Geomechanical model for sediment profiles

Modèle géomécanique pour des profils sédimentaires

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ABSTRACT

Idealized sediment profiles based on the tangent modulus concept have been developed over some years. The aim of this study was to extend and refine this model. A methodology based on an existing geomechanical model for estimation of porosity and density profiles for natural sediments, including sands and sandstones, and clays and claystones or shales have been developed. This paper describes some of the basis for the development of the geomechanical model, interpretation of laboratory tests and field data from wells, and some results using the model. The bounding values of the controlling parameters are estimated accounting for geotechnical experience of sand and clay, and by interpretation of selected borehole profiles and well logs. The expected porosity trend with depth can now be predicted for normally consolidated profiles or for profiles with known stress history. The results from analyses with program MECAD (MEchanical Compaction And Diagenesis) show that the model works satisfactorily. The computed results show good agreement with observed data and confirm the possibility of the model to correctly reproduce mechanical sedimentary compaction. Creep effects have been evaluated, and creep has little influence on the reduction in porosity for sediments with porosity less than 30%. The effect may be substantial for sediments with high porosity.

RÉSUMÉ

Des profils sédimentaires idéalisés et basés sur le concept du module tangentiel ont été développés au fil des ans. Le but de la présente étude est de prolonger et raffiner ce genre de modèle. Une méthodologie basé sur un modèle géoméchanique est présentée et permet l'évaluation des profils de porosité et de densité pour des sédiments normalement consolidé, incluant des sables et des grès, des argiles et des claystones ou des shales. Après une brève introduction du modèle existant, le modèle géomécanique est présenté, suivi par l'interprétation d'essais en laboratoire et de données de forages. Les valeurs limites pour les paramètres de contrôle sont estimées à partir de l'expérience géotechnique acquise sur les sables et les argiles, et à la suite de l'interprétation des profils de forage et des puits de sondage. Le profil de porosité en fonction de la profondeur peut maintenant être estimé pour des sédiments normalement consolidés ou pour des profils dont l'histoire de contrainte est connue. Une concordance satisfaisante entre les résultats de terrain et les analyses avec le programme MECAD (tassement mécanique et diagenesis) prouvent que le modèle peut reconstruire de manière satisfaisante le phénomène de compaction sédimentaire. L'influence du fluage a été évaluée et ce dernier a peu d'influence sur la réduction de la porosité pour des sédiments avec la porosité moins de 30%. L'effet peut être substantiel pour des sédiments avec une porosité élevée.

Keywords : geotechnical engineering, geomechanical model, porosity, density

1 INTRODUCTION

Idealized soil profiles based on the tangent modulus concept model, by which an expected porosity trend with depth can be predicted for normally consolidated profiles or for profiles with known stress history, have been worked on over some years. In an industrial project (SINTEF, 2005) a study was performed with the aim of extending and refining this model. In this project a methodology for estimation of porosity and density profiles for natural sediments, including sands and sandstones, and clays and claystones or shales has been developed. The methodology is based on the existing geomechanical model (Janbu, 1970, 1985), and the effect of creep has been evaluated. The model is combined with a diagenesis model for sand provided by StatoilHydro. A diagenesis model for clay has not yet been accounted for. This paper focus on mechanical compaction of clay and sand. The bounding values of the controlling parameters are estimated accounting for a world wide geotechnical experience of sand and clay, and by interpretation of selected bore hole profiles and well logs.

2 BASIS FOR THE DEVELOPMENT

2.1 *Tangent modulus concept*

A stress dependent tangent modulus is applied for calculation of mechanical compaction (Janbu, 1970). The modulus (M) can be expressed by the general modulus function:

$$M = m\,\sigma_a \left(\frac{\sigma'}{\sigma_a}\right)^n \tag{1}$$

where

- m is a modulus number
- σ' is the current effective stress
- σ_a is a reference effective stress = 1bar = 100 kPa
- n is an exponent (range 0 to 1)

A strain increment (dε) is expressed as:

$$d\varepsilon = \frac{d\sigma'}{M} \tag{2}$$

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The strain (ε) due to an effective stress increase from σ_1' to σ_2' can be calculated by integration:

$$\varepsilon = \int_{\sigma_1'}^{\sigma_2'} \frac{1}{M} d\sigma' \tag{3}$$

2.1.1 *Sand*

For sand, the exponent is n=0.5 in Equation 1, and the modulus function becomes (Janbu, 1970):

$$M = m\sqrt{\sigma_a\ \sigma'} \tag{4}$$

The strain equation becomes:

$$\varepsilon = \int_{\sigma_1'}^{\sigma_2'} \frac{1}{m\sqrt{\sigma_a \cdot \sigma'}} d\sigma = \frac{2}{m}\left(\sqrt{\frac{\sigma_2'}{\sigma_a}} - \sqrt{\frac{\sigma_1'}{\sigma_a}}\right) \tag{5}$$

In his Rankine lecture Janbu (1985) presents a figure showing the modulus number m for sands and silts as a function of the porosity. A hatched area is shown in Figure 1 for silts, and a shaded for sands. In general, the modulus number decreases with increasing porosity, and is lower for finer sand/silt than for coarser.

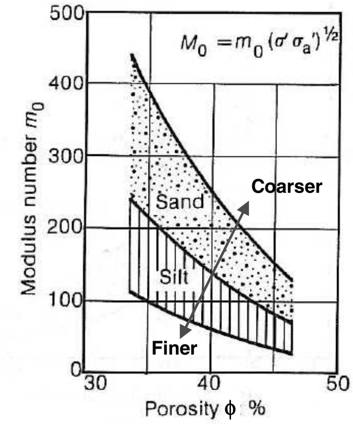

Figure 1. Modulus number (m) for sand as function of porosity (ϕ) (Janbu 1985). (Symbol M_0 is used for M, and m_0 is used for m).

The shown correlation is developed from built in samples that have been loaded to high stresses (up to 5 MPa). The Equation 5 should therefore be suited for calculation of the porosity change due to mechanical compaction.

2.1.2 *Clay*

For normally consolidated clay, the exponent is n=1, and the modulus function becomes:

$$M = m\,\sigma' \tag{6}$$

The strain equation becomes:

$$\varepsilon = \int_{\sigma_1'}^{\sigma_2'} \frac{1}{m \cdot \sigma'} d\sigma' \tag{7}$$

Janbu (1985) presents a plot connecting the in-situ water content and the modulus number for clays, see Figure 2. The modulus number is plotted against the in-situ water content, defined as the ratio weight of water to weight of solids. Only water saturated samples are included, so the corresponding porosity can be calculated knowing the density of solids (or if not known, assuming 2.65 to 2.70 g/cm^3).

The correlation shown in Figure 2 is determined from natural samples that have been loaded to a stress level above its preconsolidation stress, where the preconsolidation stress is the highest effective stress the sample has "seen" previously.

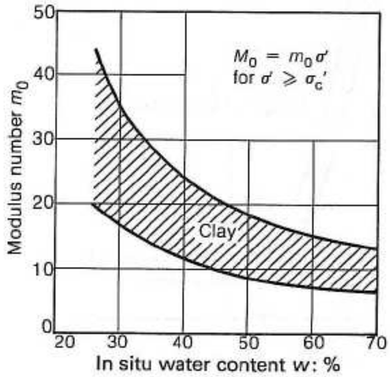

Figure 2. Modulus number (m) for clay as function of water content (w). (Symbol M_0 is used for M, and m_0 is used for m).

The correlation is therefore good for calculating the porosity change for a soil that is loaded from in-situ stress conditions, and where the porosity is reduced by, say 10%. This case of loading can be modeled by selecting one fixed modulus number, associated with the in-situ porosity or water content. But it is not necessarily good when the objective is to follow the compaction from around 70% porosity and down to 30% porosity or lower.

A reassessment of the modulus function is therefore made in 3.2, where the modulus number is plotted against the porosity the sample had in the oedometer when the stress has passed the preconsolidation stress, and not against the usually higher in-situ porosity. Using such a formulation, it will be possible to calculate the porosity change by integration of Equation 7 from a low to a very high stress by integration, where the modulus number m is a continuous function of the porosity; m = m(ϕ).

2.1.3 *Natural strain*

When modeling the porosity history of a clay from around 70% porosity and down to 20 – 30%, we will conceptually combine the results from several tests on natural clays, where the loading starts from a different porosity from one test to another. The strain reference will therefore also be different from one test to another. The only logical way to overcome this problem is to apply the so called "natural strain", where the strain increment in the model is at any time related to the present sample height h, and not the initial sample height h_0. The incremental strain ($d\varepsilon_N$) then becomes:

$$d\varepsilon_N = -\frac{dh}{h} \tag{8}$$

where
- $d\varepsilon_N$ is the incremental "natural" strain
- dh is the change in height
- h is the current height

The equation integrates into:

$$\varepsilon_N = -\int_{h_1}^{h_2} \frac{dh}{h} = -\ln\frac{h_2}{h_1}; \qquad \text{where } h_2 < h_1 \tag{9}$$

3 INTERPRETATION OF LABORATORY TESTS

3.1 *Shallow oedometer tests*

A large number of oedometer tests on clays from various sites have been interpreted. The tests are sampled from sediment depths less than 220 m below sea floor at the following offshore sites:

- Troll SI 1983. Block 31/2, water depth approx. 303 m. NGI 1984.
- Troll SI 1989. Block 31/6, water depth approx. 303 m. NGI 1989.
- Snorre B 1998. Block 34/4, water depth approx. 350 m. NGI 1998.
- Gullfaks C Block 34/10, water depth approx. 217 m. NGI 1984.
- Ormen Lange Site 28. Block 6403/5, water depth approx. 1600 m. NGI 2002.
- DSDP Leg 86. Hole 576A, water depth approx. 6130 m. Marine Georesources and Geotechnology.
- DSDP Leg 75. Hole 532A, water depth approx. 1330 m. Marine Georesources and Geotechnology.

3.2 *Basic input parameters*

Oedometer tests and CK_0-tests (consolidated oedo-triaxial tests) have been interpreted according to the modulus concept described in 2.1. For clays and claystones the aim was to establish a connection between the modulus number (m) and the porosity (ϕ) for normally consolidated materials. The modulus number was interpreted from an M-σ' plot as a straight line from origo through the normally consolidated part of the test. The modulus number ($m_{N,sec}$) versus porosity (ϕ) at the preconsolidation stress (p_c') can then be plotted as shown in Figure 3. A function can be assigned to fit the test results. In this case, the following function seems to give a good fit:

$$m = m_0(1-\phi)/\phi^2 \quad \text{where } m_0\text{=3, range 2.5 to 3.5} \tag{10}$$

The above equation is enough to calculate the strain for a stress increment, for example under a load on the terrain, but in a sedimentation model the objective is to calculate the porosity as function of depth.

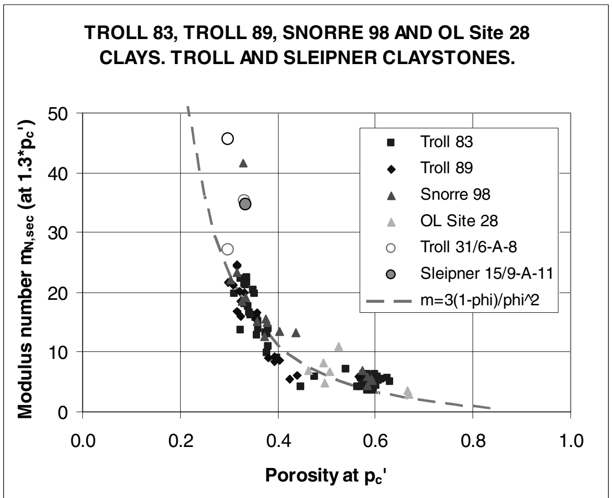

Figure 3. Modulus number ($m_{N,sec}$) versus porosity at the preconsolidation stress (p_c').

Therefore, we also need the reference porosity (ϕ_0). For clays, the strain becomes infinite according to Equation 10 if the stress increases from zero to a finite stress. The modeling must therefore start from a finite, small stress (σ_0'), and the reference porosity (ϕ_0) needs to be defined at this stress. ϕ_0 will be a function of a number of factors, but the most important factors are: Clay content and mineralogy. Higher clay content means higher porosity, and smectitic or swelling clays will have higher porosity than illitic clays. Figure 4 shows a relationship that has been developed for clays with low smectite content, for a reference stress of σ_0' = 0.1 MPa.

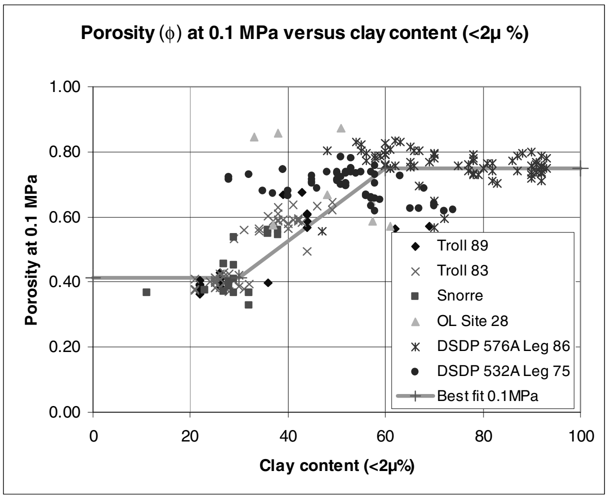

Figure 4. Porosity at reference stress of 0.1 MPa versus clay content (<2μ%).

The modulus number m depends on the state and characteristics of the sediment. For sand, important factors are porosity, angularity, grain size and grains size distribution, and mineral. For quartz rich sands, the relation shown in Figure 1 has been collected from empirical data. Interpretation of laboratory tests on sand and sandstone confirms and expands the findings of Janbu (1985) as shown in Figure 5.

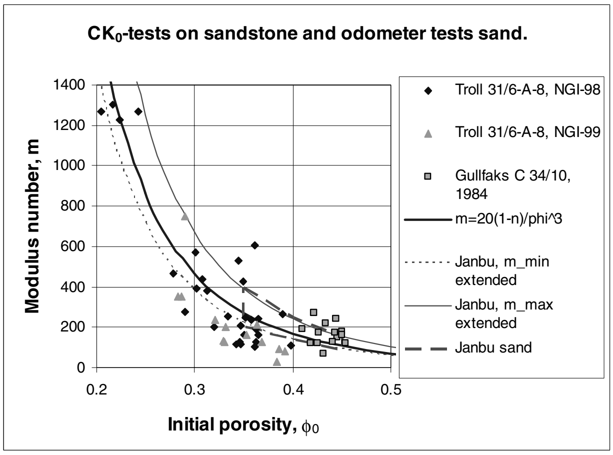

Figure 5. Modulus number versus initial porosity for fine-grained sand and sandstone.

3.3 *Creep tests*

The time resistance concept (Janbu, 1985) has been used to interpret stepwise loading oedometer tests on clays and sandstone. For stepwise loading in oedometers each load step is applied instantaneously and then left constant for some time during which the sample gradually compresses. In total stress terms this is a rheological phenomenon or creep. Time (t) is action and strain (ε) is response. The time resistance (R) is the tangent to the ε-t curve, and is defined as:

$$R = \frac{dt}{d\varepsilon} \tag{11}$$

The R-t curve is often parabolic near the origin (t=0), in accordance with the classical theory of primary consolidation. After some time (t_0) the R-t curve becomes linear and can be described by the creep resistance number (r_s):

$$R = r_s(t - t_r) \text{ where } t_r \text{ is the intercept of R-t on time axis.} \tag{12}$$

Combining (11) and (12) and integrating, the following expression for creep strain emerges:

$$\varepsilon_C = \frac{1}{r_s} \ln \frac{t}{t_0} \text{ for } t_r \text{ equals zero and } t > t_0 \tag{13}$$

Interpretation of oedometer tests on clays and CK_0 triaxial tests on sandstones for each load level results in creep resistance numbers (r_s) for porosities ($\phi_{pc'}$) at the preconsolidation stress level (p_c') as shown in Figure 6. For clays with porosities higher than 30% in the normally consolidated state the creep resistance number is normally less than 1000.

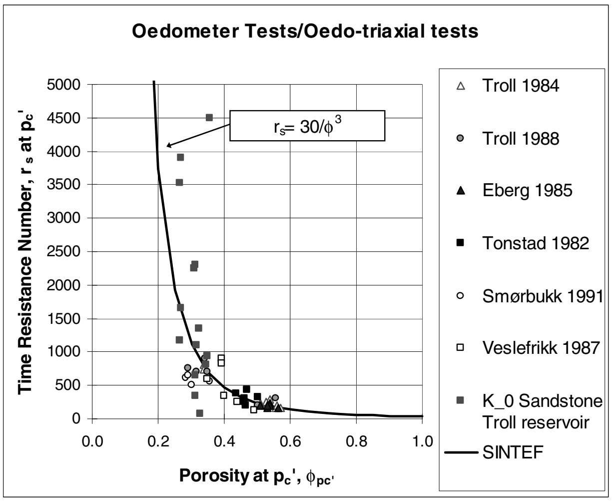

Figure 6. Time resistance number r_s versus porosity $\phi_{pc'}$.

4 GEOMECHANICAL MODEL FOR SEDIMENTATION

4.1 *Sediment porosity model for clay*

For clay, the porosity after mechanical compaction will be determined by integration from an "unconsolidated" porosity (ϕ_0) at a low reference stress (σ'_0). The "unconsolidated" porosity (ϕ_0) will be a function of clay content and of clay mineral. Figure 4 shows the proposed relation between ϕ_0 and clay content as developed for illitic clays. The clay content is expressed as weight% of grains smaller than 2μ. For more smectitic clays, the unconsolidated porosity will be higher.

An equation is obtained by which we can calculate the shortening of a specimen which is exposed to a stress increase from σ_0' to the new stress σ'. The shortening as expressed through the length ratio $\lambda = h/h_0$.

$$\lambda = \frac{h}{h_0} = (1-\phi_0)\left[1 + \frac{1}{\frac{1}{m_0}\ln\frac{\sigma'}{\sigma_0'} + \frac{1-\phi_0}{\phi_0}}\right] \tag{14}$$

Here, the following definitions apply:

ϕ_0	is the "unconsolidated" porosity at a low stress σ_0'
σ_0'	is a low stress with known "unconsolidated" porosity ϕ_0
σ'	is the compaction effective stress; the maximum effective for which the clay has been mechanically compacted
h_0	is the clay element height before mechanical compaction, i.e. at porosity ϕ_0 and effective stress σ_0'
h	is the clay element height after mechanical compaction, after it has been exposed to the compaction effective stress σ'
λ	is the height ratio; $\lambda = h / h_0$

The resulting porosity after mechanical compaction is expressed as:

$$\phi = 1 - \frac{1-\phi_0}{\lambda} \tag{15}$$

Diagenetic transformations in clay have not been accounted for or implemented in the model. Important mechanisms for clay diagenesis are the Opal A to Opal-CT transformation which has effects on porosity reduction at depths deeper than 1000-1200 mbsf, and the smectite to illite transformation starting at depths about 1500 mbsf. These mechanisms produce compaction and can result in excess pore pressure. The model will therefore predict too high porosities and too low densities for claystone/shale at depths > 1000-1200 mbsf. The transformation of Opal-A to Opal-CT and conversion of illite to smectite should be part of future work within sedimentation modelling.

4.2 *Sediment porosity model for sand*

Oedometer tests on sand with varying relative density have shown that m may vary from 150 to 500 m is thus a function of the initial porosity of the sand, but m is considered a constant throughout the stress history for a given sand, and does not change as the sand is being compressed. For sand, the material model is based on the linear strain, $\varepsilon = -\Delta h/h_0$. The height ratio $\lambda = h / h_0$ can be expressed as:

$$\lambda = \frac{h}{h_0} = 1 - \varepsilon \text{ where } h < h_0 \tag{16}$$

The strain can be obtained from Equation 5, setting the initial effective stress equal to zero (σ_1'=0):

$$\lambda = \frac{h}{h_0} = 1 - \frac{2}{m}\sqrt{\frac{\sigma'}{\sigma_a}} \tag{17}$$

where σ' is the compaction effective stress; the maximum effective stress for which the sand has been mechanically compacted.

The resulting porosity (ϕ) after mechanical compaction is expressed as:

$$\phi = 1 - \frac{1-\phi_0}{\lambda} \tag{18}$$

Sand diagenesis can be calculated according to Statoil's model (Walderhaug et al 2001). The basic concept is that diagenesis is temperature driven, and pressure does not play a primary role. The effect of diagenesis in sand layers can be accounted for provided that burial curves can be produced.

4.3 *Effect of creep*

Creep is interpreted through the "time resistance" concept (Janbu 1985). The creep strain (ε_C) after a time (t) can be calculated as:

$$\varepsilon_C = \frac{1}{r} \ln \frac{t}{t_0} \tag{19}$$

Here, r is the creep resistance number, and t_0 is a reference time at start of creep.

Table 1. Calculated effect of creep at t = 10 million years.

ϕ	r	$t_{0\,(hrs)}$	ε_C	ϕ_c	$\Delta\phi$	$\Delta\phi/\phi$
0.3	800	24	0.028	0.280	-0.020	-0.07
0.4	400	24	0.055	0.365	-0.035	-0.09
0.5	240	24	0.092	0.449	-0.051	-0.10
0.6	130	24	0.169	0.518	-0.082	-0.14

Table 1 shows a parametric study of the creep effect. The porosity "before" creep is varied from 0.3 to 0.6 (30% to 60%), and the time resistance number is taken from Figure 6 for each porosity value. A "low" time resistance number is selected for each case. The creep time is 10 million years. The value of the reference time is 24 hours (corresponding to the typical time step in incremental loading tests).

The creep strain (ε_C) is small for the 30% porosity case, and the porosity gets reduced from 30% to 28%. This a small effect compared to the uncertainty in a porosity prediction.

The creep strain (ε_C) is large for the 60% porosity, where the porosity gets reduced from 60.0% to 51.8%. This is a significant effect and shows that creep can be important for more porous clays.

5 RESULTS FROM GEOMECHANICAL MODEL

5.1 *Troll A – platform site*

The geomechanical model has been computerized in an Excel worksheet program called MECAD (MEchanical Compaction And Diagenesis). MECAD has been applied on the shallow sediments (<220m) at the Troll Field, North Sea. The soil investigation performed in 1989 (NGI, 1989) served as input and as a quality check of the model. Main input to the model was the clay fraction and the assumed pressure history (there were no layers of clean sand).

The clay fraction (<2μ%) as measured at Troll A in Figure 9 has been used to choose the unconsolidated porosity for the clay layers. Quaternary sediments reach down to 200m depth and below is Tertiary sediments. A modulus number m0=3.5 has been used for all clay layers. Additional burial preload has been taken as the preconsolidation stress (pc') minus the vertical effective stress (p0'). Figure 7 - Figure 9 compare measured profiles of water content (w), density (ρ) and final porosities with those predicted by MECAD. The analyses show a good fit compared to measured laboratory values. However, a higher modulus or higher unconsolidated porosity in units 8 and 10 would have resulted in a better fit.

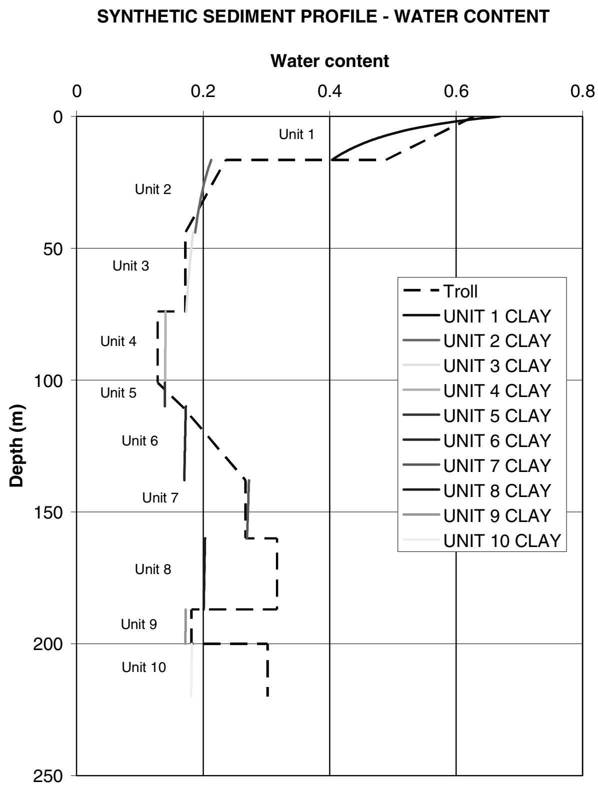

Figure 7. Water content derived from MECAD.

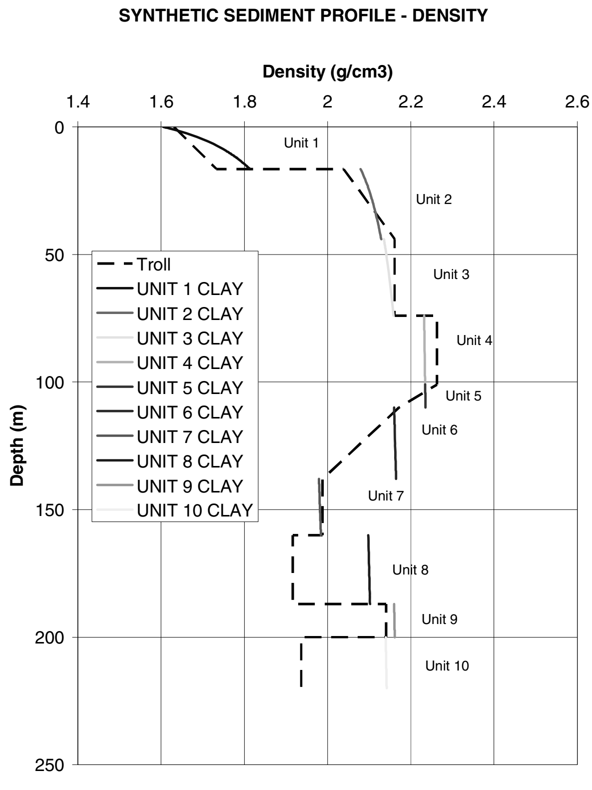

Figure 8. Density derived from MECAD.

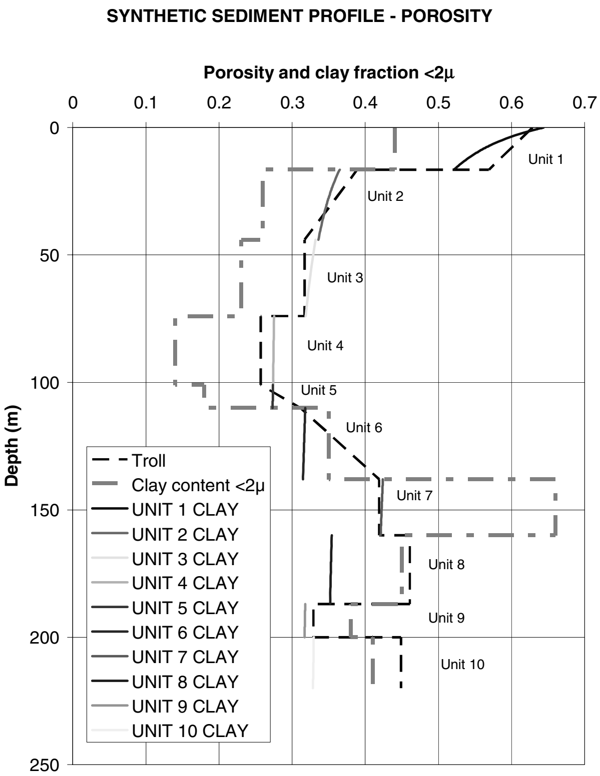

Figure 9. Porosity derived from MECAD.

Figure 9 also shows the clay content profile which is input to the model.

The geomechanical model has also been applied to several North Sea fields for depths up 4000mbsf showing good correlation to well log data. However, diagenetic transformations for clay have not yet been developed or been implemented in the geomechanical model. The present model therefore predicts too high porosities and too low densities for clay sediments subjected to diagenesis.

6 CONCLUSIONS

The models for clay and sand presented in this paper, and implemented in program MECAD, can give realistic depth profiles of porosity and density provided a minimum input of litho-stratigraphy and pressure profile.

The effect of creep has been studied, and we conclude that the contribution of creep is small for sediments with porosities less than 30%, the effect of creep is increasing for porosities in excess of 30% and the effect of creep is significant for porosities in excess of 60%. The implication is that creep plays an important role for porosity reduction in shallow sediments or deeper sediments with high porosities preserved due to overpressure.

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