

In a second phase of continuum modelling, combined compaction and subsidence calculations were performed in the same model. In an effort to reduce the artificial effect of a continuous overburden, frictionless model boundaries were simulated at the extreme outer boundaries of the reservoir. As expected the predicted subsidence bowl showed greater similarities to the bathymetric measurements of real behaviour [3]. The subsidence to compaction ratios mostly

ranged from 0.78 to 0.88 which appears to be closer to presently measured values, though considerable uncertainties accompany such measurements.

2.1 Discussion of input into continuum models

The material property input into continuum models; e -log p' or other stress-strain relationships, is of fundamental importance to the accuracy of any computation. The persistence of high porosity material in the Ekofisk reservoir suggests the the material can withstand a larger pore pressure decline before yield and subsequent pore collapse occurs, than anticipated from laboratory results. Such a result can largely be explained by a weakening of the core material upon drilling and recovery.

Drilling vibration and general disturbance during coring results in a very low percentage recovery of core material from weak (high porosity) formations. This is particularly common in high porosity chalks from the Valhall field. It is unrealistic to assume that in slightly stronger material no disturbance occurs. A gradual increase in sample weakening will occur with increasingly, weak material to a point of eventual breakdown of the core [1].

Superimposed on this disturbance is stress relief and temperature reduction upon removal from the reservoir. This results in strain relaxation of the core [4].

The strains developed during laboratory tests, and the subsequent modelling of reservoir drawdown, will therefore overestimate the magnitudes of strain encountered in-situ. The quantification of the affect of disturbance on the material properties has not been investigated, and therefore cannot be assessed at this time.

Another potential source of error is the size of sample tested in the laboratory. It is well known that the size and shape of sample tested in the laboratory affects the measured mechanical properties [1]. However, unlike the testing and modelling of discontinua, the affect of sample size on 1-d compaction of weak rocks has not been investigated.

3. DISCONTINUUM SUBSIDENCE MODELLING USING UDEC

It appears inherently reasonable to argue that an overburden consisting of 150 km³ of shale with interbeds of limestone, cannot behave in practice as a continuum. Bedding planes and sub-vertical or vertical regional joints and faults obviously dissect this huge mass of rock into countless major slabs and blocks,

together with the detailed structures that are too numerous to ever consider in any modelling exercise. When such a body of rock is strained due to an underlying compaction process, deformation occurs by slip rather than bending. Seen in detail, the deformation will resemble the flexure of a leaf spring, with interbed slip due to the stretching required to accommodate the subsidence. Zones of large strains may also cause slip on sub-vertical features, as seen in the more extreme case of long-wall mining.

With this philosophy in mind it was natural to choose the finite difference code UDEC [5] to investigate the potential for discontinuum behaviour in the Ekofisk subsidence. Bearing in mind the relative weakness and high deformability of the shale overburden, bedding plane or fault slip was not certain. The kilometer sized blocks that were modelled could bend with ease. In the model the upper 500 m of seabed was considered as a very soft continuum.

In view of the uncertainties involved, the simple linear sub-routine for joint behaviour was utilized in these first UDEC studies. Single values of c (cohesion), ϕ (friction angle), K_n (normal stiffness) and K_s (shear stiffness) were required as input data. Since the 150 km³ of overburden was modelled with a very small number of blocks, each joint was of fault-like dimensions. Input parameters were chosen using the results of normal and shear loading tests on joints, with extrapolations to fault-sized features [6].

The inherent scale effect in laboratory shear loading required extrapolation to in situ conditions. The approach adopted is shown in Figure 4. Tests with UDEC using small-scale, high shear stiffnesses showed continuum type behaviour, with limited slip and characteristically small values of the subsidence-compaction ratio. When shear stiffnesses of the order of 0.01 MPa/mm were used; appropriate to kilometer size faults, behaviour was dominated by bedding plane and fault slip, and ratios of subsidence to compaction were as high as 0.86 to 0.95, which appeared to be consistent with the approximate initial estimates of compaction obtained from logs.

The type of behaviour obtained with realistically low shear stiffnesses is shown in Figure 5. The three diagrams show the assumed geometry, deformation vectors, and zones of joint slip (where line thickness is proportional to slip magnitude).

The method required to induce the subsidence was similar to that used in the continuum modelling. The lower boundary of blocks representing the reservoir was displaced in proportion to the calculated compaction distribution. However,

in the UDEC modelling this displacement occurred over a given number of time steps.

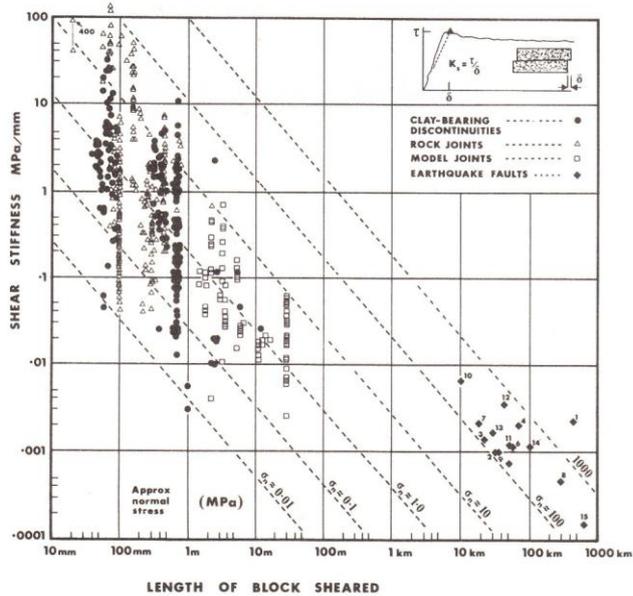


Figure 4. Large scale values of bedding plane and fault shear stiffness were derived by data extrapolation [6].

As an example, in one of the studies of possible seafloor subsidence by the year 2010, the compaction was built up in steps, and equilibrium was achieved for each increment. At compaction maxima of 1.1, 2.2, 3.3, 4.4 and 5.5 m (year 2010) the subsidence maxima at the centre of the subsidence bowl were found to be 0.9, 1.9, 2.9, 3.9 and 4.8 m respectively. A final ratio of $S_{max}/C_{max} = 0.91$ was indicated by these computations.

Marked increases in the distribution of overburden shearing are evident for these five gradually applied increments of compaction. Maximum values of discontinuity shear were concentrated on vertical and sub-vertical features, the shearing reaching a maximum (for the assumed block size) of 25 cm immediately above the reservoir at a radius of 3 km. The maximum shear on existing bedding planes was approximately 10 cm, and occurred at the boundary between layers of different stiffness at 1600 m depth.

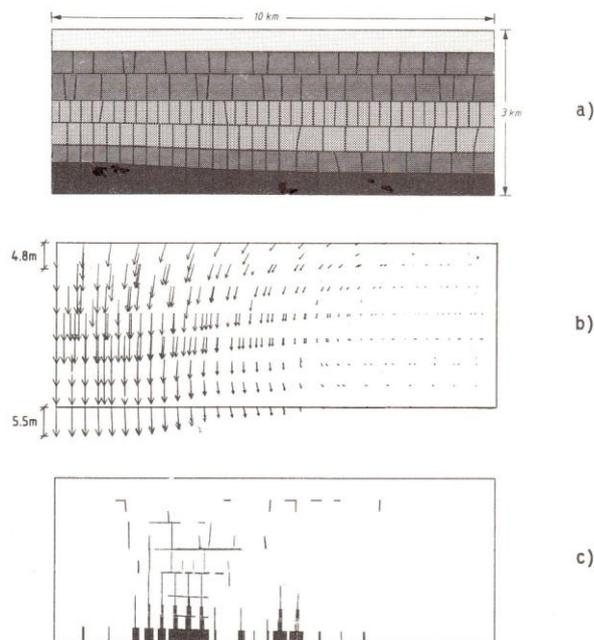


Figure 5. Axisymmetric analyses of reservoir subsidence at Ekofisk using the UDEC method: a) bedding and faults, b) deformation vectors, c) shear displacements.

An interesting parallel to this predicted behaviour is the interbed shear of 23 cm and seismicity (magnitude 2.4 - 3.2) reported at the Wilmington field in California [7]. In this classic reservoir subsidence problem a maximum surface subsidence of at least 9 m was registered. The reported interbed shear caused damage to numerous oil well casings. In this instance, movement was concentrated along thin interbeds of claystone and shale sandwiched between thick massive beds of sandstone and siltstone.

4. COMPACTION PHENOMENA IN THE JOINTED RESERVOIR

Oriented drill core logged by Phillips Petroleum Co. Ltd. geologists indicated that the chalk reservoir was intersected by several sets of joints. The most persistent in terms of reservoir production were two sets of steeply dipping conjugate joints. Several levels of the reservoir were heavily jointed in this manner, with block sizes down to a few centimeters.

Numerical modelling of a typical heavily jointed section of the reservoir was performed using a high porosity matrix with a I-D strain modulus of 0.33 GPa, and a low porosity matrix with a modulus of 3.33 GPa. Input data for the joints was obtained from joint surface characterization and tilt tests to obtain joint roughness, and from uniaxial and triaxial tests on cylindrical samples. Formulations for full-scale shear strength were based on the Barton- Bandis model [6].

Discrete blocky models of typical conjugate jointing were generated with the discontinuum code UDEC, using reservoir-scale joint properties derived from these laboratory tests. The UDEC model shown in Figure 6 contains 70 discrete blocks, representing a vertical 1 m² "window" view of a heavily jointed zone. These models were consolidated to initial reservoir effective stress levels, and then loaded internally (joints and matrix) by an appropriate reduction of fluid pressure. The figure shows the deformation caused by this fluid pressure reduction.

The first blocky model of simulated low-porosity chalk showed a maximum joint shear of 1.2 mm, and an average of 79 μm on all joints that sheared. The combined effect of joint closures and (slightly dilatant) shears was 1.8 μm average closure of joint apertures; i.e. the conductivity was only slightly reduced by this major fluid pressure decline.

A second UDEC model of reservoir jointing was designed to simulate the high porosity jointed chalk. Reduction of internal fluid pressure this time caused larger shears (maximum 3.9 mm), and an average shear of 394 μm on all the joints that sheared. The pattern of joint shearing is illustrated in Figure 7.

The combined effect of joint closures, occasional local joint openings, and virtually non-dilatant shear was 2.0 μm average closure of all joint apertures, i.e. even in the high porosity chalk model the effect of the compaction process on the joints was only slightly negative.

Joint shearing would normally cause an increase in the rock mass' Poisson's ratio. Under I-D strain conditions it has the effect of increasing K_0 . The higher horizontal stress helps to limit compaction. The joint shearing helps to maintain conductivity. Both these behaviour modes are very beneficial to reservoir management.

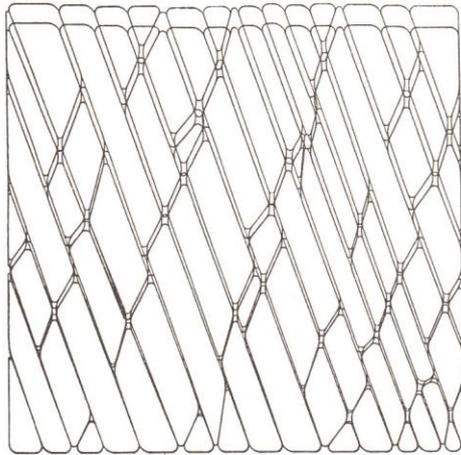


Figure 6. UDEC model of a 1x1 m heavily jointed reservoir zone, showing compaction under 1-D strain.

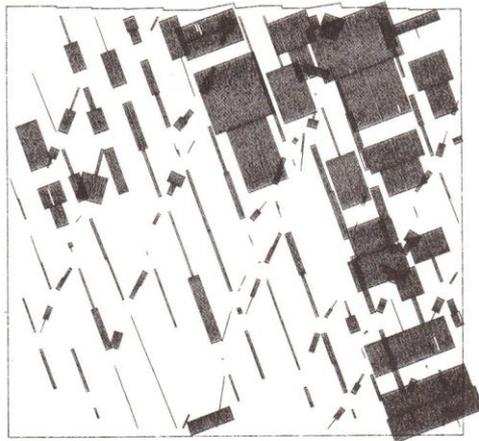


Figure 7. Joint shear locations from UDEC model caused by pore pressure reduction in joints and matrix. (Each line represents 50 μm shear).

5. LABORATORY TESTS OF JOINT CONDUCTIVITY

The conductivity of the reservoir joints was also investigated during this laboratory programme. Coupled joint closure-conductivity tests performed using heated oil at 80°C, revealed a "plastification" of the most porous (43,6%) chalk when the normal stress was raised to the level of the unconfined compression strength. These unusual tests were performed in the equipment described by Makurat [8].

The "plastification" occurred within the natural joint plane as the conductivity was reducing with increasing stress. A less porous jointed sample demonstrated an unexpected increase in conductivity between normal load cycles, after marked closure in the first cycle. This may be due to a superficial work hardening and smoothing of the joint walls with successive cycles, resulting in better conducting qualities.

During subsequent shear displacement of about 2 mm, the joint conductivity reduced gradually by at least one order of magnitude, possibly due to gouge production. Reversed shear caused the conductivity to rise again.

Special high pressure joint conductivity tests were also performed in a triaxial cell with inclined joints. Access to the joint plane was made with thin tubes so that fluid flow in the joint plane could be measured while the joint was undergoing small amounts of shear at full reservoir effective stresses of about 30 MPa. In these tests the initial (disturbed) joint conducting apertures of 35 to 67 μm were successively reduced by the combined shear and normal loading to values below 5 μm . However, in most cases conductive capability was maintained.

5.1 Potential for drainage of the overburden due to joints

The behaviour of joints is fundamental to the behaviour and compaction potential of the reservoir overburden. Recent studies have considered the matrix compaction of the overburden. Jones et al. [9] considers the pore pressure decline in the reservoir affecting differently sized joint defined blocks, and models the strain associated with drainage of these blocks. A more extreme case of overburden compaction has been considered by Janbu and Christensen [10] - compaction resulting from a decrease in the overpressure in a shale to a level below the hydrostatic gradient. This latter case can be considered unrealistic due to the low permeabilities which exist in shale overburdens.

The drainage and compaction of overburden resulting from pore pressure drawdown in the underlying reservoir can only occur to any extent if there exists pore

pressure connection between the two lithologies. The joint system is an obvious source of potential drainage, however, the ability of a joint system to transmit pore pressure decreases and aid the consolidation of the shale mass is unknown at near reservoir pressures and will be dependant upon the relationship between joint dilation upon shearing and gouge production.

CONCLUSIONS

1. Non-linear modelling of the reservoir compaction with a modified Cam Clay material model in the CONSAX code, appears to give a reasonably good fit to the approximate 1985 contours of compaction derived from log interpretation when an accurate porosity model is used as input.
2. Application of the calculated compaction distribution as a displacement boundary condition to overburden models, indicates a poor fit with subsidence measurements when modelling the overburden as a layered elastic continuum, but a good fit when modelling the overburden with the discrete element code UDEC.
3. UDEC discontinuum analyses of the overburden suggest that slip on joints, faults and bedding planes may be a realistic mechanism for explaining the measured subsidence bowl and the relatively high ratio of subsidence to compaction apparently observed at Ekofisk.
4. UDEC modelling of representative heavily jointed zones in the reservoir using extrapolated laboratory joint test data provides insight into what may be a previously unrecognised mechanism of deformation for jointed media. Loading both the matrix and joints by an internal reduction in fluid pressure in one-dimensional strain causes joint slip, relative mass bulking, partial maintenance of joint apertures (and therefore conductivities) and a compaction magnitude somewhat smaller than when the chalk is unjointed.
5. Flat-lying joints would not show this positive behaviour, and such a rock mass would obviously deform more than an unjointed body of rock.
6. This unexpected mass-bulking mechanism with steeply dipping joints may explain the continued high productivity still experienced from the Ekofisk reservoir.
7. Considerable sources of error still remain with regard to laboratory testing of weak rocks - and with the extrapolation of laboratory results to field conditions.

6. ACKNOWLEDGEMENT

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