

ANALYSER OG FORSØK FOR BELYSNING AV SETNINGER PÅ EKOFISK
NUMERICAL ANALYSES AND LABORATORY TESTS TO INVESTIGATE THE
EKOFISK SUBSIDENCE

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SAMMENDRAG

Ekofiskinnsynkningen influerer 150 km³ av Nordsjøens havbunnsedimenter. Nesten 3 meter innsynkning, med nåværende hastighet 40-45 cm pr. år har forårsaket igangsetting av flere undersøkelser av fenomenet. NGI, under kontrakt med Oljedirektoratet, har tatt i bruk avansert ikke lineær endelig element og diskrete element- metoder for å undersøke de forskjellige kompaksjonsprosesser i det 300 meter tykke krittreservoaret som ligger 3 km under havbunnen. Disse detaljerte beregninger er brukt som en grensetilstand for storskala kontinuum og diskontinuum analyser (med lagdelinger og forkastninger) for å vurdere innsynkningsomfang og størrelse. Detaljerte labforsøk var foretatt på de reservoarsprekkene, for å måle skjærfasthet, stivhet og konduktivitet med 80°C Ekofiskolje. Disse forsøk dannet grunnlaget for spesielle numeriske modeller av deformasjonen og de permeabilitetsforandringer som kan være forårsaket av en 20 MPa reduksjon i reservoarporetrykk i en oppsprukket, deformerbar og permeabel reservoarbergart utsatt for endimensjonal tøyning. En interessant og helt uventet oppførsel ble oppdaget med disse diskontinuum analyser, som kan få stor betydning for fremtidig produktivitet i reservoaret.

SUMMARY

The Ekofisk subsidence is influencing 150 km³ of the seabed sediments in the North Sea. Nearly 3 meters of subsidence at a present yearly rate of 40 to 45 cm/year has set in motion several studies of the phenomenon. NGI, under contract with the Norwegian Petroleum Directorate, has utilized advanced non-linear finite element and discrete element methods to investigate various compaction processes in the 300 meter thick chalk reservoir located 3 km beneath the seabed. These detailed calculations were used as a displacement boundary condition for large-scale continuum and discontinuum analyses (with bedding planes and faults) in order to investigate the extent and size of the subsidence. Detailed laboratory tests were performed on the reservoir joints, to measure their shear strength, stiffness and conductivity to hot (80°C) Ekofisk oil. These tests provided the input data for special numerical modelling of the deformation and permeability changes that can be caused by a large reduction in reservoir pore pressure in a jointed, deformable and permeable reservoir rock subjected to one-dimensional strain. An interesting and quite unexpected type of behaviour was discovered during these discontinuum analyses, which can have an important influence on future productivity in the reservoir.

INTRODUCTION

The Ekofisk field which is operated by Phillips Petroleum Company, is one of several hydrocarbon reservoirs associated with the Central Graben in the southern North Sea. The Maastrichtian and Paleocene (Tor and Ekofisk) chalks form an extensively jointed gentle anticlinal-domal structure, 300 meters in thickness at 3 km depth. The reservoir is pear-shaped in plan, with maximum dimensions of approximately 9 km (EW) by 14 km (NS).

The higher porosity chalks (30 to 45 %) which are undergoing non-linear deformation have caused a central compacting zone measuring approximately 30 km² in area (approx. 4 by 7 km). The area of seabed presently affected by the subsidence appears to be more circular in shape (approx. 7 by 9 km) and covers an area of approximately 50 km².

Numerical modellers are therefore faced with the problem of predicting the subsidence of some 150 km³ of overburden (mostly shales), using laboratory samples of the chalk and shale as small as 15-30 cm³; a discrepancy in volume of six-

teen orders of magnitude.

COMPACTION MODELLING USING A NON-LINEAR CONTINUUM MODEL

Non-linear finite element continuum analyses of the compaction process were performed with the CONSAX code (D'Orazio and Duncan, 1982). This program uses eight-noded isoparametric elements. Known distributions of porosity and fluid pressure time histories were modelled. A modified Cam Clay Model was used to simulate the non-linear void ratio - log effective stress curves, which represent the pore collapse behaviour of the most porous chalk.

An example of one of the four porosity distributions that was modelled is reproduced in Figure 1.

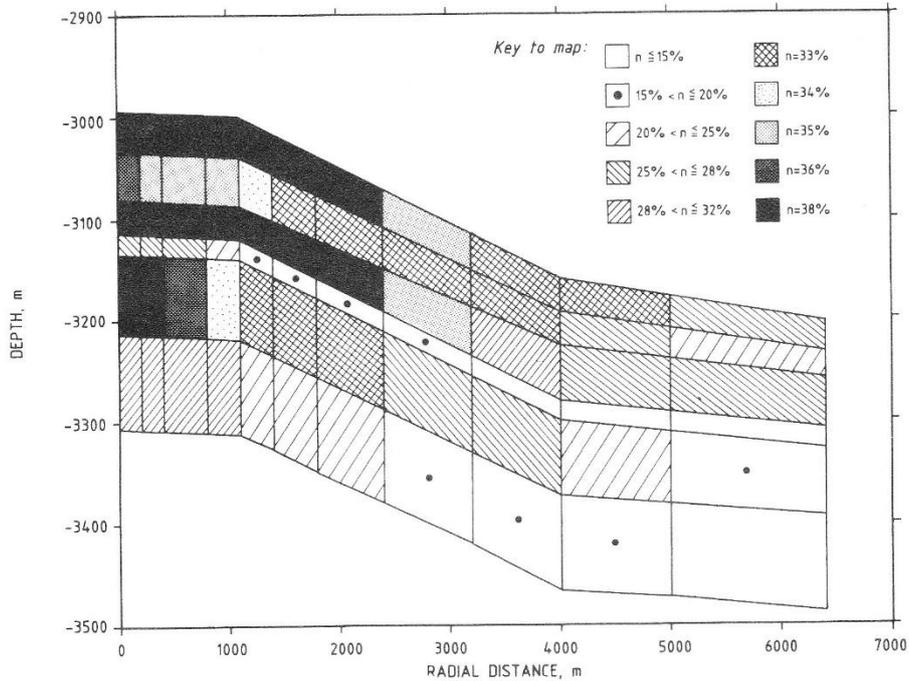


Figure 1. Example of one of the N-S cross-section porosity distributions investigated in CONSAX.

The CONSAX code was used in an exisymmetric format, and only vertical deformation was allowed along the vertical boundaries.

Triaxial, one-dimensional strain tests have been performed by Phillips and by the University of London using Ekofisk chalk plugs to represent the relevant range of porosities. An appropriate non-linear material model was developed by NGI to represent the measured stress-strain characteristics, with stress-dependent stiffness and strength. One of the material models used in NGI's analyses is illustrated in simplified form in Figure 2.

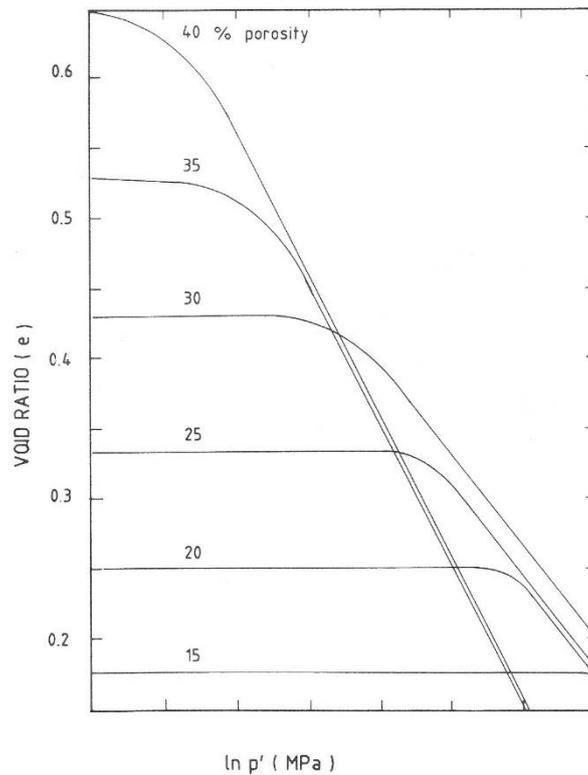


Figure 2. Material model B (simplified) used in the CONSAX compaction model (p' is the mean effective stress).

The various zones used to model the reservoir were loaded by

specific pore pressure decline histories, distributed according to radius within the upper and lower halves of the reservoir. The latter are separated by a so-called tight zone of lower porosity.

The reservoir compaction modelling was performed with four different porosity distributions (cases I, II, III, IV in order of increasing porosity). Three values of K_0' (0.9, 0.7, 0.5, termed 1, 2 and 3) and two material models (A and B) were utilized. Model A simulated the onset of pore collapse at a higher effective stress than model B, and therefore predicts stiffer behaviour.

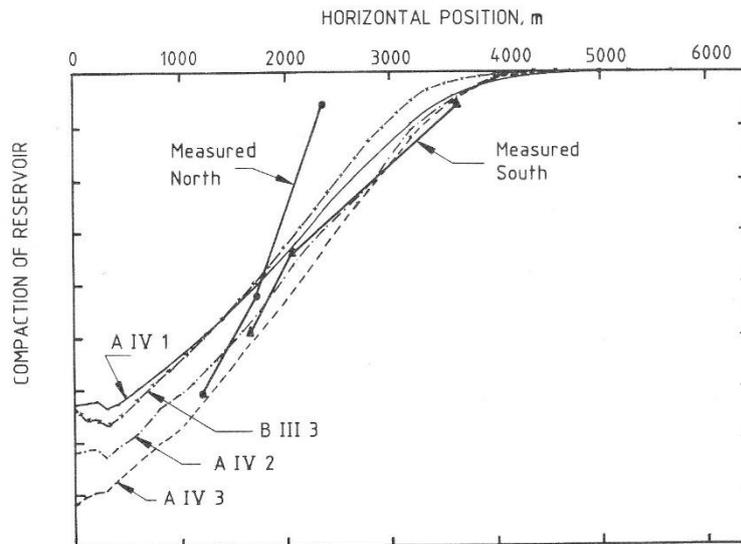


Figure 3. Examples of compaction predictions for the N-S cross-section for the period 1972-1985.

Figure 3 illustrates four examples of compaction for the north-south cross-section through the reservoir. Comparison with approximate geophysical log interpretations of total compaction ("measured north, measured south") appear to be reasonably good.

The range of parameters investigated, showed that the definition of pore collapse stress levels is the most important parameter, closely followed by the applied horizontal stress level. A change of K_0' from 0.9 to 0.5 typically resulted in an increase in maximum compaction of about 0.9 meter. Variations in porosity distribution caused slightly smaller

changes in compaction magnitudes.

SUBSIDENCE MODELLING USING A CONTINUUM MODEL

One of the displacement distributions (B III 3, Figure 3) derived from the detailed non-linear compaction modelling was used as a boundary displacement condition for large scale subsidence modelling. This was initially performed with a linear elastic layered continuum FEM analysis, using the elastic part of the CONSAX code Cam Clay Model. The desired displacement distribution (B III 3) was applied to stiff "dummy elements" on the bottom boundary of the finite element mesh. The outer boundary of this axisymmetric model was set at a radius of 20 km. The B III 3 compaction distribution was applied over the inner radius of 4800 meters.

Four elastic layers were modelled, and the deformation moduli selected for these layers ranged from 0.15 GPa (upper 500 meters) to 12 GPa (lower 1000 meters) in the various runs performed. Numerous intermediate values were also modelled.

In each case investigated, Poisson's ratio was given values of 0.2, 0.3, and 0.4. This resulted in significant variations in the maximum calculated subsidence. The stiffness ratios for the layers 0-500, 500-1000, 1000-2000 and 2000-3000 meters were assumed to be in the ratio 1:2:10:20 respectively. A second distribution of much lower stiffness (maximum 0.7 GPa) was less sensitive to Poisson's ratio.

An example of a typical subsidence calculation is illustrated by the deformed mesh in Figure 4. This same example is compared with bathymetric measurements of the seabed in Figure 5. It is immediately seen that a continuum model, even a layered continuum model, gives a very poor fit to the observed subsidence bowl. This is the reason why discontinuum analyses are preferred for large scale subsidence modelling, as described later.

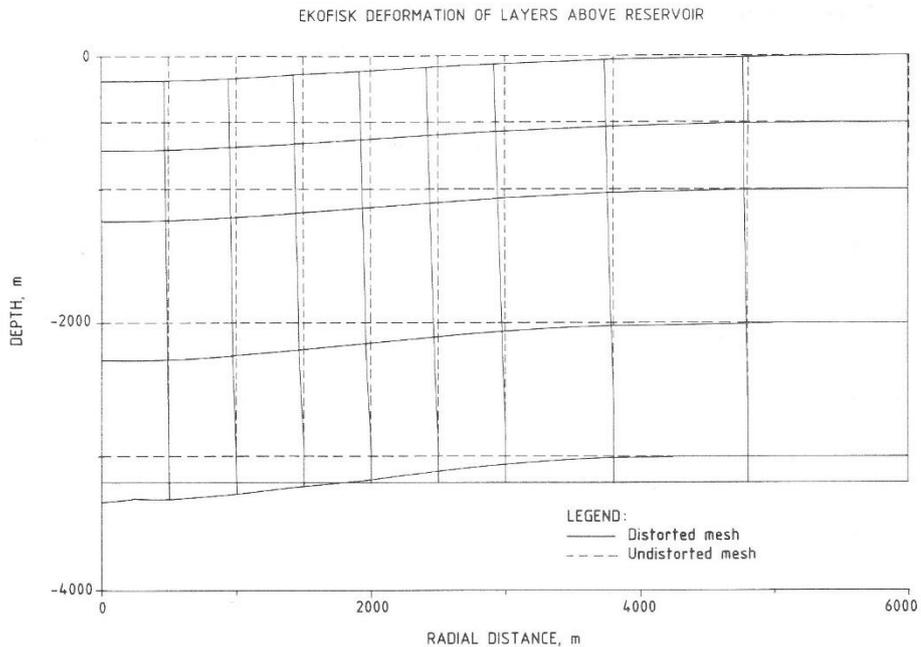


Figure 4. Example of horizontal and vertical distributions of displacements for subsidence model "case A", with Poisson's ratio = 0.3.

These elastic, layered, FEM continuum models of the subsidence predicted maximum surface deformations representing approximately 52 to 65% of the calculated compaction. This relatively small range of values was obtained using a large range of layer stiffnesses and horizontal stress levels.

NGI's elastic, layered, FEM continuum model showed maximum radii of subsidence ranging from approximately 7.0 to 10.0 km when the modelled maximum radius of compaction was 4.8 km, as calculated with the non-linear CONSAX model. The calculated 5 cm contours of subsidence occurred at radii ranging from approximately 5.7 to 8.0 km, compared to the modelled 5 cm contour of compaction which was given a radius of 4.5 km.

The bathymetric measurements of the sea-floor illustrated in four cross-sections in Figure 5, indicate a tighter subsidence bowl than calculated using the elastic, layered, FEM continuum model. The average measured radius is approxima-

tely 4000 meters, and the range approximately 3000 to 5000 meters.

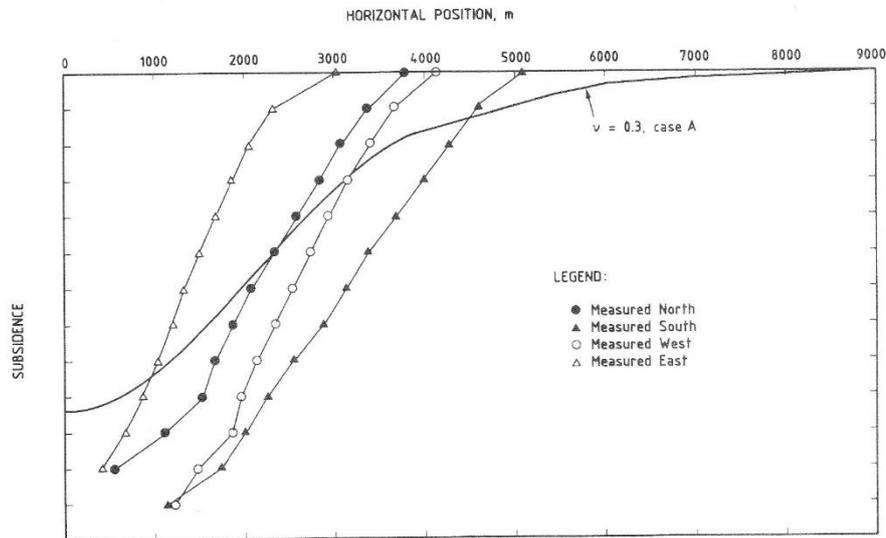


Figure 5. Comparison of "case A" $\nu = 0.3$, with bathymetric measurements of subsidence bowl. Note influence of scale on apparent radius of influence, when comparing Figures 4 and 5.

DISCONTINUUM MODELLING PHILOSOPHY

The area of the subsidence bowl at Ekofisk, covers at least 50 km^2 . This implies that at least 150 km^3 of rock is, or has been involved in the motion, which presently occurs at a maximum central rate of approximately 40-45 cm per year.

The huge volumes involved here would usually justify consideration of continuum analyses, particularly if the material involved had appreciable cohesive and tensile strength. However, it is a matter of common geological observation that rockmasses, whether sedimentary, metamorphic or igneous do not have tensile strength or cohesion above the scale of the natural jointing and bedding, unless the latter are mineralized.

At scales beyond the natural block size, deformation generally occurs by joint opening or shear, by fault move-

ments, or by bedding plane slip. Looked at from afar, the process appears to be one of continuous, isotopic deformation. The actual mechanism is probably discontinuous, and is controlled by quite different laws of deformation. In place of the finite strains of a solid body, we have the infinite (or extremely large) local strains characteristic of relative block motion.

If slip occurs anywhere, the discontinuous model will always show a different distribution of stress and deformation to the closest equivalent continuum model. In applying a discontinuous model to the Ekofisk problem, the key to its validity will lie in the degree to which it mirrors observed behaviour.

SUBSIDENCE MODELLING USING "UDEC"

Discontinuum modelling was performed with the two-dimensional time-marching, finite difference computer program UDEC (Cundall, 1980). The 3 km of overlying sediments were modelled as discretely layered and jointed media.

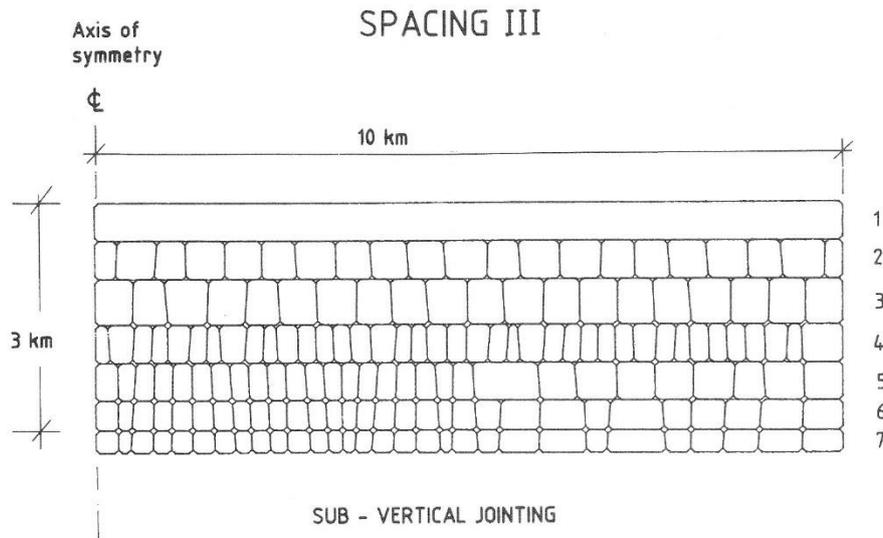


Figure 6. An example of UDEC modelling of the subsidence process, with sub-vertical joints and faults.

Through-going faults or joints were modelled at greatest depth, and discontinuous jointing at shallower depth. A deformable, but unjointed elastic monolith was used to model the upper 500 meters of soft sediments. An example of one of the geometries investigated is shown in Figure 6.

The seven layers illustrated in the figure were assigned deformation moduli, based on recent VSP (vertical seismic profiling) performed by Phillips. The bedding planes and major joints (or faults) were assigned appropriate low values of shear stiffness to be in accordance with the block sizes of 0.25 to 1.0 km. Values of shear and normal stiffness were selected using the methods described by Barton (1982). Values for friction angles and dilation angles were also required. In the selection of parametric values, emphasis was focussed on large-scale, clay-bearing features, since it was felt that these would have most relevance to the scale of problem being investigated.

The model was consolidated to the correct effective stress levels for each layer by adjusting layer densities. The correct effective stress levels were estimated from the mud densities, by subtracting the balanced pore pressures from the total overburden stresses.

The reservoir compaction distribution that was used as a boundary condition in the elastic CONSAX model of subsidence, was also used as a boundary condition in the large scale UDEC modelling of subsidence. The compaction was applied gradually over a period of one thousand time steps. A certain time lag between completed subsidence and completed compaction was indicated.

Figure 7 illustrates the displacement vectors over the same 10 km radius of axisymmetric model as depicted in Figure 6. The distribution of displacements appears to be similar to that seen in the deformed continuum mesh shown in Figure 4.

UDEC models demonstrated that horizontal strain or slip between beds and limited vertical shears at depth may be realistic modes of subsidence deformation (see Figure 8). Horizontal slip on shale beds sandwiched between massive beds of sandstone and siltstone was an observed phenomenon at the Wilmington field, California. In a more homogeneous overburden, individual bed slip magnitudes may not be sufficient to threaten casing integrity.

The UDEC modelling showed surface displacements directed towards the centre of the subsidence bowl that reach peak values of approximately one third of the vertical compac-

JOINT SPACING III - STIFFNESS I - SUBSIDENCE DISPLACEMENTS

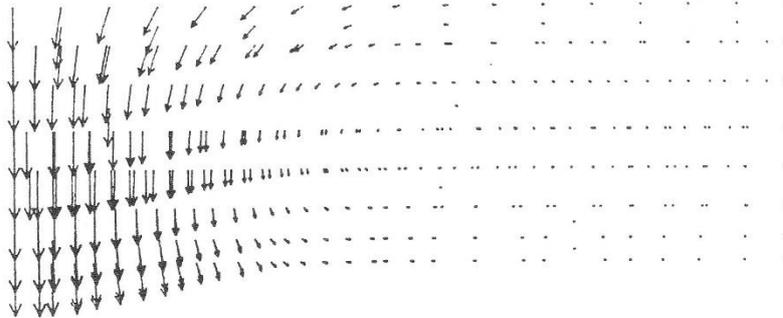


Figure 7. Displacement vectors from UDEC model depicted in Figure 6.

JOINT SPACING III - STIFFNESS I - SUBSIDENCE SHEAR DISPLACEMENTS

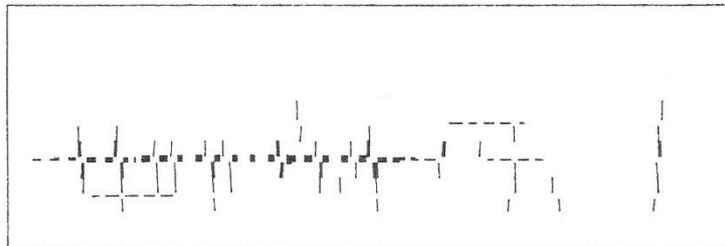


Figure 8. Distributions of fault and bedding plane slip for the model depicted in Figures 6 and 7. Line thickness is proportional to slip magnitude.

tion (see Figure 9). This surface stretching is a common feature of major subsidence bowls, and developed to a maximum of 3.7 meters at the Wilmington field where the maximum subsidence was approx. 9 meters (see Figure 10).

Increasing the joint, fault and bedding plane shear strengths and stiffnesses tended to produce a wide subsidence bowl that resembled the elastic continuum behaviour. Reduction of the shear strength and stiffness to lower, fault-scale values, combined with the modelling of a larger number of blocks, produced the tightest subsidence bowls (radii = 5.3 - 5.4 km). These resembled the measured subsidence (3.7 to 5.1 km radius, N and S sectors) more closely than the continuum models.

Ratios of maximum subsidence to maximum compaction varied from 0.52 to 0.65 in the elastic, layered, FEM continuum models. In the UDEC models this ratio varied from 0.75 (stiffer joints, faults and bedding planes) to 0.85 (less stiff discontinuities).

HISTORY MATCHING

The only precision measurements of subsidence presently available for the Ekofisk field are those performed by satellite since March of 1985. The precision currently available is 1 ppm (10^{-6}) over a 10 km horizontal range, or approximately ± 1 cm. The current yearly rates predicted from these monthly measurements generally lie in the range 40 to 45 cm for the central platform.

History matching of total compaction magnitudes is inexact due to the limitations of geophysical log interpretation. Data presented in Figure 3 suggests an apparently satisfactory match for the southern section of the reservoir. Utilization of a realistic compaction distribution as a boundary displacement in UDEC discontinuum models has resulted in realistic calculated subsidence bowls.

These show relatively tight radii and maximum predicted subsidences which are extremely close to the measured (mid 1985) bathymetric data. However the original bathymetric measurements used as reference are based on a coarser grid than the 1985 measurements, so uncertainties in the interpolation are inevitable.

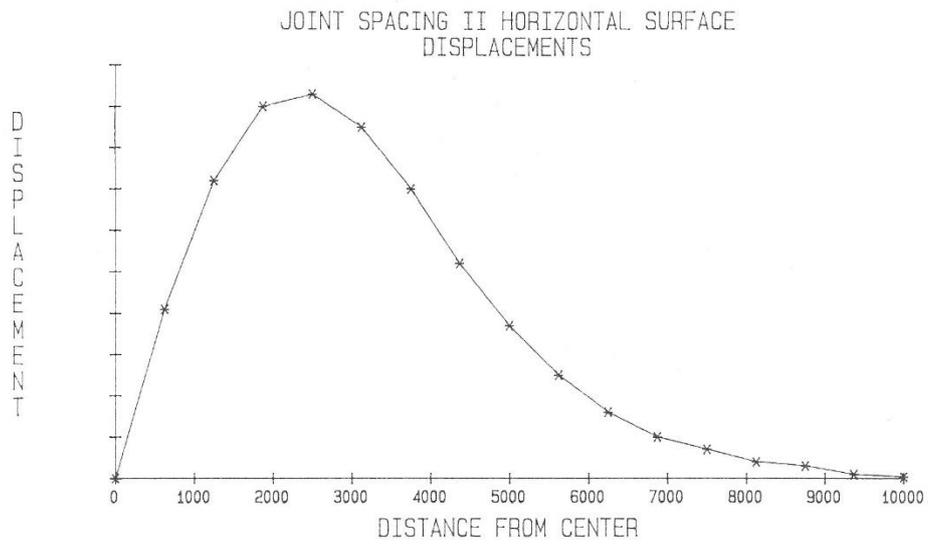


Figure 9. Distribution of horizontal displacements for a model with vertical joints and faults, with the same average block sizes and stiffnesses as in Figure 6.

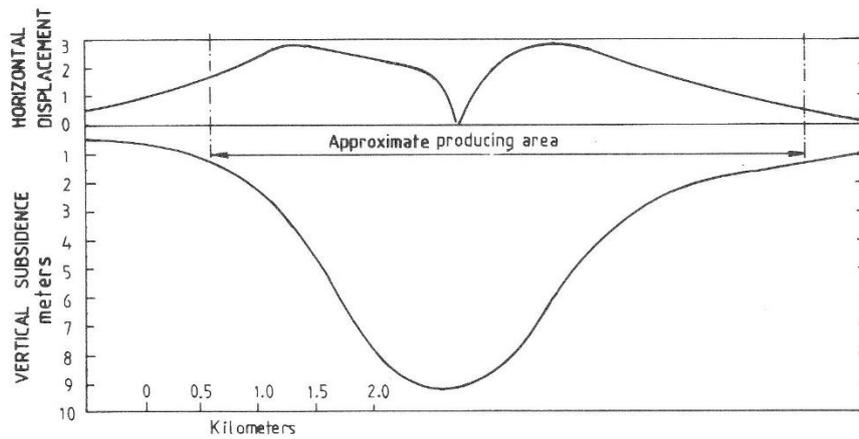


Figure 10. Subsidence measurements at Wilmington, Long Beach California. (Measurements along minor axis of elliptical 75 km² subsidence bowl) After Yerkes and Castle, 1970.

The most reliable source of history match available is that based on satellite measurements, in which current yearly rates of subsidence can be matched with subsidence calculations for the last year of pressure decline, for example for the 12 month period 1/84 to 1/85. Results of the four parametric studies shown in Figure 3 need conversion to subsidence rates to obtain the desired history match.

Calculations based on UDEC models show good agreement with the measured subsidence rate of 42-45 cm per year. These calculations are based on analysis of the UDEC models reproduced in Figures 11 and 12, in which compaction increments were applied, to investigate the corresponding increments of subsidence.

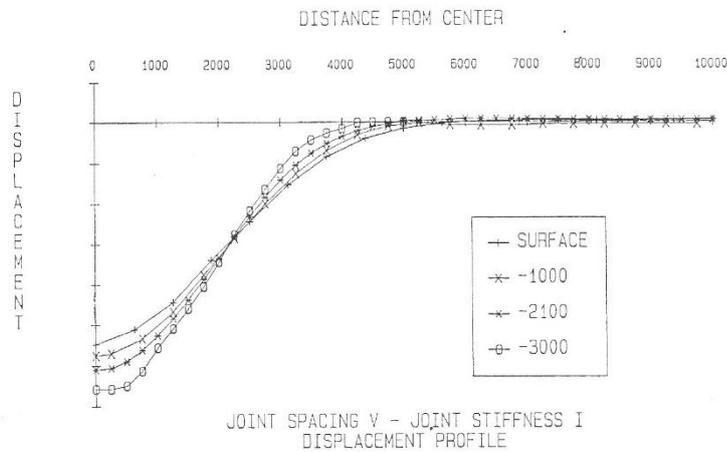


Figure 11. Subsidence of overlying layers after initial compaction.

CHARACTERIZATION OF RESERVOIR JOINTING

Recent core analysis reports describing the Ekofisk reservoir jointing indicate the presence of several, thick, heavily jointed zones. Two sets of steeply dipping conjugate tectonic joints appear to be a dominant feature over much of the gently domed reservoir structure.

The widespread presence of jointing suggested to us that the compaction process could be affected by the jointing; likewise that the jointing could be affected by the compaction, perhaps resulting in changes in conductivity. A suite of laboratory tests was therefore conducted on represen-

tative reservoir joints, to provide input data for numerical experiments. In these experiments a realistic joint structure and porous chalk matrix was subjected to the effects of fluid pressure decline under conditions of one dimensional vertical strain. These numerical experiments were performed with a new version of UDEC, and are described later.

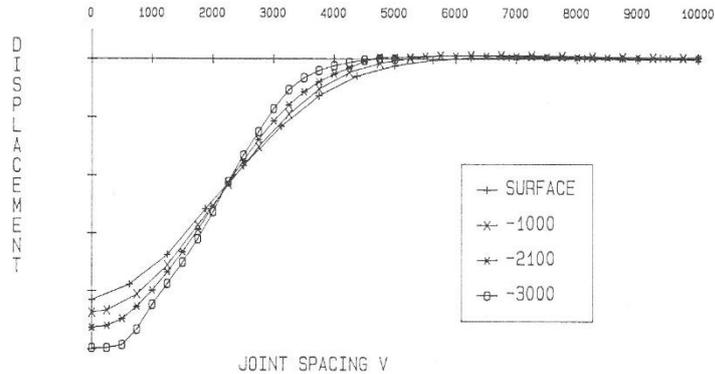


Figure 12. Additional compaction caused an increase in subsidence.

NGI's laboratory studies of tectonic jointing in the Ekofisk chalk indicated that non-planar but relatively smooth joints were most typical. These had joint roughness coefficient (JRC) values in situ of about 5. The basic angle of friction (ϕ_b) for smooth flat surfaces tested in heated oil (80°C), ranged from 32-33°, only slightly lower than when oil was absent. The peak friction angles of the natural joints with 80°C oil saturation ranged from 33° to 38°. The normal closure of the joints was typically non-linear and hysteretic (i.e. displayed permanent closure under repeated cycles).

These laboratory scale, medium-stress results were extrapolated to reservoir conditions by incorporating high stress triaxial shear test data for intact chalk. Peak friction angles for the joints under reservoir conditions (effective normal stresses = 10 to 30 MPa approx.) were estimated to be 36° - 34° for low porosity chinks, and 34° - 32° for high porosity chinks.

Shear stress-displacement, dilation-displacement and normal stress-closure curves were derived using the constitutive joint model described by Barton et al. (1985) and Bandis et al. (1985). Three sets of relevant curves are reproduced in Figures 13, 14 and 15.

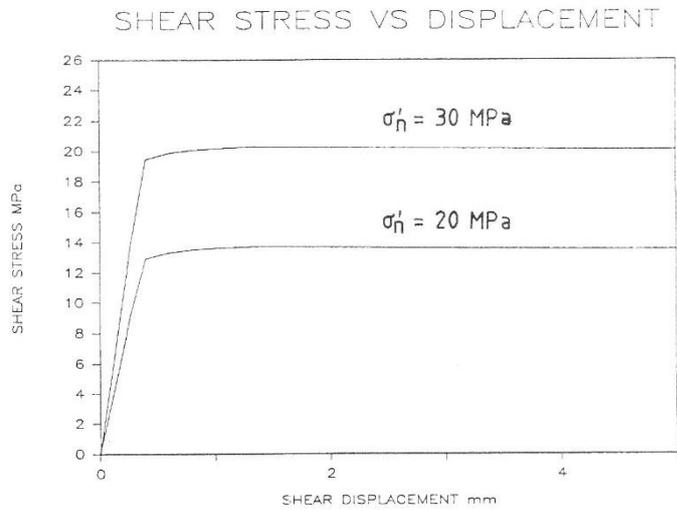


Figure 13. Shear stress-displacement curves predicted for reservoir joints.

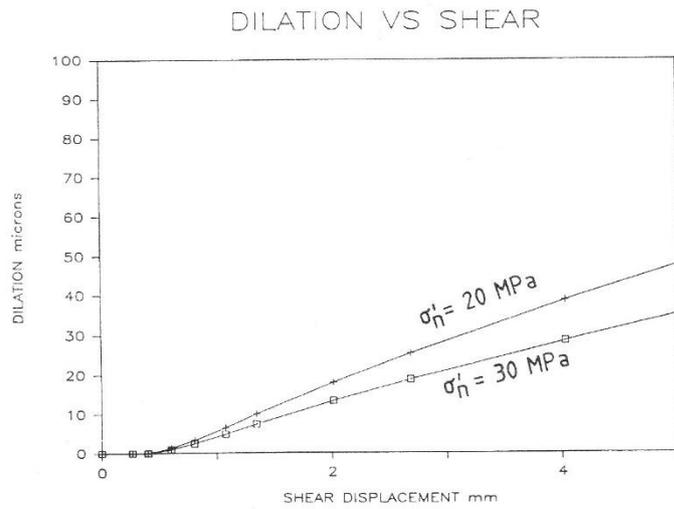


Figure 14. Corresponding dilation-displacement curves predicted for reservoir joints.

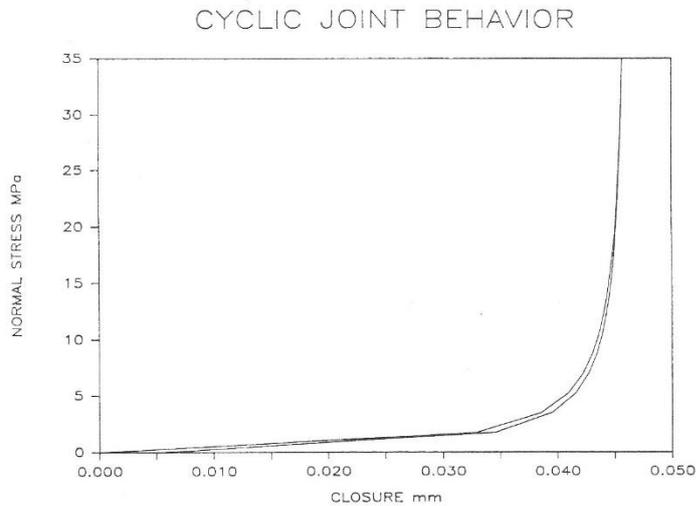


Figure 15. Normal stress-closure curves. (4th cycle)

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 (1985).

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.

NUMERICAL MODELLING OF JOINT COMPACTION EFFECTS

Several zones of closely spaced conjugate tectonic joints are a feature of many of the cores recovered from the Ekofisk reservoir. Large numbers of joints seem likely to be affected by the fluid pressure drawdown, and could be expected to contribute in some way to the compaction mechanism and to the maintenance or decline of conductivity in the reservoir. These possibilities were investigated by means of some unique numerical experiments.

Discrete blocky models of typical conjugate jointing were generated with the discontinuum code UDEC, using reservoir-scale joint properties derived both from the laboratory tests, and from constitutive models of joint behaviour designed especially for the high stress behaviour. The UDEC model shown in Figure 16 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.

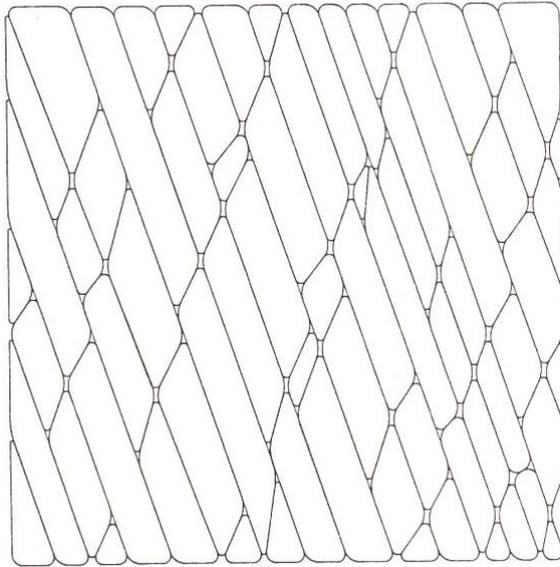


Figure 16. Numerical representation of 1 m² of a typical heavily jointed zone in the Ekofisk reservoir.

The first blocky model of simulated low-porosity chalk (assumed 1-D strain modulus = 3.33 GPa) 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 (1-D strain modulus of matrix = 0.33 GPa; assumed average linear elastic value). 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.

HIGH POROSITY CHALK - REDUCED PORE PRESSURE

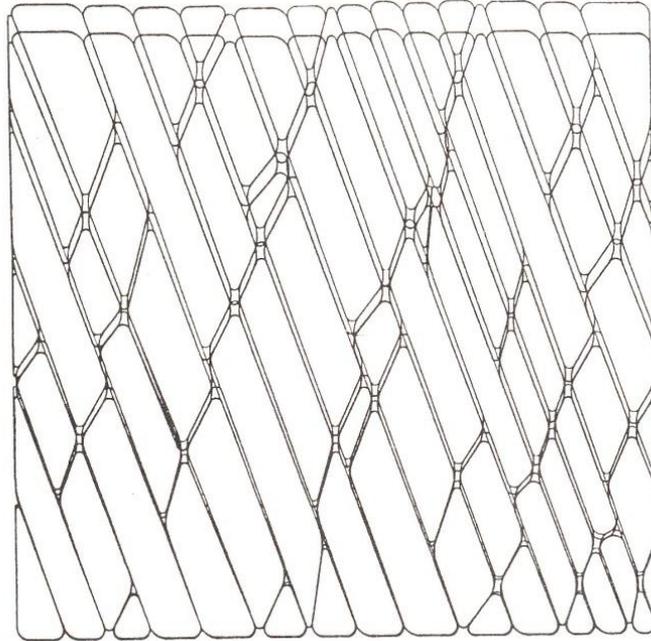


Figure 17. Net effect of fluid pressure drawdown on a consolidated, high porosity model. The deformation is shown at correct scale relative to the assumed structure.

HIGH POROSITY CHALK - REDUCED PORE PRESSURE SHEAR DISPLACEMENTS

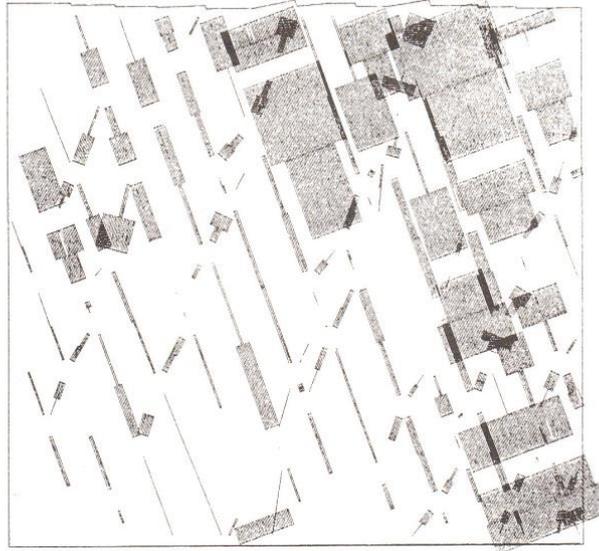


Figure 18. Flag diagram showing relative shear magnitudes on individual joints, at scale of $50 \mu\text{m}$ per line thickness.

The deformed shape of the jointed structure is shown in Figure 17. The locations where shear was particularly marked are clearly illustrated in Figure 18. Concentration of shearing appears to be concentrated in the most heavily jointed right-hand zone. Block wedging resulting from unequal dip angles may be preventing large shears from occurring in the lower-left zone.

The combined effect of joint closures, occasional local joint openings, and virtually non-dilatant shear was $2.0 \mu\text{m}$ 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.

The total compaction of the blocky UDEC models as a result of fluid pressure withdrawal was different from that of the matrix alone. In the case of the low porosity model (assumed $K = 3.33 \text{ GPa}$), 0.43% compaction occurred; slightly less than the 0.60% the matrix alone would have compacted. In

the case of the high porosity model ($K = 0.33$ GPa), 4.82 % compaction occurred; also less than the 6.0 % the matrix alone would have compacted under the same effective stress change. This remarkable result is probably due to relative increases in the bulk Poisson's ratio of the mass compared to its reduced value under a pure matrix 1-D compaction process.

The relative change in the bulk Poisson's ratio, results in a corresponding relative increase of K_0 (ratio of effective horizontal to vertical stress) compared to its reduced value in a pure matrix fluid-drawdown compaction process. The final values of K_0 calculated by UDEC for the two jointed models were 0.65 (low porosity) and 0.60 (high porosity). These values are considerably higher than those measured in triaxial one-dimensional strain tests on core plugs over the same stress range.

The relative mass-bulking effect described above is likely to be optimal in the case of steeply dipping joints. Relative mass-contraction would occur with flat-lying joints, under fluid pressure drawdown. The good maintenance of productivity observed at Ekofisk despite the compaction may be confirmation of relative mass-bulking effects caused by the steeply dipping conjugate tectonic joints.

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.
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 suggest that slip on joints, faults and bedding planes may be a realistic mechanism for explaining the tight measured subsidence bowl and the relatively high ratio of subsidence to compaction observed at Ekofisk.
4. Numerical (UDEC) modelling of representative heavily

jointed zones 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, near-maintenance of joint apertures (and therefore conductivities) and a compaction magnitude somewhat smaller than when the chalk is unjointed. This unexpected mechanism may explain the continued high productivity still experienced from the Ekofisk reservoir.

ACKNOWLEDGEMENTS

This work was performed for the Norwegian Petroleum Directorate, under Kjetil Tonstad's project direction. His helpful guidance, and that of Phillips staff in Bartlesville and Stavanger is gratefully acknowledged. Particular thanks are due to Rolf Wiborg, John Jewhurst and Helen Farrell.

NGI gratefully acknowledge the expert consulting assistance of Tim D'Orazio in the CONSAX modelling, and Mark Christianson who performed all the UDEC modelling. Stavros Bandis made major contributions to the joint testing and constitutive modelling.

Permission to publish this work is gratefully acknowledged.

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